

国際化推進共同研究概要

〔採択番号〕 25EA-1

タイトル: Mesoscale to microscale variability in the NW-Pacific and
Kuroshio areas

研究代表者: CHANG Ming-Huei

所内世話人: ENDOH Takahiro

研究概要:

令和7年11月20・21日(木・金)に国立台湾大学海洋研究所にて、国際ワークショップを開催した。日本から8名、台湾から10名の研究者、乱流微細構造プロファイラーを製造しているカナダのRockland Scientific社のCEO、その販売代理店であるJFEアドバンテック社の日本・台湾の担当者が参加したほか、台湾の国家科学及技術委員会の局長が講演発表を聴講した。黒潮が海底地形の背後につくる乱流、潮汐流が内部重力波を介して海底地形上方につくる乱流、海底境界層内の乱流やメソスケール・サブメソスケール渦の観測結果、ならびに、これらのパラメタリゼーションについて、生態系や環境場への影響を含む活発な議論があった。

Report on 2025 RIAM International Joint Research Project (#25EA-1)

Mesoscale to microscale variability in the NW-Pacific and Kuroshio areas

CHANG, Ming-Huei

(Institute of Oceanography, National Taiwan University and Ocean Center, National Taiwan University)

Objective

Turbulent mixing plays an essential role in the ocean by smoothing (stirring & diffusion) the distribution of water properties and materials, consequently affecting the physical and biogeochemical environment. As part of the international joint program of RIAM (#18EA-2, #19EA-3, and #20EA-2), we carried out the field experiments over the I-Lan Ridge between Taiwan and Yonaguni Island, Japan, where strong turbulent mixing is caused by the interaction of the Kuroshio current with steep bottom topography. The RIAM researchers also joined the field experiments to deploy their microstructure profiler, TurboMAP-L. Through the intercomparison of the observed data in the research workshop held at RIAM, we quantified the turbulent dissipation and associated nutrient transport in the Kuroshio current over the I-Lan Ridge as well as their downstream extent, the results of which have been published in Q1 journals. Based on the success of our international joint program of RIAM, including the workshop held in Matsuyama (#24EA-2), we decided to collaborate with RIAM on a new research project focusing on the effects of mesoscale (~100 km) and submesoscale (1~100 km) eddies as well as tidal currents on the mixing processes in the Northwest (NW) Pacific and Kuroshio areas.

Primary Members

The members involved in this collaborative research and their roles are:

- CHANG, Ming-Huei (National Taiwan University, Professor): Representative person
- ENDOH, Takahiro (RIAM, Associate Professor): RIAM advisor
- JAN, Sen (National Taiwan University, Professor): Data analysis and numerical modeling
(Note: He was a representative person of #18EA-2, #19EA-3, and #20EA-2)
- YANG, Yiing Jang (National Taiwan University, Professor): Observation and data Analysis
- CHEN, Jia-Lin (National Cheng Kung University, Associate Professor): Numerical Modeling
- CHENG, Yu-Hsin (National Taiwan Ocean University, Assistant Professor): Observation and data analysis

- YEH, Yu-Yu (National Taiwan University, Technician): Observation and data analysis
- HIBIYA, Toshiyuki (Tokyo University of Marine Science and Technology, Emeritus Professor): Theory and numerical modeling

- GUO, Xinyu (Ehime University, Professor): Numerical modeling
- NAGAI, Takeyoshi (Tokyo University of Marine Science and Technology, Associate Professor): Data analysis and numerical modeling
- HASEGAWA, Daisuke (Japan Fisheries Research and Education Agency, Senior Researcher): Observation and data analysis
- INOUE, Ryuichiro (Japan Agency for Marine-Earth Science and Technology, Senior Researcher): Data analysis
- TSUTSUMI, Eisuke (Kagoshima University, Assistant Professor): Observation and numerical modeling
- WANG, Shuya (WPI-AIMEC, Tohoku University, Associate Professor): Numerical modeling
- TAKAHASHI, Anne (AORI, The University of Tokyo, Postdoc Researcher): Data analysis and numerical modeling

Summary of our activities

We held the research workshop entitled “Mesoscale to microscale variability in the NW-Pacific and Kuroshio areas” at Institute of Oceanography, National Taiwan University on November 20-21, 2025. Eight Japanese researchers, 10 Taiwanese researchers, 3 participants from oceanographic instrument manufacturers including a CEO of Rockland Scientific Inc., and a director general of NSTC (National Science and Technology Council) attended the workshop. The research budget provided for this joint research project has been used to support the travel expenses of the following 3 researchers:

- HIBIYA, Toshiyuki (Tokyo University of Marine Science and Technology, Emeritus Professor)
- ENDOH, Takahiro (RIAM, Associate Professor)
- TSUTSUMI, Eisuke (Kagoshima University, Assistant Professor)

At the end of the workshop, we agreed to continue our collaborative research and hold the workshop at Kyoto University in the next fiscal year.

The agenda of the workshop is attached below.



Mesoscale to microscale variability in the NW-Pacific and Kuroshio areas

20-21, November

R215, Building of the Institute of Oceanography, National Taiwan University

● Day 1 (Nov. 20)

9:00-9:20 Registration

9:20-9:30 Opening remarks

Prof. Ming-Chih Lai

Director General, Department of Natural Science and Sustainable Development,
NSTC

Prof. Takahiro Endoh

RIAM, Kyushu University

Section 1: (Chaired by Prof. Toshiyuki Hibiya)

09:30-10:00 Toshiyuki Hibiya (TUMST)

Exploring a new parameterization for abyssal tide-induced near-field mixing

10:00-10:30 Yohei Onuki (KU)

Breaking of internal waves simulated in a distorted domain model

10:30-11:00 Yusuke Sasaki (TU)

Impact of bottom-generated internal waves on spatial structure of near-field turbulent mixing

11:00-11:30 Chien-Pei Yiu (NTU)

Inferring internal solitary wave properties and climatology in the northern South China Sea using bottom pressure recorder

11:30-13:00 Lunch break

Section 2: (Chaired by Prof. Shih-Nan Chen)

13:00-13:30 Shih-Nan Chen (NTU)

A dynamical model for the meridional drift of oceanic mesoscale eddies

13:30-14:00 Shuya Wang (TU)

Submesoscale topographic wake generated by flow-seamount interaction in the Tokara Strait: energy cascade and instability

14:00-14:30 Yu-Hsin Cheng (NTOU)

Drifting Wirewalker Measurements in the Wake Region off Green Island

14:30-15:00 Ming-Huei Chang (NTU)

Instabilities and turbulence of the Green Island wake

15:00-15:30 Coffee break

Section 3: (Chaired by Prof. Takahiro Endoh)

15:30-16:00 Kai-Chieh Yang (NTU)

An overview of Seaglider observations around Taiwan

16:00-16:30 Fabian Wolk (RSI)

Microstructure-based detection of underwater vehicle wakes

16:30-17:00 Takahiro Endoh (KU)

Vertical eddy viscosity observed in a bottom Ekman layer over the continental shelf of the East China Sea

17:00-17:30 Sen Jan (NTU)

Inferring Minjiang River runoff from distinct salinity drops observed by a coastal data buoy

● **Day 2 (Nov. 21)**

Section 4: (Chaired by Prof. Jia-Lin Chen)

09:00-09:30 Jia-Lin Chen (NCKU)

Observations and modeling of vortex structures in the near-field wake

09:30-10:00 Daisuke Hasegawa (FRA)

Diversity and vertical export processes of spring phytoplankton blooms in the Kuroshio–Oyashio confluence region

10:00-10:30 Je-Yuan Hsu (NTU)

Toward Understanding of Air-sea Interaction through Autonomous EM-APEX Floats

10:30-11:00 Yu-Heng Tseng (NTU)

A Sea-ice-modified KPP parameterization and its impacts on AMOC Simulation and Physical Pathways

11:00-11:30 Ying-Chih Fang (NSYSU)

Short-term variability of the Kuroshio in response to an impinging anticyclonic eddy

11:30-12:00 Discussions and closing remark

国際化推進共同研究概要

〔採択番号〕 25EA-2

タイトル: Expanding DustRGB Monitoring for Dust Activity Analysis Across Mongolia: Spring and Autumn Focus

研究代表者: BATBOLD Chultem

所内世話人: YUMIMOTO Keiya

研究概要:

モンゴルから中国北部にわたるゴビ砂漠は、黄砂の主な発生源であり、東アジアの大気環境に大きな影響を与えている。本研究では、従来広く研究がなされてきた広域的な砂塵嵐だけではなく、涸れ池や谷など狭い地域で大量の砂が舞い上がる局所的な発生源（ダストホットスポット）の時空間的パターンとその変化の分析を行った。分析には静止気象衛星「ひまわり8号・9号」観測で得られた放射輝度から算出されたDustRGBやD*パラメータの画像を用い、2017年から2023年の7年間を対象とし、Google Earthに結果を入力することで、現地の地形等の状況と結びつけた発生源の詳細な特定を行った。

その結果、ダストホットスポットおよびゴビ砂漠のダスト活動には大きな年々変動が見られ、2018年以降は明確な増加トレンドが確認された。2017年はダスト検知日数10日、ホットスポット25カ所であったが、2021年にはダスト検知日数54日、ホットスポット160カ所、広域的なストームが17回観測されるなど、黄砂がとても活発であった。春季における黄砂は3月の積雪量が大きく影響することが知られており、2021年3月の積雪量はとても少なかった。また、地理的な特徴として、モンゴル南部のゴビ砂漠周辺が発生源の主体ではあるが、2021年を始めとする黄砂活動の盛んな年では、それに加えモンゴル北東部でも黄砂が発生していることがわかった。近年のダストストームの頻発と激甚化は、気候変動に加え、鉱山開発や過放牧による土地劣化といった人為的要因によって増幅されていることが示唆されており、今後は多衛星データの統合による監視精度の向上と長期的なトレンド分析が必要である。

Expanding DustRGB Monitoring for Dust Activity Analysis Across Mongolia: Spring and Autumn Focus

Department of Environment and Forest Engineering,
School of Engineering and Technology,
National University of Mongolia,
Doctor Chultem BATBOLD

The Content of the Result: *Observed Dust Hotspots Over Mongolia: A Comparative Results of 2017 and 2023*

1. Introduction

Mongolia experiences significant wind storms in the spring and autumn associated with the formation and dissolution of the Siberian anticyclone. Particularly, southern Mongolia is a part of the Asian dust source region, which remains a critical issue in the East Asian region (Shin et al. 2021; Luo et al. 2022), posing major threats to surrounding environment and human health. This summary compares dust detection data over Mongolian territory during the spring months (March to May) in 2017 and 2023, using DustRGB from Japanese Himawari-8/9 geostationary satellite imagery overlaid on Google Earth. March, April, and May are spring months in Mongolia, characterized by transitional weather as temperatures gradually rise from winter to summer. The objective is to identify local dust hotspots and regional-scale dust storms, analyze their patterns, and determine trends over the given periods.

2. Materials

2.1. The region of interest

The region of interest is defined by the coordinates of the southwest (41°N, 87°E), northwest (52°N, 87°E), northeast (52°N, 120°E), and southeast (41°N, 120°E). Afterwards, we identified dust source spots and analyzed them by Increasing the scale.

2.2. Meteorological data

For selecting the time for data analysis, we relied on two meteorological factors: wind speed and cloud cover in the Gobi region, the main source of natural dust in Mongolia. The meteorological data were downloaded from the website ‘Visual Crossing,’ where weather history and forecasts are accessible (<https://www.visualcrossing.com/>). Hourly data can be obtained from the website (in some cases, three-hourly data for wind gusts and air pressure, although this is not always available).

2.3. Satellite image processing

Kyushu University provided the dust RGB retrieval code for Himawari-8/9, the Japanese geostationary satellite. The use of geostationary satellites plays an essential role in monitoring dust dispersion because these satellites can provide temporal coverage of when dust storm events evolve and spatial coverage of how wide the dust plume dispersed (Yamamoto, 2016). Himawari-8/9, a new-generation geostationary meteorological satellite, was launched on October 07, 2014, by the Japan Meteorological Agency (JMA) and put into operation on July 07, 2015. Himawari-8 remained operational until 2022, and its observational role was taken over by Himawari-9, the successor of Himawari-8. The Advanced Himawari Imager (AHI) onboard Himawari-8/9 has 16 spectral channels ranging from 0.47 to 13.3 μm wavelength, consisting of 3 visible, 3 near-infrared, 10 infrared channels. A high temporal resolution of 10-min to scan full disk observation enables Himawari-8/9 to observe continuously monitor specific regions for meteorological phenomena, including dust plumes (Bessho et al. 2016).

2.4. Google Earth base map

We identified the source areas by using Google Base Map as the background for the dust RGB images with a code extraction. Next, the National Atlas of Mongolia (Mongolian Academy of Science (MAS) 2009) was employed for detecting geographical objects that are potential dust hotspots.

2.5. D^* parameter

The D^* parameter was used to detect mineral dust based on thermal infrared observations from the Advanced Himawari Imager (AHI) onboard the Himawari-8/9 geostationary satellite. The D^* algorithm, originally proposed by Hansell et al. (2007) and later refined for East Asia by Shin et al. (2021), exploits the distinct spectral emissivity characteristics of mineral dust in the infrared window region. Specifically, D^* is defined as an exponential function of the ratio between the brightness temperature difference (BTD) of the 10.4 μm and 12.4 μm channels and that of the 8.6 μm and 10.4 μm channels. This formulation enhances dust signals while reducing misclassification of thin cirrus clouds that commonly affect conventional two-channel BTD methods.

In this study, the D^* algorithm was adopted and applied to Mongolia, where dust frequently originates from arid and semi-arid surfaces such as the Gobi Desert, dry lake beds, and disturbed soils. To account for regional surface and atmospheric characteristics, the D^* -based dust detection was combined with masking criteria using $\text{BTD}_{8.6-10.4}$ to suppress false detections over clear-sky desert surfaces and fog-affected regions, following the approach of Shin et al. (2021). This adaptation is particularly important for Mongolia, where strong surface temperature contrasts and low atmospheric water vapor can lead to erroneous dust identification. The resulting D^* parameter provides a robust indicator of dust presence and relative intensity, suitable for continuous day- and night-time monitoring of dust activity over Mongolia.

3. Representative results

In Figure 1 and Table 1, the number of dust hotspots over the years (2017–2023) in March, April, and May can be seen. The dust activity over Mongolia during 2017–2023 exhibits pronounced interannual variability, as reflected in the number of dust-detected days, detected dust hotspots, and regional-scale dust storms. The year 2017 represents a low-activity baseline, with very few dust-detected days and only two regional-scale dust storms during the entire spring season. From

2018 onward, all indicators show a clear increase, suggesting enhanced dust emission and transport conditions. Moderate but persistent dust activity was observed during 2019–2020, accompanied by a substantial rise in detected dust hotspots, indicating widespread activation of dust source regions. Dust activity peaked in 2021, which recorded the highest number of dust-detected days, the largest number of detected dust hotspots, and the greatest frequency of regional-scale dust storms, particularly in March. Although a slight decline is observed in 2022 and 2023, dust activity remains higher than in the early study period, indicating sustained springtime dust conditions. Across all years, March consistently emerges as the most dust-active month, highlighting the dominant role of early-spring surface and meteorological conditions in controlling dust emissions over Mongolia.

Quantitatively, the total number of dust-detected days increased from 10 days in spring 2017 to 31 days in 2018, and remained elevated thereafter, reaching 42 days in 2019, 39 days in 2020, and peaking at 54 days in 2021. Over the same period, the number of detected dust hotspots rose sharply from 25 in 2017 to 59 in 2018, 103 in 2019, and 112 in 2020, with a maximum of 160 hotspots in 2021, indicating widespread activation of dust source regions. Correspondingly, the frequency of regional-scale dust storms increased from only 2 events in 2017 to 5 in 2018, 4 in 2019, and 8 in 2020, before reaching a peak of 17 events in 2021. Although dust activity declined slightly in subsequent years, 121 hotspots and 6 dust storms were recorded in 2022, while 95 hotspots and 17 dust storms occurred in 2023, demonstrating that both dust emission intensity and large-scale dust transport remained substantially higher than during the early study period. These numerical trends reinforce the conclusion that springtime dust activity over Mongolia intensified after 2018, with 2021 representing an exceptional year in terms of both frequency and spatial extent.

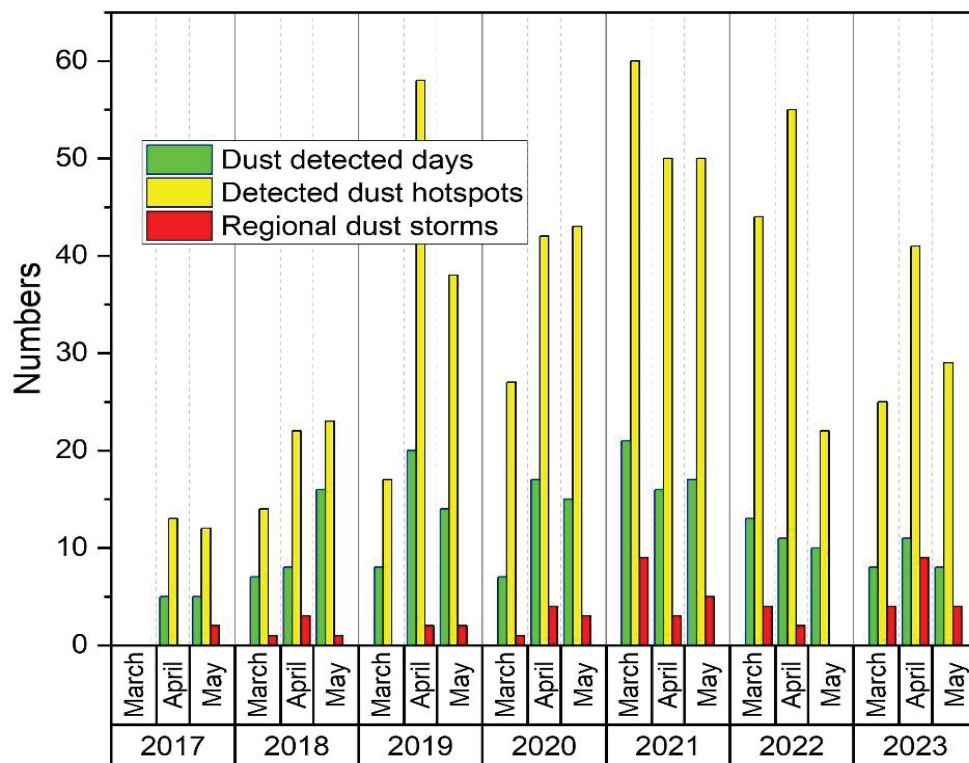


Figure 1. Number of Dust-Detected Days, Dust Hotspots, and Regional-Scale Dust Events Over the Years

Table 1. Number of Dust-Detected Days, Dust Hotspots, and Regional-Scale Dust Events Over the Years

Years, month		Dust detected days		Detected dust hotspots		Regional scale dust storms	
2017	March	0	10	0	25	0	2
	April	5		13		0	
	May	5		12		2	
2018	March	7	31	14	59	1	5
	April	8		22		3	
	May	16		23		1	
2019	March	8	42	17	103	0	4
	April	20		58		2	
	May	14		38		2	
2020	March	7	39	27	112	1	8
	April	17		42		4	
	May	15		43		3	
2021	March	21	54	60	160	9	17
	April	16		50		3	
	May	17		50		5	
2022	March	13	34	44	121	4	6
	April	11		55		2	
	May	10		22		0	
2023	March	8	27	25	95	4	17
	April	11		41		9	
	May	8		29		4	

The spatial distribution of detected dust hotspots reveals strong geographic clustering across Mongolia (Figure 2). Dust hotspots are predominantly concentrated in the southern and southwestern regions, particularly across the Gobi Desert and adjacent semi-arid zones, while comparatively fewer hotspots are observed in the northern, forested, and mountainous regions. Interannual variability is evident, with sparse and localized hotspot occurrences in 2017, followed by a marked expansion in both the number and spatial extent of hotspots after 2018. During peak dust years, especially 2021, hotspots become more densely distributed and spread eastward and northward from the core Gobi source regions, indicating widespread activation of dust-prone surfaces. Persistent hotspot locations appearing across multiple years suggest the presence of recurrent dust source areas, likely associated with bare soil, dry lake beds, mining areas, and degraded pasturelands. Overall, the spatial pattern underscores the dominant role of southern Mongolia as a primary dust emission region while highlighting the increasing spatial influence of dust activity during high-intensity years.

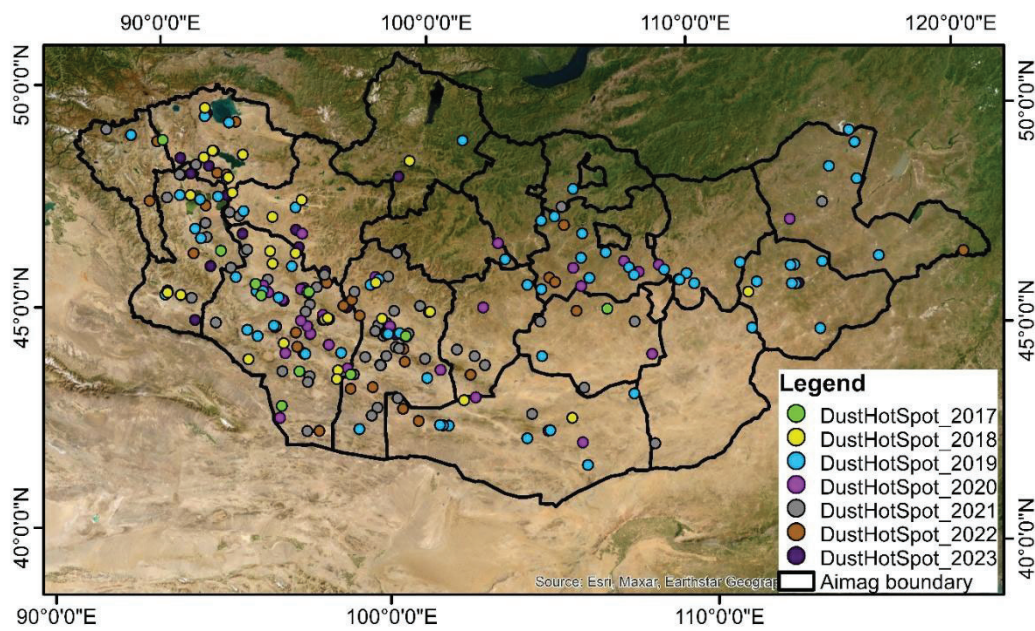


Figure 2. Detected Dust Hotspots, March–May 2017 to 2023.

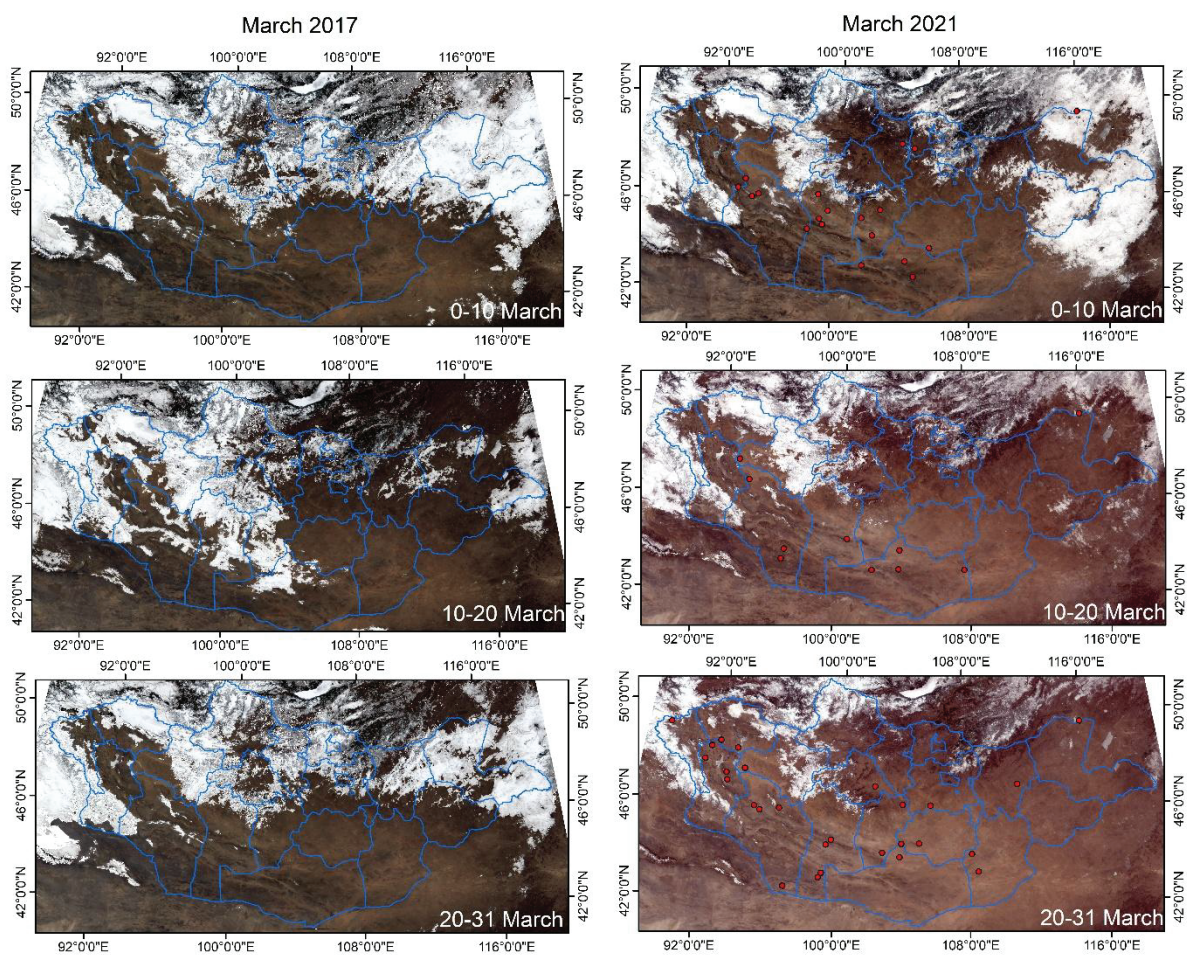


Figure 3. Snow cover in March 2017 and March 2021 by 10 days. <https://mongolia.sibelius-datacube.org/map/EN#>

Several factors influence dust dispersion during the spring season, among which snow cover is particularly important in early spring (March). Snow cover conditions for 2017 and 2021 are presented in Figure 3, representing years with the lowest and highest dust activity, respectively. In March 2017, no dust dispersion was detected, coinciding with extensive snow cover over major dust source regions. In contrast, March 2021 was characterized by substantially reduced snow cover, creating favorable surface conditions for dust emission and dispersion. This contrast suggests a strong suppressive effect of snow cover on dust activity in early spring. To further quantify this relationship, we plan to calculate the statistical association between dust activity indicators and snow cover extent.

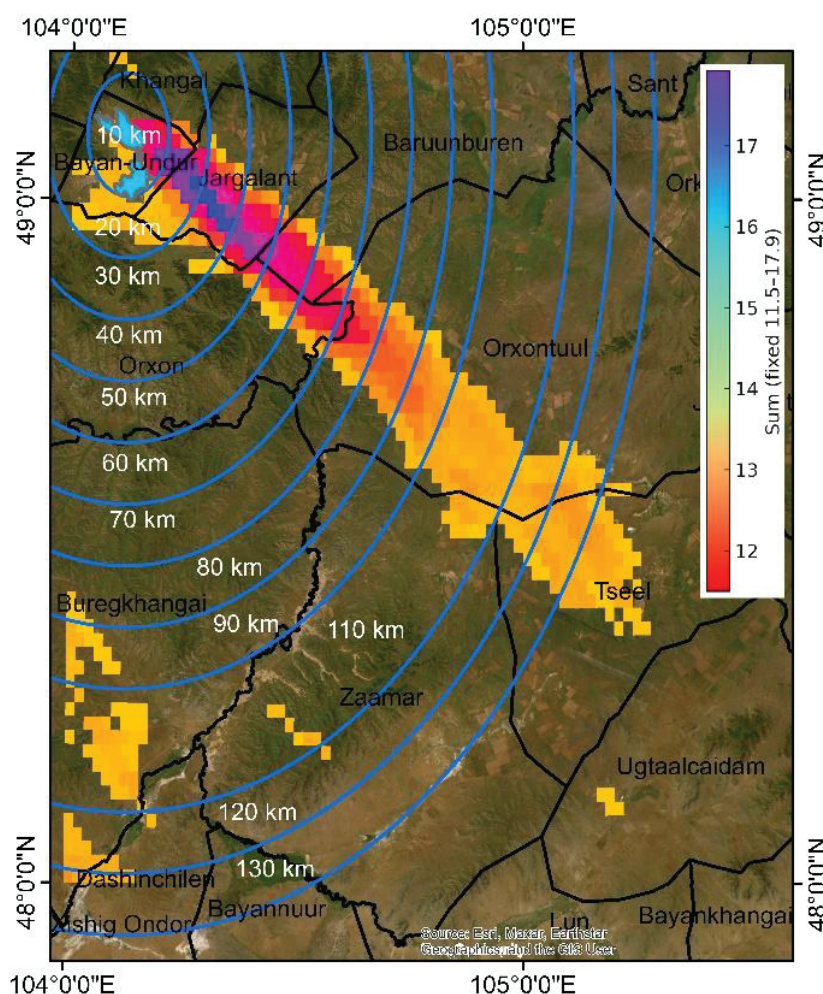


Figure 4. Red component sum from 04:00 to 08:30 UTC, November 11, 2020

We developed composite images to identify the most vulnerable and affected areas influenced by dust source regions by overlapping 10-min resolution satellite observations. A dust event on 11 November 2020 (UTC) is presented as a representative example (Figure 4). This image-processing approach enables the visualization of dust dispersion pathways and the spatial extent of source influence at high temporal resolution. The resulting products provide valuable information for identifying frequently active dust source areas, including those associated with anthropogenic emissions, and can support future dust monitoring strategies and mitigation planning. mitigation strategy of adverse impact in site.

To examine the influence of wind on dust activity, 10 m wind fields from the ERA5-Land reanalysis were used. Figure 5 presents a representative dust event together with the corresponding wind conditions at the time of occurrence. The figure illustrates the role of near-surface wind speed and direction in initiating dust emission and controlling subsequent dust transport.

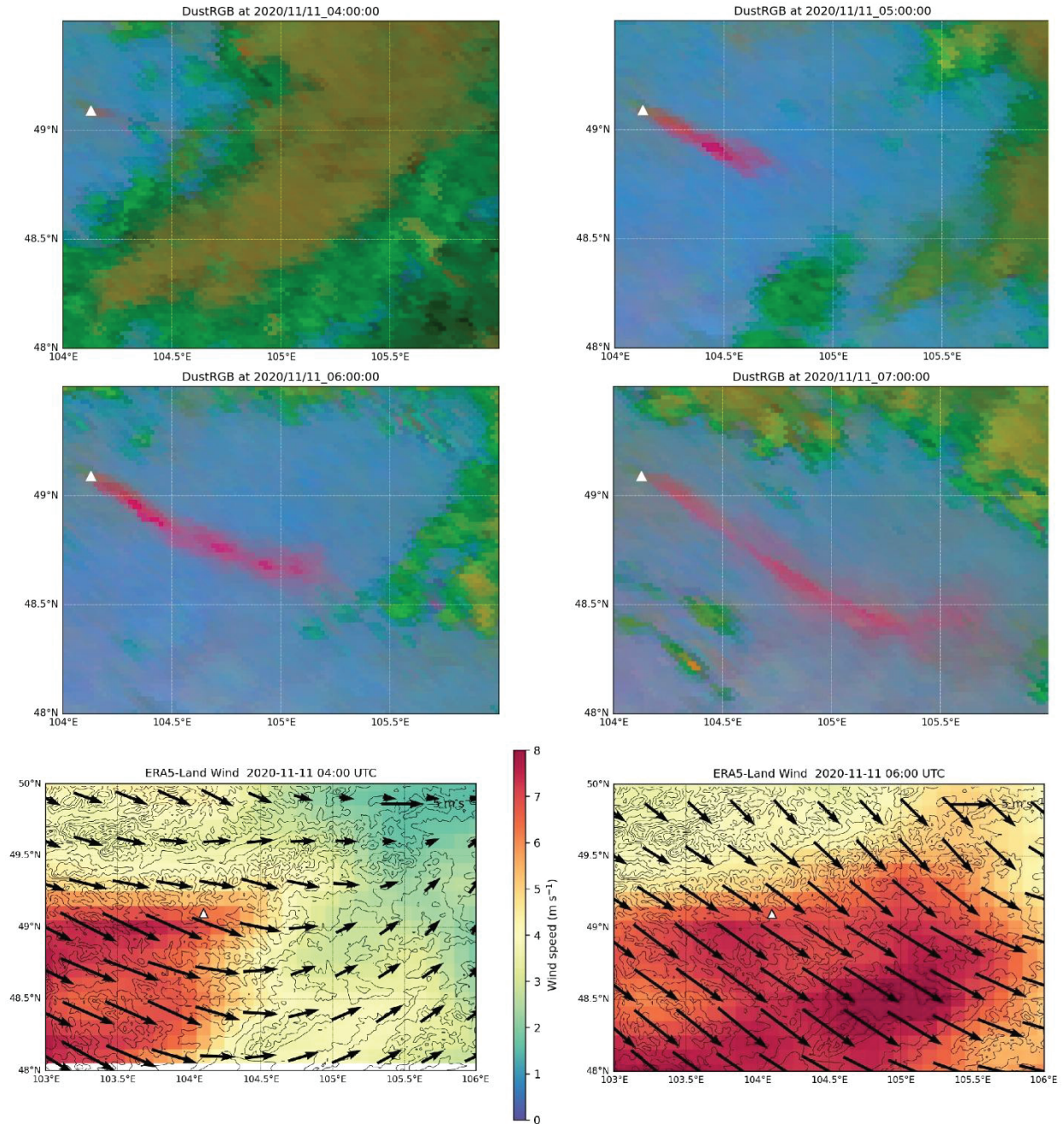


Figure 5. Representative dust RGB images on November 11, 2020. And ERA5-Land 10 m wind field over the Gobi region on 11 November 2020 at 04:00 and 06:00 UTC. Wind vectors (u_{10} , v_{10}) are overlaid on wind speed shading. Topographic contours are derived from the ETOPO1 Global Relief Model.

4. Conclusion

This study provides a comparative analysis of dust activity in Mongolia during the spring months of 2017 and 2023 using Himawari-8/9 DustRGB satellite imagery. The findings highlight key dust hotspots, sources, and dispersion patterns over time. While both years exhibited peak dust activity in April, notable differences emerged in the spatial distribution, intensity, and anthropogenic influence on dust emissions. Particularly, 2023 showed a wider extent of dust activity, with increased contributions from mining, agriculture, and land degradation in the Great Lakes Depression and other regions.

The observed increase in dust storm intensity and frequency suggests that climate change and land use changes may be exacerbating Mongolia's dust emissions. The expansion of mining operations, pasture degradation, and the desiccation of water bodies further contribute to dust dispersion.

Future research should extend the analysis to include additional years (2016–2025) to better understand long-term trends. Incorporating data from other geostationary and medium Earth orbit satellites, such as FY-4A and SEVIRI (Meteosat), could enhance dust detection accuracy and improve dust transport modeling. A multi-satellite approach will provide better spatial and temporal coverage, facilitating a more comprehensive understanding of Mongolia's evolving dust dynamics and their broader regional impacts.

5. References

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国際化推進共同研究概要

〔採択番号〕 25EA-3

タ イ ト ル： Seasonal Predictability of Earth System Processes During Multi-Year La Niña Events

研究代表者： CHIKAMOTO Yoshimitsu

所内世話人： TOKINAGA Hiroki

研究 概 要：

本国際化推進共同研究は、複数年ラニーニャ現象に対する地球システムの応答の力学的理解を深化させ、季節的な予測可能性の向上と国際連携の強化を目的としている。本研究では、複数年ラニーニャ現象を含む熱帯域の大気海洋結合現象の力学が、中緯度域の季節的な水循環の変化、極端現象、および生態系応答に及ぼす影響を調べ、さらに、海洋メモリーの持続性が従来の季節予測を超える時間スケールの予測可能性に与える示唆について、観測および気候モデルの両面から検討した。その結果、複数年ラニーニャ現象は、中緯度域の水循環に甚大な影響を及ぼしており、北太平洋における地球システム過程の季節～十年規模の予測可能性にとって重要であることが明らかになった。今後は、力学的な診断研究・地球システムモデル・予測可能性評価を組み合わせた国際共同研究を推進し、Utah State University、RIAM、九州大学間の連携をさらに発展させる予定である

Seasonal Predictability of Earth System Processes During Multi-Year La Niña Events

Yoshimitsu Chikamoto (Associate Professor, Utah State University)

Primary Member: Hiroki Tokinaga (Professor, RIAM, Kyushu University)

Outcomes in International Joint Research:

Supported by the RIAM International Joint Research program, I conducted research activities in Japan from November 25 to December 12, 2025, with the primary objective of strengthening international collaboration on seasonal predictability through improved dynamical understanding of Earth system responses to multi-year La Niña events. This visit focused on integrating perspectives from climate dynamics, ocean–atmosphere interaction, and Earth system predictability to address emerging gaps in seasonal-to-decadal climate prediction.

During this period, I participated in three international workshops and two invited seminars. The workshops included *the Workshop on Climate Extremes* in Kyoto; *the 2025 International Workshop on Interbasin Interaction, Its Impacts on Predictability, and Related Climate Phenomena* held at the University of Tokyo (Hongo Campus); and the general meeting of *the “Habitable Japan” project supported by the MEXT Grant-in-Aid for Transformative Research Areas (A)* at Hiroshima University. In addition, I delivered seminars at the Department of Earth and Planetary Sciences, Kyushu University, and at the Atmosphere and Ocean Research Institute, University of Tokyo. I also visited the RIAM, Kyushu University, for in-depth discussions on collaborative research planning.

Throughout these activities, close interactions with Prof. Hiroki Tokinaga and other project members facilitated extensive exchanges on ongoing research progress, recent scientific findings, and methodological approaches related to multi-year climate variability. A major focus of discussion was the role of coupled atmosphere–ocean dynamics, including multi-year La Niña events, and how these processes influence seasonal hydroclimate anomalies, extreme events, and ecosystem responses. We examined both observational evidence and modeling perspectives, including the persistence of ocean memory and its implications for forecast skill beyond conventional seasonal timescales.

A key outcome of this international exchange was the identification of seasonal-to-decadal predictability of Earth system processes in the North Pacific as an important and emerging research frontier. While substantial progress has been made in understanding ENSO impacts on interannual variability, our discussions highlighted a significant research gap in understanding how coupled atmosphere–ocean dynamics regulate seasonal-to-decadal variability of marine ecosystems in the North Pacific. Addressing this gap requires coordinated efforts that combine dynamical diagnostics, Earth system modeling, and predictability assessment across multiple timescales.

The visit substantially advanced the foundation for continued collaboration between Utah State University, RIAM, and Kyushu University. Concrete plans were initiated to pursue joint analyses and future funding opportunities targeting seasonal-to-decadal predictability of Earth system processes. Overall, this RIAM-supported research visit successfully strengthened international research ties, clarified shared scientific priorities, and established a clear pathway toward advancing predictive understanding of Earth system processes under persistent climate variability.

Conference Presentation:

[Invited Oral] Chikamoto, Y.: The Role of Tropical Inter-Basin Interactions in the 2020-23 La Niña events. *2025 International workshop on interbasin interaction, its impacts on predictability, and related climate*, Dec 03, 2025 – Dec 04, 2025, Tokyo, Japan and Online.

国際化推進共同研究概要

〔採択番号〕 25EA-4

タ イ ト ル: Bifurcation dynamics of western boundary currents

研究代表者: Chen Shih-Nan

所内世話人: KIDA Shinichiro

研究 概 要:

黒潮は北赤道海流 (NEC) を起源とし、フィリピン沖で北向きの黒潮、南向きのミンダナオ海流に分岐する。本研究は、このフィリピン沖で起こるNEC分岐を支配する力学過程、特に分岐緯度の季節変動を制御するメカニズムを明らかにすることが目的である。観測からは、NECの分岐点が太平洋上の風と比べて極めて弱くしか南北移動しないことが知られている。今年度は、理想化した矩形領域と風の分布を与えた二層モデルを用いて基礎的な力学過程を検討した。数値実験からは風の南北移動と比べて分岐点の南北移動が確かに弱くなることが確かめられた。さらに計算領域の東西幅を拡大しても、分岐点の季節変動の振幅が有限のまま維持されることが明らかになった。これは従来のバロクリニック力学では説明できず、バロトロピック力学が重要な役割を果たしている可能性を示唆している。

Bifurcation dynamics of western boundary currents

National Taiwan University, Shih-Nan Chen

1. Abstract

This project investigates the mechanisms controlling the bifurcation of the NEC along the Philippine coast. During the current fiscal year, we used an idealized two-layer model to examine the underlying dynamics. A key finding is that the seasonal variability of the bifurcation point remains finite even as the zonal extent of the model domain increases. Future work will focus on further diagnosing the model results to clarify the responsible dynamics, particularly the roles of barotropic processes and the island integral constraint.

2. Aim of research

The Kuroshio originates from the North Equatorial Current (NEC), which bifurcates along the coast of the Philippines. The northern branch feeds the Kuroshio, while the southern branch forms the Mindanao Current. This research project aims to improve understanding of the fundamental dynamics governing the bifurcation of the NEC and the processes that control the latitude of the bifurcation point. Observations indicate that the NEC bifurcation latitude varies on both seasonal and interannual timescales, largely in response to latitudinal shifts of the NEC.

3. Method

We employ a two-layer isopycnal model representing the equatorial Pacific, following the configuration of Qiu and Chen (2010). An idealized ocean basin and wind forcing are prescribed to isolate the basic dynamical mechanisms that determine the location of the bifurcation point. Wind forcing moves north and south for 10 degrees on the seasonal time scale. Model results are compared with corresponding analytical solutions.

4. Results

The model successfully reproduces variability in the bifurcation point that agrees well with the analytical solution. The results indicate that the seasonal signal propagates via baroclinic Rossby waves in a manner consistent with the mechanism proposed by Qiu and Chen (2010).

By varying the zonal width of the model domain, we further examined how the seasonal variance of the bifurcation point depends on basin geometry. The analytical solution predicts that the magnitude of the latitudinal variability should decrease and ultimately vanish as the western boundary becomes increasingly distant from the eastern boundary. Contrary to this expectation, the model results show that the variability approaches a finite, nonzero value.

5. Discussion

A key finding is that the seasonal variability of the bifurcation point remains finite even as the zonal extent of the model domain increases. This behavior requires further clarification, given that the

zonal length of the equatorial Pacific is extremely large. We hypothesize that barotropic dynamics—an essential component of the Rossby wave response represented in the two-layer model—play an important role in sustaining this variability. This aspect will be examined in greater detail in future work. In addition, we plan to analyze observational data to evaluate how realistically the two-layer model reproduces the bifurcation dynamics of the North Equatorial Current.

6. Achievements

Workshop presentation

Shinichiro Kida and Shih-Nan Chen, The seasonal cycle of the North Equatorial Current bifurcation point, the origin of Kuroshio, Material circulation and biological, physical, and chemical processes in the East Asian Marginal Seas, 2026/01/06

7. Research Group

Representative Shih-Nan Chen

RIAM advisor Shinichiro Kida

国際化推進共同研究概要

〔採択番号〕 25EA-5

タ イ ト ル: Convective impact on clouds, composition, and dynamics of the upper troposphere and lower stratosphere

研究代表者: UHEYAMA REI

所内世話人: EGUCHI Nawo

研究 概 要:

2025年には米国連邦職員の渡航制限や10～11月の米国政府閉鎖（43日間）により、対面での研究打合せや戦略会議を実施できず、研究の進展に遅れが生じた。しかし上山氏は、NASAのACCLIP航空機観測データを用いた解析に基づく筆頭著者論文を Geophysical Research Letters に発表し、本共同研究の目的に沿った成果を挙げている。また、NURTUREなどのNASA航空機観測計画に気象予報担当として参加し、上部対流圏・下部成層圏の予備観測データにも貢献している。さらに2026年3月2～3日には九州大学西新プラザで「中層大気と対流圏の相互作用」に関するハイブリッド型ワークショップを開催し、日米韓の研究者・学生がのべ26名参加して研究成果の共有を行う予定であり、共同研究費は主要参加者の渡航支援に充てられた。

Convective impact on clouds, composition, and dynamics of the upper troposphere and lower stratosphere

Rei Ueyama (NASA Ames Research Center)

Travel restrictions for US federal employees in 2025 prevented our joint research team – the applicant Rei Ueyama, Prof. Nawo Eguchi (RIAM, Kyushu University), and Dr. Kunihiro Kodaera (i-SPES, Kyushu University) – to meet in person for our annual research discussions and strategy sessions. The 43-day lapse in appropriations (i.e., US government shutdown) in October-November 2025 also caused a set-back in research progress. Despite these circumstances, the applicant has published a first-authored paper in *Geophysical Research Letters* based on NASA Asian summer monsoon Chemical and Climate Impact Project (ACCLIP) airborne data analysis (Ueyama, et al. 2025), a work that is closely aligned with the goals of this international joint research. She also continues to support NASA airborne campaigns as a Meteorological Forecaster (e.g., North American Upstream Feature-Resolving and Tropopause Uncertainty Reconnaissance Experiment – NURTURE), with access to preliminary airborne data in the upper troposphere and lower stratosphere.

In our attempt to best utilize the international joint research funds in 2025, we have organized a two-day workshop on the “Interactions between the Middle Atmosphere and the Troposphere” at Kyushu University in 2-3 March 2026. This hybrid workshop will be attended by approximately 18 scientists and three students from Japan, South Korea, and the US. The goal of the workshop is to share our current research in middle atmospheric processes and their interactions with the troposphere. The applicant will participate remotely and present preliminary results from this international joint research project. We have allocated the joint research funds to support travel of several key attendees.

References

Ueyama, R., Smith, W.P., Brown, M., Jensen, E., Ziemba, L., Bui, T.P., et al. (2025). On the fate of aerosols produced by new particle formation in the upper troposphere and lower stratosphere. *Geophysical Research Letters*, 52, e2025GL116860. <https://doi.org/10.1029/2025GL116860>

Workshop

Title: Interactions between the Middle Atmosphere and the Troposphere

Date: 2-3 March 2026

Location: Nishijin Plaza, Kyushu University

Organizers: Nawo Eguchi, Kunihiro Kodaera, Rei Ueyama and Shunsuke Noguchi

Registration form:

<https://docs.google.com/forms/d/e/1FAIpQLSf4U4ZM5n5VHEbRxiL8UFssH7HnIIZI3WwmMcFRTGLHox9tKg/viewform>

Participants:

On-site

- Prof. Seok-Woo Son, Drs. Young-Ha Kim and Chang-Hyun Park and Mr. Dongchan Hong(student) (Seoul National University)

- Nawo Eguchi, Shunsuke Noguchi, Kunihiro Koda and Toshihiro Hirooka (Kyushu University)
- Dr. Ayako Yamamoto (Obirin University)
- Drs. Patrick Martineau and Akira Yamazaki (JAMSTEC)
- Prof. Masatomo Fujiwara and Dr. Yoshio Kawatani (Hokkaido University)
- Mr. Tomoyuki Shibata (student) (University of Tokyo)
- Dr. Yosuke Yamashita (NIES)
- Dr. Yayoi Harada (MRI)

Online

- Drs. Rei Ueyama and Soo-Hyun Kim (post-doc) (NASA)
- Dr. Mijeong Park (NSF NCAR)
- Prof. Kaoru Sato (University of Tokyo)
- Dr. Yoshihiro Tomikawa (NPI)

国際化推進共同研究概要

〔採択番号〕 25EA-6

タイトル: Sea surface temperature warming of the Japan/East Sea in future climate

研究代表者: SONG Hajoon

所内世話人: KIDA Shinichiro

研究概要: 北西太平洋における将来の海面水温 (SST) 予測は、他の海域と比較して異常に大きな上昇を示しており、今後、日本および韓国周辺の海洋生態系に深刻な影響を及ぼす可能性がある。本研究は、将来気候下において空間的に不均一と予想される日本海 (JES) の海面水温 (SST) および海面塩分 (SSS) 変化の空間パターンを支配するメカニズムを解明することを目的とする。高解像度モデルを用いて力学的ダウンスケーリングを行い、異なる温暖化シナリオのもとで2100年までの海面水温を予測する数値実験を行った結果、現実に近い平均値と季節変動を示す海峡通過流量が再現することに成功した。実験結果は内部変動によってSST上昇の空間パターンが生じていることを示した。今後は、より詳細な熱収支解析を行い、SSTの上昇パターンと通過流量、および亜寒帯前線の位置や東韓暖流との関係を検証する。

Sea surface temperature warming of the Japan/East Sea in future climate

Yonsei University, Hajoong Song

1. Abstract

We aim to examine the mechanism behind the spatial patterns of sea surface temperature (SST) and sea surface salinity (SSS) changes in the future climate using outputs from a high-resolution regional model of the Japan/East Sea (JES). Future projections of ocean states in the JES have been produced using high-resolution ($1/12^\circ$) data under different warming scenarios up to 2100, with a dynamic downscaling method. The changes in SST and SSS between 2020 and 2100 are spatially heterogeneous. The basic heat budgets are examined to determine whether the patterns may be influenced by flow dynamics in the JES, such as the location of the subpolar front and the East Korea warm current.

2. Aim of research

Future projections of the SST over the northwest North Pacific suggest an anomalously large increase compared to other areas of the global ocean, posing significant threats to marine ecosystems near Japan and South Korea. This proposed research aims to investigate the spatial patterns of SST warming in the JES under future climate, which is anticipated to be substantial yet spatially heterogeneous. This collaboration was initiated from the Korea-Japan workshop held in April 2024, where researchers at RIAM presented a study based on observations and an idealized model, titled "Role of Japan Sea Throughflow in the spatial variability of the long-term sea surface temperature trend". The SST warming in the JES in the past 30 years is suggested to be influenced by the flow pattern. Meanwhile, researchers at Yonsei University recently produced a high-resolution future projection of ocean states in the JES. Our goal is to combine the two studies and examine the mechanism behind the SST warming under the future warming scenario.

3. Method

We use outputs from a high-resolution model of the JES based on the MITgcm. Future conditions in the JES are projected using the delta method. Large-scale and long-term climate signals are provided by K-ACE, a global state-of-the-art coupled model developed in Korea. High-resolution spatial and temporal variability along the open boundaries, as well as atmospheric forcing, are prescribed using ERA5 and ORAS5. We evaluate transports through the major straits, SST, and upper-ocean heat content simulated by the model, and examine the mechanisms driving their projected changes.

4. Results

The model successfully reproduces the seasonal cycle of transports through the Korea/Tsushima Strait, Tsugaru Strait, and Soya Strait. The simulated SST shows complex spatial patterns,

highlighting the combined importance of ocean dynamics and local wind forcing. Changes in local winds influence both the strength of the wind-driven gyre in the JES and the position of the subpolar front.

5. Discussion

We have constructed a realistic projection of the JES under future climate conditions. Both the annual mean and seasonal variability of strait transports are well reproduced. A long-term trend in the outflow transports is identified, which may be linked to changes in large-scale wind forcing over the Pacific. Variability in the Kuroshio, as well as changes in stratification near the Korea/Tsushima Strait—the primary heat source for the JES—may also play important roles. The relative importance of these processes requires further investigation, together with an assessment of internal JES changes, including shifts in the subpolar front.

Achievements

Workshop presentation

Chuyuan Zhuang, Shinichiro Kida, Changes of Seasonal Cycle in the Western North Pacific, Ocean monitoring and Wave measurements around seas surrounding Japan, 2025/12/4

A session proposed by Dr. Shinichiro Kida and Dr. Hajoon Song has been accepted for the AOGS 2026 annual meeting. "Physical and Biogeochemical Processes: Observational and Modeling Studies"

6. Research Group

Representative Hajoon Song

RIAM advisor Shinichiro Kida

国際化推進共同研究概要

〔採択番号〕 25EA-7

タイトル : Atmospheric Coupling Process from the troposphere to the thermosphere/ionosphere.

研究代表者 : CULLENS Chihoko

所内世話人 : EGUCHI Nawo

研究 概 要 :

本課題は、対流圏から熱圏・電離圏に至る大気結合過程における重力波の役割を解明する。重力波は下層大気から上層大気へ運動量とエネルギーを輸送し、大気循環や風系、電子密度に大きな影響を与える。特に台風などの対流活動に伴い発生する重力波は中間圏・下部熱圏、さらに電離圏まで伝播する。2018年の台風Yutu事例では、衛星観測（CIPS、AIRS）で同心円状の重力波が捉えられ、ECMWF-IFSやERA5再解析でも同様の構造が再現された。さらに45年分のデータ解析から、重力波運動量フラックスは下部では台風強度と相関するが、約20km以上では背景風の影響が支配的となることが示された。加えてQB0（成層圏準2年周期振動）位相別解析では、西風期の方が高高度まで相関が及び、重力波伝播特性へのQB0影響が示唆された。

Title: Atmospheric Coupling Process from the troposphere to the thermosphere/ionosphere

Chihoko Cullens, University of Colorado at Boulder / LASP

Gravity waves transport momentum and energy from the lower atmosphere to the upper atmosphere and drive atmospheric circulations. Convectively generated gravity waves can propagate up to the mesosphere and lower thermosphere, and even higher into the thermosphere and ionosphere, and cause large disturbances in winds and electron densities in the upper atmosphere (e.g., Vadas & Liu, 2013, Cullens et al., 2023). Therefore, it is important to understand coupling process between the troposphere/stratosphere to the thermosphere through gravity waves.

Figure 1 shows typhoon-generated gravity wave comparisons between observations and the high-resolution European Centre for Medium-Range Weather Forecasting Integrated Forecasting System (ECMWF-IFS) and ECMWF reanalysis v5 (ERA5). The satellite-based Cloud Imaging and Particle Size (CIPS) instrument and Atmospheric Infrared Sounder (AIRS) observed concentric gravity waves generated by Typhoon Yutu in late October 2018 at altitudes of 50–55 and 30–40 km, respectively. These concentric gravity wave characteristics compared well with ECMWF-IFS and ERA5. Concentric GWs simulated by ECMWF and ERA5 occur at similar locations and timing as the AIRS and CIPS observations.

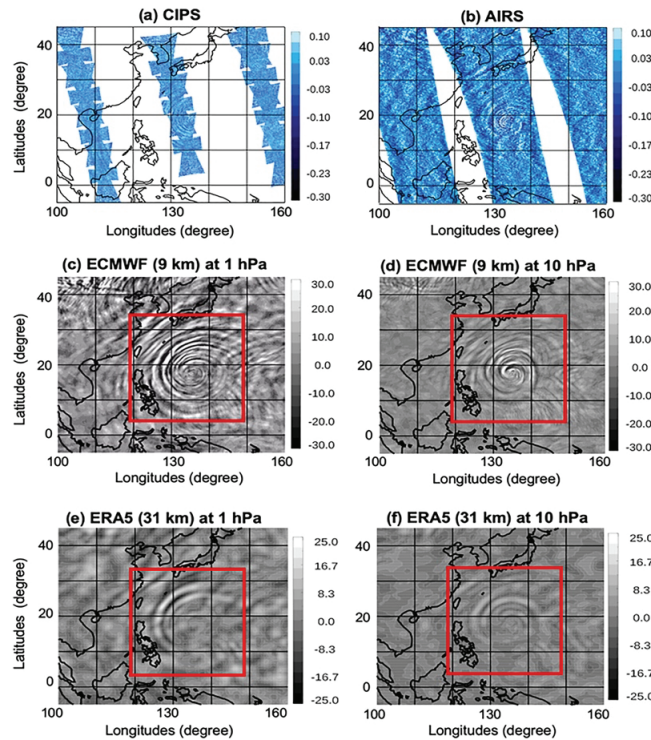


Figure 1. Snapshots of concentric GWs from (a) CIPS RAA(%) at ~50–55 km and (b) AIRS brightness temperature (K) at ~30–40 km and vertical wind perturbation from (c, d) ECMWF-IFS and (e, f) ERA5 at 1 hPa and 10 hPa on October 27, 2018. Red boxes indicate $\pm 15^\circ$ from the center of typhoon locations.

Based on our case studies, we have analyzed 45 years of ECMWF and ERA5 data to study relative importance of gravity wave propagation conditions (background wind conditions) and gravity wave sources (strength of typhoon).

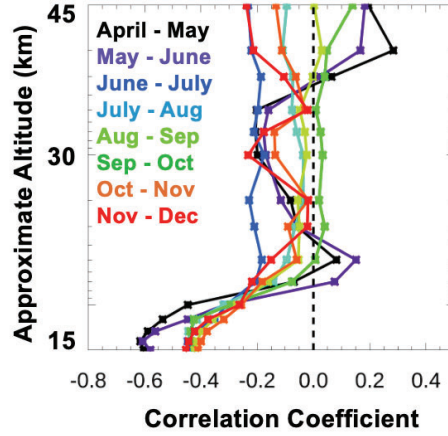


Figure 2. Correlation coefficient between GW-MF and minimum pressure of typhoon. Different colors represent different months.

Figure 2 shows correlation coefficient between strength of typhoon (minimum central pressure of typhoons) and gravity wave momentum flux (GW-MF) at each altitude. There are negative correlations between minimum central pressure of typhoons and GW-MF below 20 km altitudes; however, such correlations disappear above ~ 20 km. On the other hand, changes in background wind indicated by wind rotation and speed have negative correlations above ~ 20 km. These results suggest that influences of strength of typhoons are stronger up to ~ 15 km, then background winds that affect gravity wave propagation are more important above ~ 20 km for atmospheric coupling process.

Furthermore, in order to understand quasi-biannual oscillation (QBO) influences on GW and typhoons, typhoon cases are separated by phases of QBO at 30 hPa. Based on availability of data, we have analyzed 651 typhoon cases. Out of 651 typhoon cases, XXX are eastward phase of QBO (QBO-E), and XXX are westward phase of QBO (QBO-W). Correlations are shown in Figure 3. During QBO-W, negative correlations extends higher than during QBO-E phase. It could be due to preferred propagation directions of gravity waves; however, further analysis is needed to understand QBO influences on typhoon-generated GWs. Our results were presented at International Workshop on Typhoon Science and Technology Research 2025 (IWTRC 2025) in October 2025, and these results will be summarized and submitted to JGR-Atmosphere in 2026.

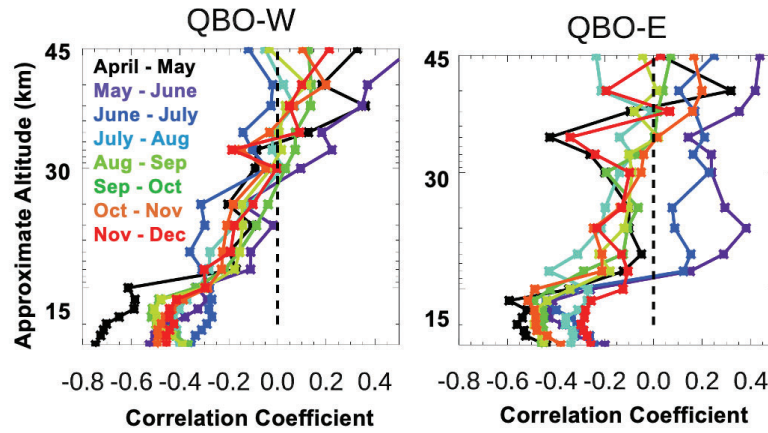


Figure 3. Same as Figure 2 but results are separated by QBO phases. QBO winds are identified by zonal winds at 30 hPa from ECMWF data.

国際化推進共同研究概要

〔採択番号〕 25NU-1

タイトル: ECRH/ECCD modeling for QUEST by use of ray-tracing and Fokker-Planck codes

研究代表者: BERTELLI Nicola

所内世話人: IDEI Hiroshi

研究概要:

QUEST 装置同様の球状トカマクであるスペイン・SMART 装置での電子サイクロトロン加熱・電流駆動の解析内容を議論した。報告書では主に議論した、SMART 装置での電子サイクロトロン加熱・電流駆動の解析をまとめた。2月26、27日に開催された応用力学研究所国際推進の共同研究で開催されたワークショップにて解析結果を発表し、ワークショップ参加者と議論した。QUESTでのプラズマ平衡配位を基に、QUESTでの解析を始めている。SMART 装置での解析同様に課題となる、密度が低い場合の非線形効果の扱いについて議論した。

QUEST-PPPL research collaboration by Nicola Bertelli (Feb. 27, 2026)

In the research period, Nicola Bertelli has performed a number of simulation calculations using GENRAY and TRAVIS ray-tracing codes on SMART device.

We focus on two planned operational phases characterized by different magnetic field strengths: 0.4 T and 1.0 T, which are in close relation with the QUEST experimental plan.

Throughout the simulations, an extraordinary (X-) mode polarization was assumed due to its larger absorption compared to the ordinary (O-) mode.

B = 0.4 T Plasma Scenario

In the 0.4 T scenario, we assumed a wave frequency of 28 GHz, where absorption occurs at the second harmonic. The study evaluated three specific launching positions corresponding to realistic future locations of the vacuum vessel parts.

Mid-Plane Launcher

Simulations scanned the toroidal steering angle from 0° to 30° assuming 0° poloidal angle. Table 1 summarizes the EC absorption (in percentage) for different core electron density and two values of electron temperature: 0.5 KeV and 1 KeV.

$\alpha = 0^\circ$	$n_e = 1.0 \times 10^{18} \text{ m}^{-3}$	$n_e = 1.5 \times 10^{18} \text{ m}^{-3}$	$n_e = 5.5 \times 10^{18} \text{ m}^{-3}$
$T_{e,0} = 0.5 \text{ keV}$	17% ($\beta = 19^\circ - 21^\circ$)	23% ($\beta = 17^\circ - 21^\circ$)	45% ($\beta = 3^\circ - 5^\circ$)
$T_{e,0} = 1.0 \text{ keV}$	30% ($\beta = 17^\circ - 22^\circ$)	40% ($\beta = 17^\circ - 22^\circ$)	68% ($\beta = 3^\circ - 5^\circ$)

Table 1. EC absorption (in percentage) for $B = 0.4 \text{ T}$ plasma scenario and mid-plane launcher with $\alpha = 0^\circ$ and $\beta = [0^\circ - 30^\circ]$.

Off-Mid-Plane Launcher

Simulations scanned the toroidal steering angle from 0° to 30° and the beam was angled poloidally at -45° to target the plasma center.

Table 2 summarizes the EC absorption (in percentage) for different core electron density and two values of electron temperature: 0.5 KeV and 1 KeV.

$\alpha = -45^\circ$	$n_e = 1.0 \times 10^{18} \text{ m}^{-3}$	$n_e = 1.5 \times 10^{18} \text{ m}^{-3}$	$n_e = 5.5 \times 10^{18} \text{ m}^{-3}$
$T_{e,0} = 0.5 \text{ keV}$	17% - 23% ($\beta = 20^\circ - 21^\circ$)	33% ($\beta = 20^\circ$)	36% - 43% ($\beta = 2^\circ - 13^\circ$)
$T_{e,0} = 1.0 \text{ keV}$	25% - 35% ($\beta = 19^\circ - 21^\circ$)	38% - 51% ($\beta = 19^\circ - 20^\circ$)	58% - 65% ($\beta = 0^\circ - 12^\circ$)

Table 2. EC absorption (in percentage) as in Table 1 for off- mid-plane launcher condition with $\alpha = -45^\circ$ and $\beta = [0^\circ - 30^\circ]$.

Top Launcher

To aim the beam at the plasma center, poloidal angles between 75° and 85° were scanned. This launcher position yielded the highest overall power absorption. Summary of the main results are shown in Table 3 below.

	$n_e = 1.0 \times 10^{18} \text{ m}^{-3}$				
β	0°	5°	10°	15°	20°
$T_{e,0} = 0.5 \text{ keV}$	68%	45%	75%	65%	53%
$T_{e,0} = 1.0 \text{ keV}$	85%	70%	87%	81%	73%

	$n_e = 1.5 \times 10^{18} \text{ m}^{-3}$				
β	0°	5°	10°	15°	20°
$T_{e,0} = 0.5 \text{ keV}$	68%	62%	71%	69%	69%
$T_{e,0} = 1.0 \text{ keV}$	87%	84%	89%	94%	85%

	$n_e = 5.5 \times 10^{18} \text{ m}^{-3}$				
β	0°	5°	10°	15°	20°
$T_{e,0} = 0.5 \text{ keV}$	61%	57%	50%	44%	44%
$T_{e,0} = 1.0 \text{ keV}$	84%	80%	74%	68%	67%

Table 3. EC absorption (in percentage) as in Table 1 for top launcher condition with $75^\circ \leq \alpha \leq 85^\circ$ and $\beta = [0^\circ, 5^\circ, 10^\circ, 15^\circ, 20^\circ]$.

B = 1.0 T Plasma Scenario

For the higher magnetic field phase of 1.0 T, the study explored a newly proposed X-I mode EC scheme intended for plasma start-up. This phase evaluated absorption at the fundamental harmonic using two different wave frequencies: 28 GHz and 35 GHz.

Evaluation of the power absorption and current drive is shown in figure 1 for the X-I mode scenario assuming a central density of $1.0 \times 10^{17} \text{ m}^{-3}$ and temperature of 0.1 keV and 0.2 keV.

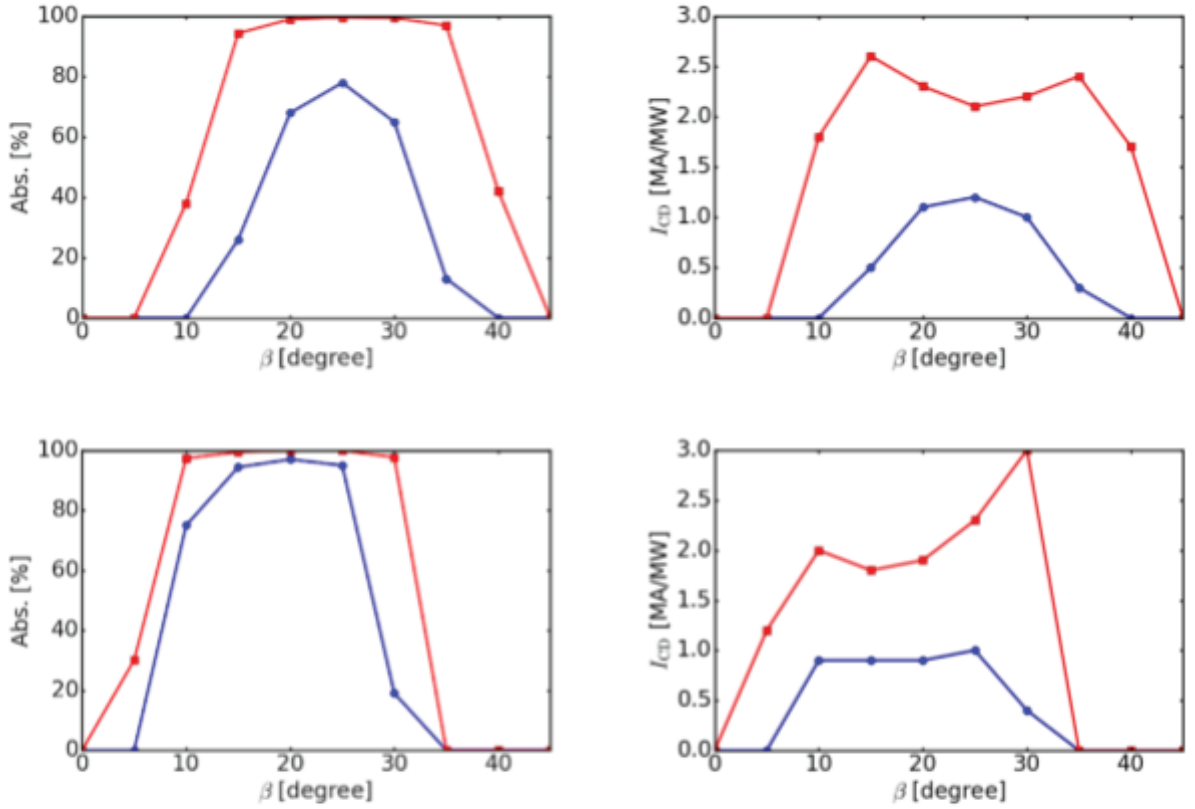


Figure 1. EC power absorption (left) and total EC current drive (right) per MW as a function of the β angle for $f = 28$ GHz (top) and $f = 35$ GHz (bottom), $\alpha = 0^\circ$, and $1.0 \times 10^{17} \text{ m}^{-3}$. $T_e = 0.1$ keV (0.2 keV) results are indicated in blue (red).

For low-density cases, the EC power absorption is virtually 100% across a wide range of toroidal angles (15° to 35°) at a temperature of 0.2 keV for both wave frequencies.

In this linear calculations, the generated current drive is highly efficient. At a central temperature of 0.2 keV, the 28 GHz frequency generated up to 2.5 MA/MW, while the 35 GHz frequency achieved up to 3.0 MA/MW.

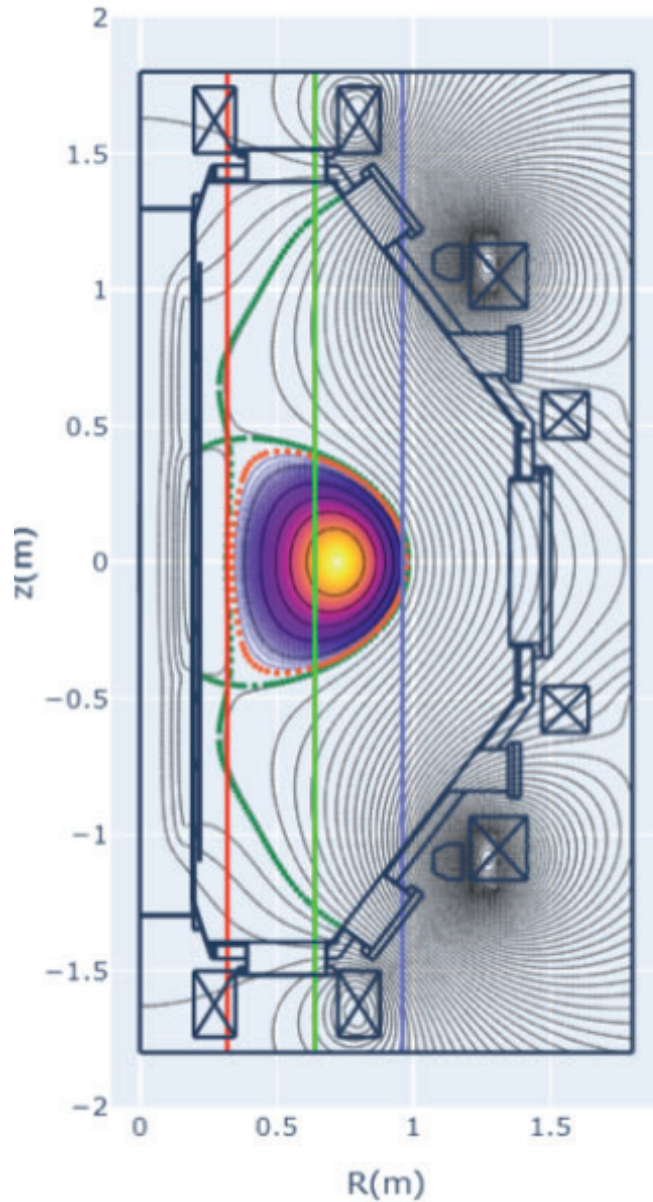
Power absorption decreases rapidly as plasma density increases because the physical distance between the EC resonance and the X-cutoff layer widens. Despite this drop in absorption, the current drive remains large (between 1 and 2 MA/MW).

Utilizing the higher 35 GHz wave frequency relaxes the density constraints, permitting higher power absorption at lower temperatures and higher densities.

In this work, the EC power deposition and EC current drive have been evaluated in the linear regime without considering potential nonlinear effects due to the low density regime.

These nonlinear effects will be presented in a future work. In particular, we plan to investigate $B = 0.5$ T and 1 T plasma scenarios for QUEST plasmas taking into account the non-linear effects by using the coupling between GENRAY ray tracing code and the Fokker-pLanck code CQL3D.

Figure 2 shows the QUEST equilibrium will be used for both the ray tracing simulations and



Fokker-Planck simulations. One can note, for this specific magnetic reconstruction at $B = 0.5$ T, the presence of fundamental resonance (red line) on the high-field side, just outside the last closed flux function and the second (green) and third (blue) EC resonances.

For this plasma scenario, we are expecting dominant absorption at the second harmonic as similarly found for the SMART device.

国際化推進共同研究概要

25NU-2

タイトル： Fullwave simulation of electron Bernstein wave mode conversion

研究代表者： SHIRAIWA Syun' ichi

所内世話人： 出射 浩

研究概要：

電子パーンスタイン波は有限温度の効果がある時に伝播する静電波で、従来の波動計算手法では2次元以上の空間で計算することが難しい。有限要素法の中で有限温度の効果を取り扱う新たな方法を開発しており、これを電子パーンスタイン波の波動計算適用することを試みている。年次報告では一次元のスラブ近似での計算結果をまとめた。今後の二次元への拡張と QUEST 実験への適用を議論し、検討を始めた。

Fullwave simulation of electron Bernstein wave mode conversion

S. Shiraiwa (Princeton Plasma Physics Laboratory)

We are developing a fullwave simulation model of the electron Bernstein wave (EBW). The EBW is an electrostatic wave and it does not appear under the cold plasma approximation. Instead, it connects to the cold plasma wave branch at upper-hybrid resonance (UHR). As the wave propagates away from UHR, the wave becomes very short compared to the electron cyclotron Larmor radius. Therefore, an accurate fullwave simulation requires a plasma dielectric model that includes all finite Larmor radius (FLR) order effects. In this regard, the full spectral representation used in the AORSA code is attractive. However, due to the small wave length compared to the plasma size, the computational resource required for resolving the wave field would be quite high. Alternatively, we chose the finite element method (FEM) and developed a novel approach to introduce the FLR effects in FEM [1]. In our method, we start from a uniform plasma Maxwellian dielectric model. For the EBW mode conversion simulation shown in the figure 1, we introduced the approximation approach discussed in [1] to so-called Stix's S using the AAA algorithm[2]. Then, we solved the resultant coupled equations for E and J simultaneously.

Figure 1 shows a simulation of EBW generation via mode-conversion from the X-mode injected from the left in the 1D slab geometry. The wave frequency and other plasma parameters are based on the O-X-B mode conversion study for NSTX [3]. In figure 1, the wave length of EBW matches with what is expected in the uniform plasma. Detailed analysis showed that the wave energy flux given as the Poynting flux before the mode conversion agrees with the kinetic energy flux computed by the sloshing term after the mode conversion. This indicates that the discretized system correctly conserved the wave energy flux. Manuscript for reprothing this work in a peer-reviewed journal is in preparation.

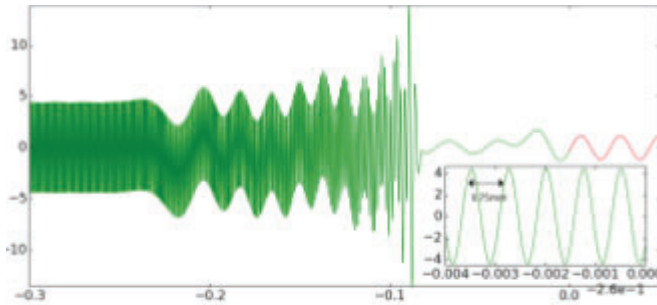


Figure 1: Simulation of the mode conversion of O-mode to the EBW via the O-X-B mode conversion.

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国際化推進共同研究概要

〔採択番号〕 25NU-3

タ イ ト ル： Free energy calculations in PANTA and PLATO: verifying turbulence predictions with experiments

研究代表者： MACKENBACH Ralf

所内世話人： MOON Chanhho

研究 概 要：

本共同研究では、プラズマ乱流の予測可能性を検証するため、乱流駆動に利用可能なエネルギーに基づく理論解析とPANTA・PLATO実験との比較を進めた。場の方程式との整合性を考慮することで、乱流が取りやすい特徴的な揺動スケールを導出し、実験検証が可能な形で提示した。PANTAでは電子温度の半径分布に着目し、理論スケーリングとの対応を調べるとともに、数値シミュレーションによる裏付けを行う計画である。また、線形的には安定であっても非線形的に不安定となり得る領域を同定し、その理解に向けた解析基盤を整備した。

これらの成果は今後の実験連携と理論発展を進める上で重要な指針を与えるものである。

The *International Joint Research Grant* (No.10_25NU-3) has been a successful undertaking, with more research currently underway. The main theoretical findings and routes for experimental collaboration with associate professor C. Moon (ムンチャンホ文贊鎬/문찬호 교수), relevant for the Joint Research Grant. Before highlighting the findings, an introduction to the methodology is in order, as will be done in the proceeding section

Introduction

The main theoretical tool used for understanding and/or bounding turbulence in plasmas, is plasma thermodynamics. Such methods have a long history [1], and have recently been receiving attention as methods to bound linear instabilities and/or turbulent energy. Specifically, it has been found that a quantity coined ‘available energy’ (A) correlates with the nonlinear energy flux in fusion experiments [2], hinting at predictive capabilities in the nonlinear regime.

This energy bound stems from two simple

properties, present in many plasma systems. Firstly the total energy (E_{tot}), which is the sum of kinetic (E_K) and field energy (E_F), is a conserved quantity. Secondly, one is able to bound the kinetic energy of the system by some lower bound, E_{min} . As such, the energy is the field as bounded from above as

$$E_F = E_{\text{tot}} - E_K \leq E_{\text{tot}} - E_{\text{min}} \equiv A.$$

The crux of the matter is, of course, how one constructs the lower bound E_{min} . In Gardner’s seminal paper [3], the main constraint in constructing this lower bound is conservation of the so-called ‘Casimir’ invariants, which are conserved quantities due to Liouville’s theorem. However an order-unity error persists when including the Casimir invariants alone, as the field-equations (e.g., Poisson’s equation) couple the distribution function to the field, and one should take care to ensure that they are consistent. A sketch of what the minimal-energy distribution function looks like without and with the constraint of the field equations, is added in Figure 1.

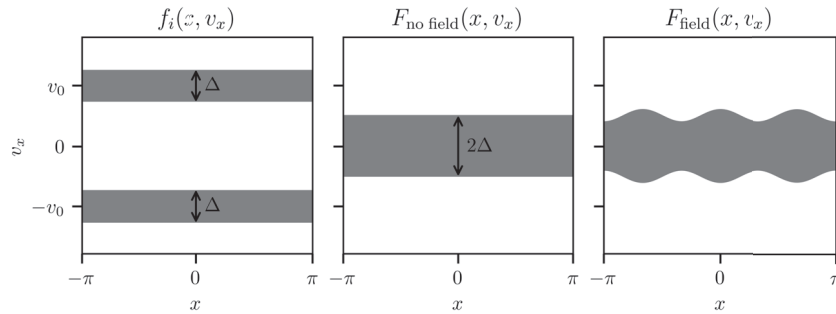


Figure 1: Left: Initially unstable distribution function. Middle: minimal-energy state without a consistent field. Right: minimal-energy state with a consistent field

Correcting for this important coupling yields measurable quantities, namely ‘optimal’ fluctuation length-scales that maximise the field energy—a point of comparison for experiments. To this end, several interesting findings shall be highlighted that are relevant for collaboration.

Findings

Firstly, by using the electrostatic gyrokinetics equations and the conservation of total energy [4], it has been shown that (in the drift-kinetic limit) energy-maximising electrostatic modes are monochromatic with wave-number

$$\rho_i k_y = (T_i^2/T_e^2 + T_i/T_e)^{1/4}.$$

The same result is found in simple Vlasov–Poisson plasmas, only with the Debye length being the relevant length scale. With this length-scale the available energy is reduced by about a factor 5 in plasmas with species of equal temperature. This suggests a robust nature of the result, and may be verified in experiment. A plot of the lengthscale and the adjusted available energy is given in Figure 2.

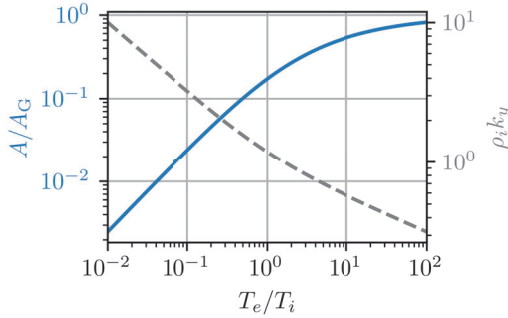


Figure 2: Fraction of energy that is available compared to the case without the constraint of the field equations (blue, solid), and the energy-maximising lengthscale (gray, dashed)

To this end, we propose experimental measurements in PANTA [5], where the ratio T_e/T_i changes as a function of radius.

Since T_i is unknown but the ion gyroradius is large, we may assume that $\nabla T_e/\nabla T_i \ll 1$ so that most variation is from the electron temperature. In this manner, one may focus on the variation in T_e across the radius, and see if the modes follow the expected scalings. Such measurements will be supplemented with simulations, further verifying/falsifying whether the predictions hold. The manuscript of this research, with predictions specific for linear devices like PANTA, has been submitted recently with acknowledgement of the gracious funding of Kyushu University [6].

Secondly, a region in parameter space ($\nabla \ln n, \nabla \ln T_i$) has been identified that is linearly stable [7], that may nonetheless be nonlinear unstable [8] (see Figure 3). This provides an interesting region in parameter space with tension between linear and nonlinear results. Simulations are to be performed in this region in parameter-space, as well as exploring if such a region can be accessed experimentally. Furthermore, a large database of nonlinear turbulence simulations ($> 6 \times 10^4$) has been constructed, with parameters somewhat relevant for PLATO [9]. It is currently discussed how this database may be used to inform experiments.

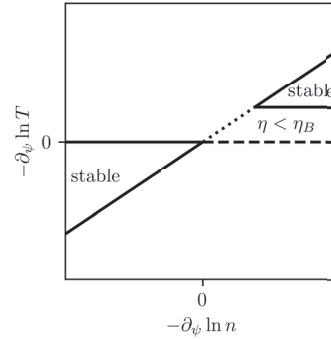


Figure 3: The region of nonlinear (in)stability. The notched region between the dashed, dotted, and solid line is linearly stable but may be nonlinear unstable.

Finally, this work has been disseminated in a presentation at the RIAM seminar room,

made accessible for both students and researchers. This has prompted more questions, viz. the possibility of using similar methods in reduced models [10]. Such possibilities are currently looked into.

Conclusion

All in all, the *International Joint Research Grant* is providing new routes for collaboration and scientific exploration. Further research is expected together with C. Moon and lab members, and this has been made possible by Grant No.10_25NU-3.

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国際化推進共同研究概要

25NU-4

タイトル: Real time modeling of QUEST ECCD experiment using the RT-4 code
by PPPL

研究代表者: ONO Masayuki

所内世話人: 出射 浩

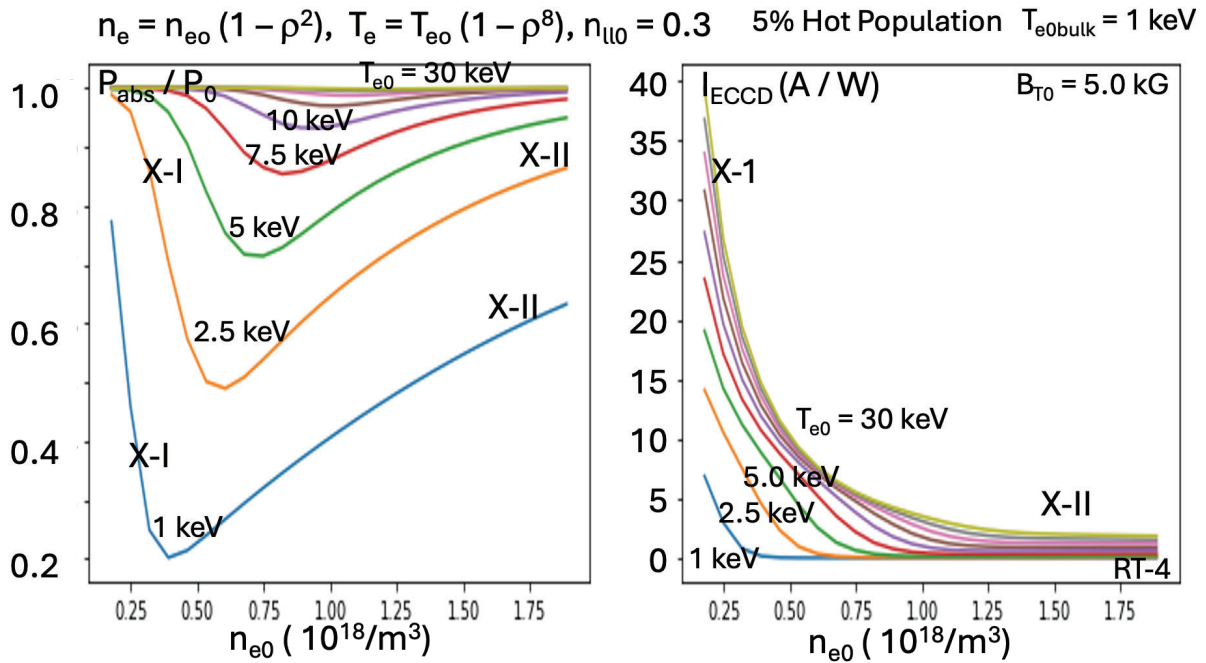
研究概要:

米国・プラズマ物理研究所の光線追跡コード RT-4 を用い、QUEST で計画されている磁場 0.5 T、更なるアップグレードでの 1T, 2T での基本・第二高調波異常波を用いた複数共鳴での電子サイクロトロン加熱(ECH)・電流駆動(ECCD)を検討・評価した。0.5 T での 28 GHz 波での ECCD にて 5 - 10 A/W といった極めて高い電流駆動効率が得られた。また、1T、2T で 51 GHz 波, 113 GHz 波を用いた ECCD での電流駆動効率は 2 - 4 A/W, ~ 1 A/W と評価された。

QUEST-PPPL research collaboration by Masayuki Ono (Feb. 27, 2026)

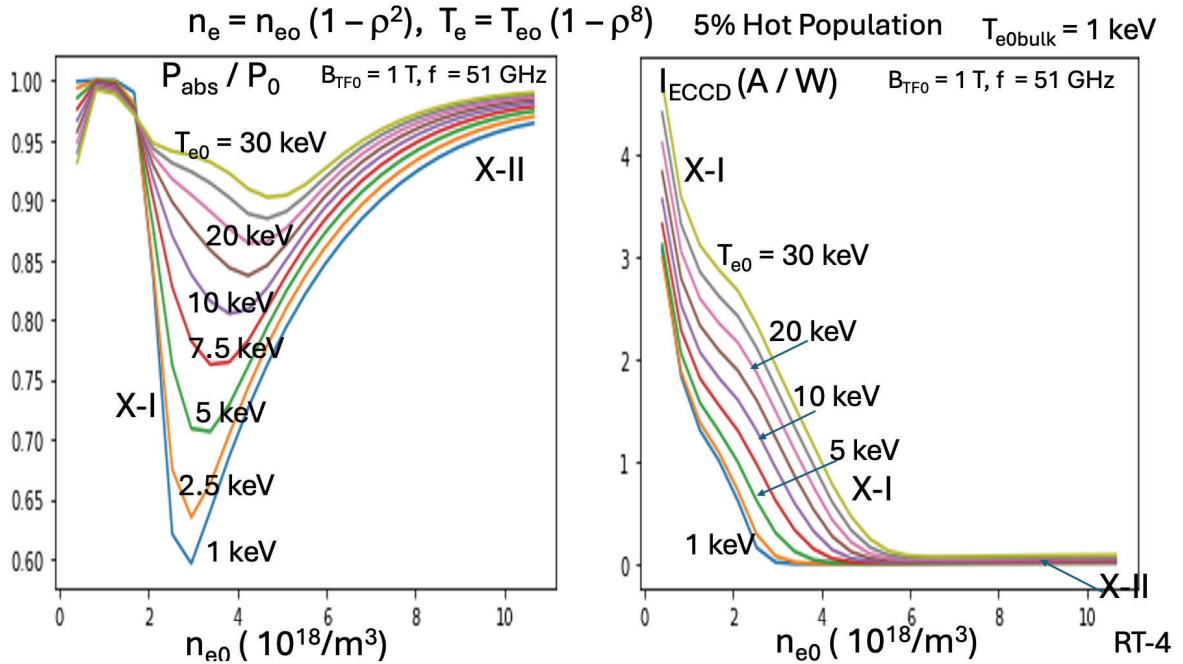
Work in collaboration with Prof. Hiroshi Idei and Kazuaki Hanada.

In the research period, Masayuki Ono has performed a number of simulation calculations using the PPPL's RT-4 ray-tracing code on X-I performance on QUEST and QUEST upgrade in collaboration with Prof. Hiroshi Idei and Prof. Kazuaki Hanada. To support the ongoing QUEST experiment using the 28 GHz gyrotron, the X-I wave ray-tracing calculations were performed for various toroidal magnetic fields (B_T) values from 2.5 kG to 5 kG in step of 0.5 kG. The bulk temperature of 1 keV. And 5 % hot population of various temperatures up to 30 keV. The strong X-I effects were seen above $B_T = 4$ kG. The predicted absorption and ECCD of the X-I and X-II are shown in the figure below.



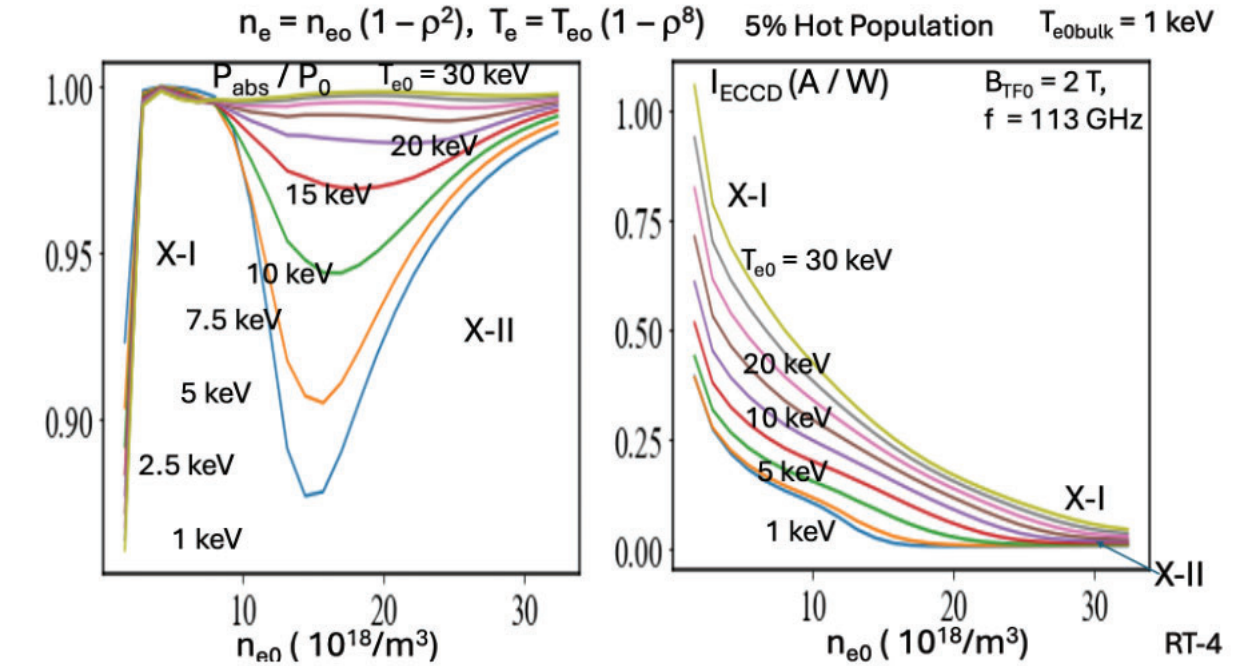
Power absorption and I-ECCD for X-I and X-II. T_{e0} of hot component scanned from 1 keV to 30 keV. Bulk T_{e0} is 1 keV

Another set of RT-4 calculations were carried out for the QUEST upgrade devices with $B_T = 1$ using the gyrotron frequencies of 51, 56, 58, 59, 60, and 62 GHz. 5% hot electron populations were assumed. With frequency lower than 60 GHz, strong X-I absorption is observed with high ECCD efficiency of ~ 2 A/W for the 56 GHz gyrotron. Even higher ECCD efficiency is obtained at 51 GHz as shown in the figure below.



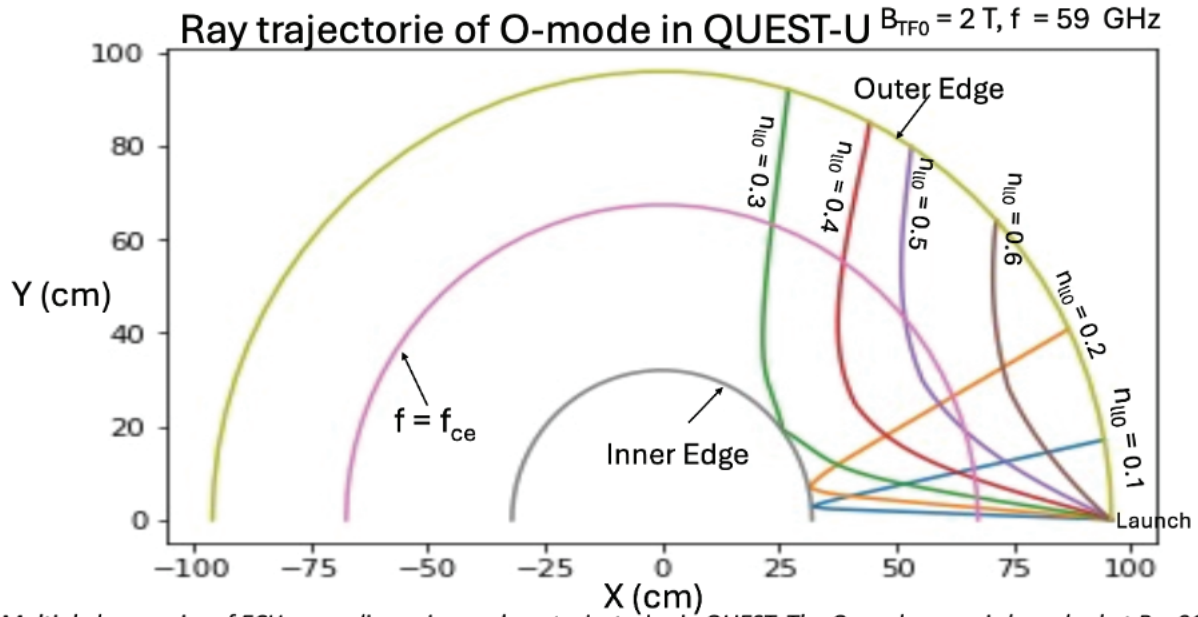
Power absorption and I-ECCD for X-I and X-II. T_{e0} of hot component scanned from 1 keV to 30 keV. Bulk T_{e0} is 1 keV

For the 2 T operations, the gyrotron frequency of 124, 120, 116, and 113 GHz were performed. As the frequency is lowered, the higher X-I absorption and ECCD were observed with at 113 GHz, $\sim 1 \text{ A/W}$ was obtained as shown in the figure below.

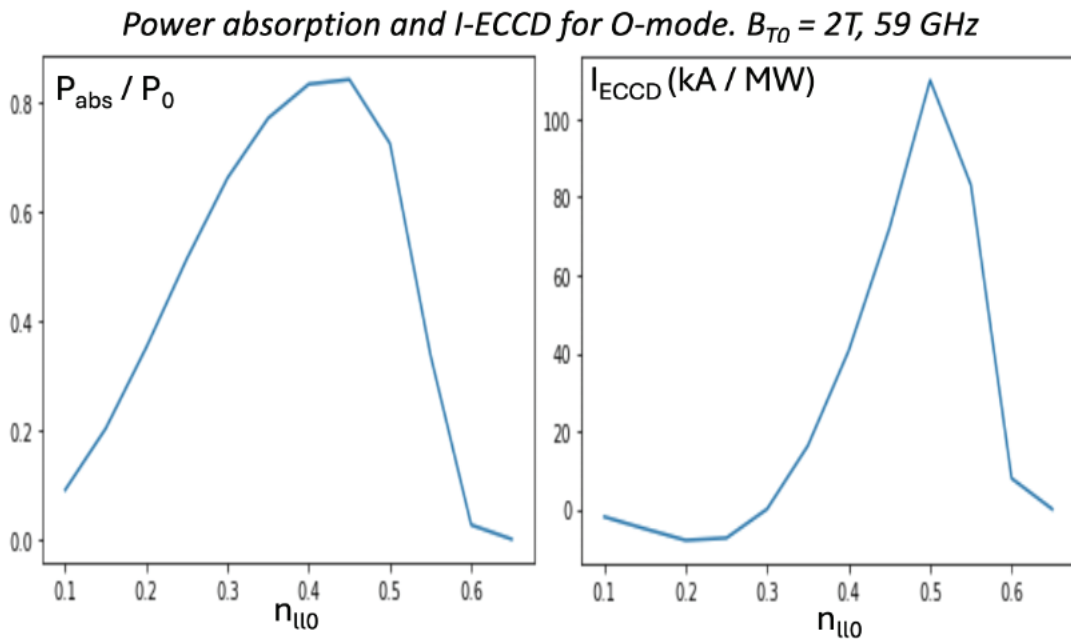


Power absorption and I-ECCD for X-I and X-II. T_{e0} of hot component scanned from 1 keV to 30 keV. Bulk T_{e0} is 1 keV

The O mode at fundamental (O-I) was also investigated with 59 GHz. A typical ECCD efficiency was 0.1 A/W at $\sim 3 \times 10^{19}/\text{m}^3$. The O-mode ray trajectories, ECH and ECCD are shown in the figures below.



Multiple harmonics of ECH wave dispersion and ray trajectories in QUEST. The O-mode wave is launched at $R = 96 \text{ cm}$. $B_{T0} = 20 \text{ kG}$ at $R_0 = 64 \text{ cm}$. The O-mode ray trajectories for various $n_{||0}$ as labelled. RT-4 is used.



RT-4

国際化推進共同研究概要

〔採択番号〕 25NU-5

タ イ ト ル : Analysis of enhanced plasma process using the 3D tomographic system
for advanced semiconductor devices

研究代表者 : CHUNG SEUNG-MIN

所内世話人 : MOON Chanhoo

研究 概 要 :

本共同研究では、先端半導体デバイスへの応用を目指し、三次元トモグラフィ計測技術と成膜プロセス解析を組み合わせた評価手法の構築を進めた。モデル材料としてWCxNy薄膜を用い、ALDによる成長特性を系統的に調査した結果、自己終端的な反応挙動と安定した成膜条件を明らかにした。さらに、温度およびガス供給条件に依存した成長領域を特定し、均一な薄膜形成に必要な基礎データを取得した。これらの成果は、プラズマプロセスの最適化および損傷低減に有用であり、複雑形状デバイスの膜厚評価と信頼性向上に貢献する。

Analysis of enhanced plasma process using the 3D tomographic system for advanced semiconductor device

Hoseo University

Seung-min Chung

1. Introduction

As semiconductor devices continue to scale toward three-dimensional (3D) architectures, precise control and in-depth understanding of thin-film deposition processes have become increasingly critical. In particular, advanced memory and logic devices demand highly uniform, conformal electrode and functional layers within complex high-aspect-ratio (HAR) structures. To meet these requirements, plasma-enhanced processes and advanced process diagnostic techniques, such as 3D tomographic analysis, are actively being investigated as key enablers for next-generation semiconductor manufacturing. Plasma-enhanced atomic layer deposition (PE-ALD) has attracted attention due to its ability to achieve low-temperature processing and enhanced reactivity. However, plasma exposure can induce damage, compositional non-uniformity, or interface degradation, especially in plasma-sensitive materials such as chalcogenides used in selector or memory devices. Consequently, there is growing interest in thermal ALD processes that can deliver comparable process controllability without plasma-induced side effects. In parallel, 3D tomographic characterization techniques are emerging as powerful tools for analyzing film growth behavior, thickness uniformity, and process-induced variations within complex device geometries. By correlating growth characteristics with three-dimensional structural information, these techniques provide deeper insight into how deposition conditions influence material formation in advanced semiconductor devices.

In this context, this study focuses on the systematic analysis of ALD growth behavior as a foundation for enhanced plasma and non-plasma process optimization. Using tungsten carbonitride (WCxNy) thin films as a model electrode material, we investigate growth characteristics relevant to advanced semiconductor devices, emphasizing how such data can serve as critical input for future plasma-assisted process tuning and 3D tomographic validation.

2. Experimental Overview

WCxNy films were deposited using a commercial showerhead-type atomic layer deposition system with tungsten hexacarbonyl ($W(CO)_6$) as the metal precursor and NH_3 as the reactant gas. Film growth was conducted on thermally oxidized SiO_2 substrates over a controlled temperature range relevant to plasma-sensitive device integration. Rather than focusing on device-level electrical performance, this report concentrates on the fundamental growth characteristics of the deposited films.

These growth parameters represent essential baseline data for interpreting plasma-enhanced deposition behavior and for validating three-dimensional process uniformity using tomographic analysis techniques.

3. Results and Discussion: Growth Characteristics Relevant to Plasma and 3D Analysis

Figure 1 presents the growth behavior of ALD WCxNy films as a function of precursor exposure, reactant exposure, deposition temperature, and ALD cycle number. Figures 1(a) and 1(b) demonstrate clear self-limiting behavior with respect to W(CO)₆ and NH₃ exposure times at 260 °C. Saturation is achieved at exposure times exceeding approximately 8 s for the precursor and 2 s for the reactant, resulting in a stable growth per cycle (GPC) of ~0.38 Å/cycle. This self-saturation behavior is a defining feature of ALD and is essential for achieving uniform film growth in three-dimensional device structures. Figure 1(c) shows the temperature dependence of the GPC, revealing a narrow ALD window between 260 °C and 270 °C. Within this window, growth remains stable and surface-reaction-limited, while temperatures above 270 °C lead to a rapid increase in GPC, indicating the onset of thermal decomposition. This narrow window provides a sensitive process regime that is particularly valuable when comparing thermal ALD with plasma-enhanced processes, where additional reactive species can significantly alter growth kinetics. Importantly, the ability to achieve stable film growth below 300 °C is advantageous for integration with plasma-sensitive materials. In advanced semiconductor devices, such low-temperature growth regimes reduce the reliance on aggressive plasma conditions, thereby mitigating potential plasma-induced damage. From a process development perspective, these results provide a critical reference point for optimizing plasma-enhanced processes by defining the minimum thermal budget required for stable film formation. Figure 1(d) confirms a linear relationship between film thickness and the number of ALD cycles, further validating the controllability and reproducibility of the process. Such linearity is essential for three-dimensional tomographic analysis, as it enables direct correlation between designed film thickness and experimentally reconstructed 3D structural data. This correlation forms the basis for advanced process diagnostics, allowing deviations in local thickness or uniformity to be quantitatively assessed.

4. Implications for Enhanced Plasma Processes and 3D Tomographic Systems

Although the present results are obtained using a thermal ALD process, the growth characteristics summarized in Figure 1 provide essential baseline information for enhanced plasma process development. By understanding the intrinsic surface-reaction-limited growth behavior, plasma conditions can be selectively introduced or minimized to enhance reactivity without compromising film uniformity or device integrity. Furthermore, these growth data are directly applicable to 3D tomographic analysis frameworks. When combined with tomographic reconstruction techniques, such growth models enable comprehensive evaluation of process uniformity across complex device

geometries, supporting the development of advanced semiconductor devices with improved reliability and scalability.

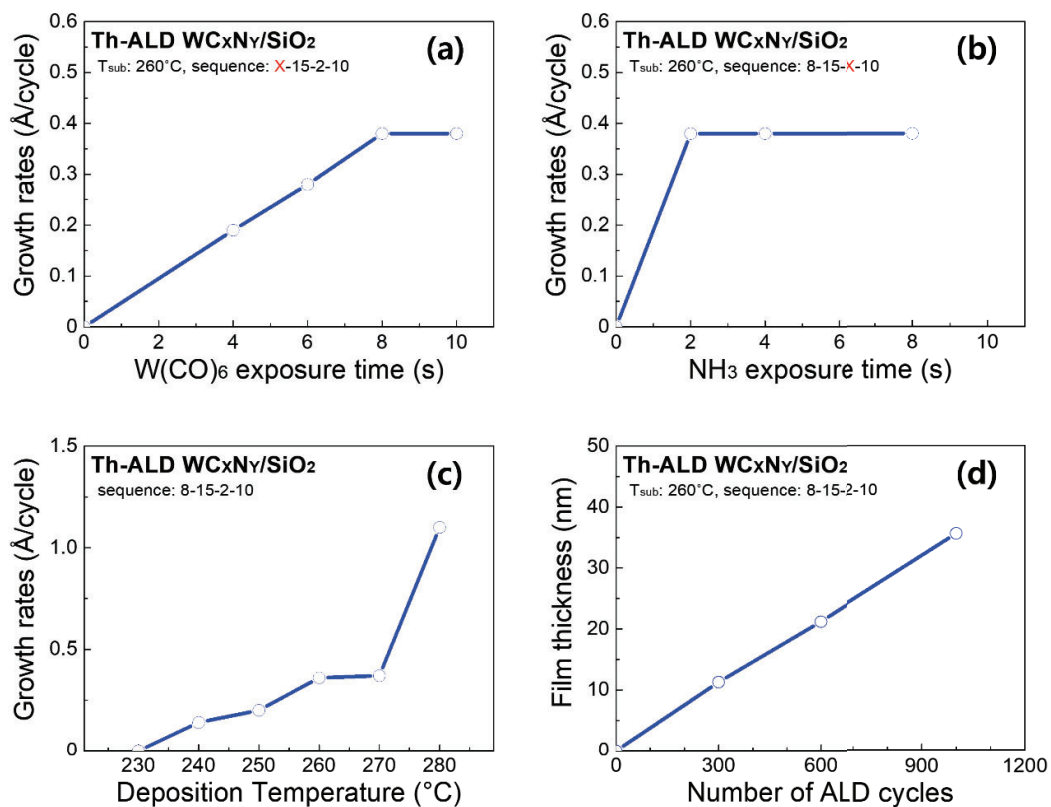


Figure 1. Growth per cycle of ALD WC_xNy on SiO_2 as a function of (a) the precursor exposure time, (b) the reactant exposure time, (c) the growth temperature and (d) the correlation between film thickness and the number of ALD cycles

国際化推進共同研究概要

〔採択番号〕 25NU-6

タ イ ト ル: Development of nonlinear plasma interaction analysis code

研究代表者: NA Yong-Su

所内世話人: MOON Chanhho

研究 概 要:

本研究は、PANTA実験データに適用可能な非線形プラズマ相互作用解析コードの開発を目的として実施した。プラズマ乱流におけるエネルギー輸送を定量的に評価するため、波数空間での三波結合に基づく解析手法を構築した。ヒルベルト変換を導入することで共役対称性の問題を解決し、線形成長率および非線形エネルギー輸送量の評価を可能とした。本手法を0.42 Paおよび0.23 Paの実験条件に適用し、圧力依存の構造変化とエネルギー輸送特性を明らかにした。本研究により、プラズマ乱流の理解が深化し、今後の共同研究の基盤を確立した。

Development of Nonlinear Plasma Interaction Analysis Code

International Joint Research Report (Grant No. 13_25NU-6)

NA Yong-Su

Department of Nuclear Engineering, Seoul National University, Seoul, Korea, Republic of

Introduction

This research was conducted as an international joint initiative between Seoul National University (Chung Huiwon and Heo Chweeho) and Kyushu University (led by Professor Moon). The primary objective was the development and implementation of a nonlinear plasma interaction analysis code tailored for experimental data from the PANTA.

Research Motivation

Understanding plasma turbulence requires a deep analysis of nonlinear interactions among fluctuations. While estimating nonlinear energy transfer is essential for quantifying energy exchange, performing this analysis directly in wave-number (k) space has been a challenge. The PANTA device utilizes a linear plasma configuration equipped with a 64-channel poloidal probe array. These Langmuir probes provide high-resolution ion saturation current fluctuation data (interpreted as electron density fluctuations), which allow for spatial Fourier transforms.

Methodology and Code Development

To overcome the challenge of conjugate symmetry in k -space—where both electron and ion diamagnetic drift directional waves are physically significant—we implemented a Hilbert transform on the original signals. This process breaks the symmetry and allows for a more accurate spectral representation. The fluctuation signals are decomposed, and the evolution of the spectral components ϕ_k is modeled using the following governing equation [1]:

$$\frac{\partial X_k}{\partial t} = L_k X_k + \sum_{\substack{k_1 \geq k_2 \\ k = k_1 + k_2}} Q_k^{k_1, k_2} X_{k_1} X_{k_2} + \epsilon_k$$

Following the methodologies established by Ritz [2] and Wit [3], we experimentally derived the linear (L_k) and quadratic ($Q_k^{k_1, k_2}$) transfer functions. These functions allow us to quantify the exact energy transferred via three-wave coupling and identify the linear growth or damping rates of the waves.

Experimental Results and Analysis

Argon plasma experiments were performed under a homogeneous axial magnetic field (700 G) and 4 kW antenna power. We compared two neutral gas pressure conditions 0.42 Pa and 0.23 Pa, observing distinct solitary wave and streamer phenomena. As illustrated in Figure 1, our analysis successfully mapped the frequency-wave number spectrum and the time evolution of raw signals for both pressure cases. Specifically, the first and second rows on the left of Figure 1 display the 64-channel probe array data for the 0.42 Pa and 0.23 Pa conditions, respectively.

By applying the nonlinear energy transfer code under stationary conditions, we determined both the direction and amplitude of energy exchange driven by three-wave coupling in k -space. The results of this analysis are shown on the right side of Figure 1, where (a) represents the 0.42 Pa case and (b) represents the 0.23 Pa case. The oblique plots within these figures further clarify the linear growth and nonlinear energy transfer occurring at specific azimuthal mode numbers m .

Conclusion and Outlook

The successful development of this analysis code was made possible through the robust technical exchange between Seoul National University and Kyushu University. By combining SNU's computational approach with the high-resolution diagnostic capabilities of Kyushu's PANTA device, we have gained deeper insights into the fundamental mechanisms of plasma turbulence. Future work will focus on utilizing this collaborative framework to investigate the origin of coherent structures generated in PANTA.

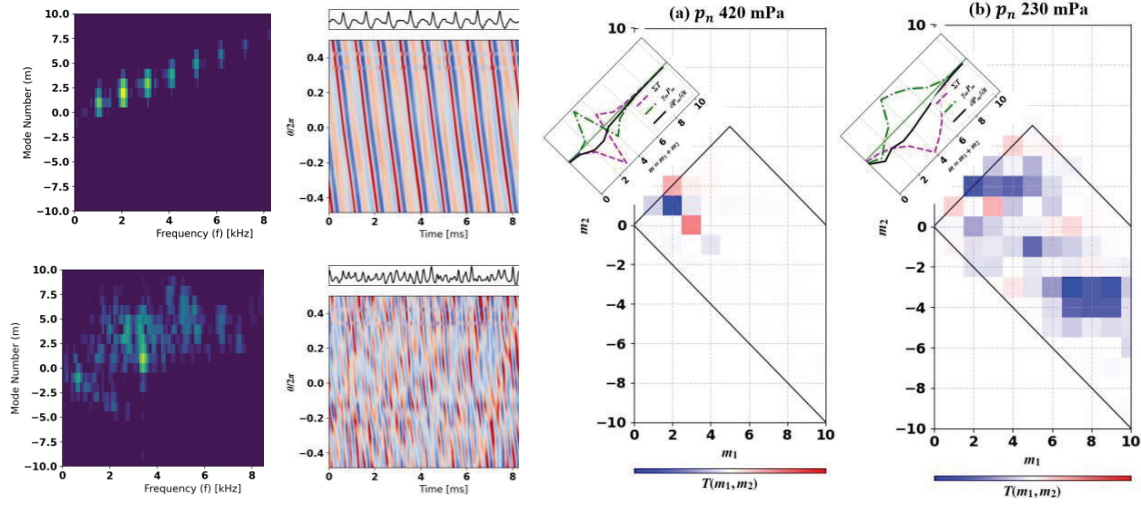


Figure 1. Spectrum and raw signal of 0.42 Pa case (first row on left) and 0.23 Pa case (second row on left) based on 64 channel probe arrays. Nonlinear energy transfer analysis code results at (a) 0.42 Pa and (b) 0.23 Pa on right. Oblique plot represents linear energy transfer and nonlinear energy transfer on specific $m_3(= m_1 + m_2)$.

Reference

- [1] Ch. P. Ritz & E. J. Powers, *Physica D: Nonlinear Phenomena* 20, 320–334 (1986).
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国際化推進共同研究概要

〔採択番号〕 25NU-7

タイトル: Study on Ar collisional-radiative (CR) model for 3-D tomographic system in PANTA

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研究概要:

本研究は、PANTA実験に適用するAr中性粒子コリジョナル・ラジアティブ（CR）モデルの検証および高度化を目的として実施した。OES（発光分光法）とマルチチャンネル・ラングミュアプローブ測定結果を比較し、電子温度 T_e および電子密度 n_e を高精度に評価できることを確認した。さらに、 T_e に高感度な 811 nm/763 nm 線強度比および n_e に高感度な 794 nm/763 nm 線強度比を特定した。これらの成果を基に、PANTAの3次元トモグラフィ計測に適用する光学バンドパスフィルターの設計指針を確立した。

Study on Ar collisional-radiative (CR) model for 3-D tomographic system in PANTA

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1. Introduction

Optical Emission Spectroscopy (OES) is widely used in plasma processing and laboratory plasmas to measure electron temperature and density because it is non-intrusive and is easy to implement. However, it is needed to develop an appropriate population kinetics model for excited atomic/ionic levels to accurately derive the plasma parameters from the OES measurement. The proper population kinetics model for non-equilibrium, low-temperature plasmas is a collisional radiative (CR) model which considers all viable collisional and radiative processes occurring in a plasma.

Chai and Kwon developed an Ar neutral CR model for low-temperature plasmas [1] and the model has several advanced features such that the radiation trapping effect and non-Maxwellian electron energy distributions are considered. It was also demonstrated that the electron temperature and density deduced from the CR model-based OES have similar trends and values to those measured by a Langmuir probe in capacitively- and inductively- coupled plasmas.

In this join research, we applied the neutral Ar CR model developed by Chai and Kwon [1] to the PANTA experiment. We measured both OES data (plasma emission spectra) and Langmuir probe data (T_e and n_e) using a broad wavelength spectrometer and the multi-channel Langmuir probe array in the PANTA experiment. We then compared T_e and n_e deduced from the CR-model based OES method with those obtained from the Langmuir probe measurement. It was found that both data are in good agreement with each other.

After the CR model was validated against the Langmuir probe in the PANTA experiment, we tried to find atomic line intensity ratios that are sensitive to T_e and n_e using the CR model. We found that the line ratio of 811 nm/763 nm is sensitive to T_e while that of 794 nm/763 nm is sensitive to n_e . Based on the obtained results, the optical bandpass filters centered at 763, 794, 811 nm with a Full Width at Half Maximum (FWHM) of about 10 nm will be fabricated and applied to the PANTA's 3D tomography system. By doing so, it is expected that the T_e fluctuations and n_e fluctuations can be separately measured from the 3D tomography system in the PANTA experiment.

2. Ar neutral CR model

Chai and Kwon developed a CR model assuming weakly ionized Ar plasma under the condition of $n_0\alpha_I \gg n_+\alpha_R$ where n_0 and n_+ are the neutral and ion densities, and α_I and α_R are the ionization and recombination rate coefficients. In the CR model, the population kinetics processes shown in Fig. 1 are included for the ground level ($[\text{Ne}]3s^23p^6$), the first excited levels ($[\text{Ne}]3s^23p^54s$), and the next excited level ($[\text{Ne}]3s^23p^54p$) of Ar I. The wavelengths and probabilities of the considered radiative transitions are listed in Table 1.

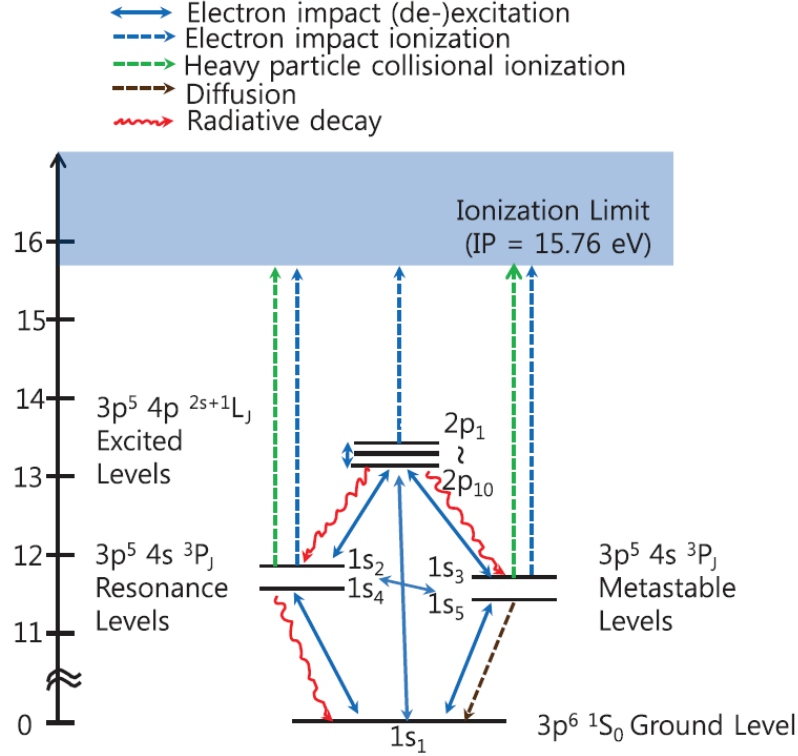


Figure 1. Energy levels and reaction processes considered in present CR modeling for Ar plasma.

Paschen notations are also given for the levels

Table 1

Wavelengths (nm) and transition probabilities in parentheses (A_{ij} , 10^8s^{-1}) for dipole allowed radiative decays of Ar I.

Excited levels	Resonance levels		Metastable levels	
	$1s_2$ ($J = 1$)	$1s_4$ ($J = 1$)	$1s_3$ ($J = 0$)	$1s_5$ ($J = 2$)
$2p_1$ ($J = 0$)	750.39 (0.45)	667.73 (0.002)		
$2p_2$ ($J = 1$)	826.45 (0.15)	727.29 (0.02)	772.42 (0.12)	696.54 (0.06)
$2p_3$ ($J = 2$)	840.82 (0.22)	738.40 (0.08)		706.72 (0.04)
$2p_4$ ($J = 1$)	852.14 (0.14)	747.12 (0.0003)	794.82 (0.19)	714.70 (0.006)
$2p_5$ ($J = 0$)	858.01	751.47 (0.40)		
$2p_6$ ($J = 2$)	922.45 (0.05)	800.62 (0.05)		763.51 (0.25)
$2p_7$ ($J = 1$)	935.42 (0.01)	810.37 (0.25)	866.79 (0.02)	772.38 (0.05)
$2p_8$ ($J = 2$)	978.45 (0.01)	842.46 (0.22)		801.48 (0.009)
$2p_9$ ($J = 3$)				811.53 (0.33)
$2p_{10}$ ($J = 1$)	1148.8 (0.002)	965.78 (0.05)	1047.0 (0.01)	912.30 (0.19)

The ground level population N_0 is assumed to be equal to the neutral gas density n_0 which is determined by the ideal gas law $p = n_0 k_B T_g$ where T_g is the gas temperature, p is pressure and k_B is the Boltzmann constant. The N_0 is assumed to be constant and the excited level population densities of the first four $1s_{5-2}$ in Paschen notation) and next ten ($2p_{10-1}$) excited states N_j ($j=1-14$) are obtained by solving the stationary rate balance equations

$$\sum_{j \neq i} n_e N_j \alpha_{ji}^{ex} + \sum_{j > i} N_j \eta_{ji} A_{ji} = \sum_{j \neq i} n_e N_i \alpha_{ij}^{ex} + \sum_{j < i} N_i \eta_{ij} A_{ij} + n_e N_i \alpha_i^I + N_i \nu_i^d \quad (1)$$

where n_e is the electron density, α_{ij}^{ex} is the electron impact excitation/deexcitation rate coefficient from i level to j level, α_i^I is the electron impact ionization rate coefficient for i level, A_{ij} and η_{ij} are transition probabilities (Einstein's A coefficient) and escape factor for the radiative transition from i level to j level. ν_i^d is the quenching probability per unit time by diffusion from high density region to low density region. The left-hand side of Eq. (1) represents populating processes of level i and the right-hand side of Eq (1) denotes depopulating processes of level i .

The data for the radiative decay of the resonant $1s_{4,2}$ and $2p_{10-1}$ levels such as transition probability A_{ij} , wavelength, statistical weight $g = 2J + 1$, and excitation energy E_i are taken from the NIST database [2]. The cross sections for electron impact excitation in the database [3] are used which are based on a semi-relativistic Breit-Pauli B-spline R-matrix (close coupling) calculations [4]. The rate coefficient of the electron impact de-excitation is obtained from the detailed balance relation $\alpha_{ji}^{ex} = g_i/g_j \exp[(E_j - E_i)/k_B T_e] \alpha_{ij}^{ex}$.

The electron impact ionization rate coefficients are given for Maxwellian EEDF by the formula

$$\alpha_i^I = \frac{9.56 \times 10^{-6} (k_B T_e)^{-3/2} \exp[\Delta E_i / k_B T_e]}{(\Delta E_i / k_B T_e)^{2.33} + 4.38 (\Delta E_i / k_B T_e)^{1.72} + 1.32 (\Delta E_i / k_B T_e)} \quad (2)$$

where $\Delta E_i = IP - E_i$ is the ionization energy of level i and the cross sections which can be integrated over any sort of EEDF are expressed by the formula

$$\sigma_i^I = \frac{\pi e^4}{E + \alpha \Delta E_i} \left(\frac{5}{3 \Delta E_i} - \frac{1}{E} - \frac{2 \Delta E_i}{3 E^2} \right) \quad (3)$$

where E is the electron energy [5].

The diffusion characteristic times $\tau_i = 1/\nu_i^d$ of the metastable $1s_5$ and $1s_3$ are expressed as $\tau_{1,3} = \Lambda^2 / D_{1,3}$ where $1/\Lambda^2 = (2.405/R)^2 + (\pi/L)^2$ for a cylindrical plasma with characteristic radius R and length L [6]. The diffusion coefficients of the metastable states $D_{1,3}$ at atomic concentration N_0 and gas temperature T_g are given by

$$D_{1,3} = D_{sc} \frac{N_{sc}}{N_0} \sqrt{\frac{T_g}{T_{sc}}} \quad (4)$$

where $D_{sc} N_{sc} = 1.8 \times 10^{18} \text{ cm}^{-1}$ and $D_{sc} N_{sc} = 1.9 \times 10^{18} \text{ cm}^{-1}$ for $1s_5$ and $1s_3$ states, respectively, and T_g^{sc} is

300 K [7].

The escape factor η of radiation trapping for the plane parallel geometry suggested by Apruzese [8]

$$\eta = \frac{1}{1 + 0.65k_0R + 0.29(k_0R)^2} \quad (k_0R < 5.18)$$

$$\eta = \frac{0.546847}{k_0R\sqrt{\log k_0R}} \quad (k_0R > 5.18) \quad (5)$$

was adopted to the CR model. Here, k_0 is the absorption coefficient at the center of the line emitted at spontaneous transition ($j \rightarrow i$) given by

$$k_0 = \frac{\lambda^3 N_i}{8\pi} \frac{g_j}{g_i} \frac{A_{ji} M^{1/2}}{(2\pi k_B T_g)^{1/2}} \quad (6)$$

EEPF $g(E)$ for non-Maxwellian, Druyvesteyn formula is expressed as [9]

$$g(E) = c_1 T_e^{(-3/2)} \exp[-C_2 (E / T_e)^x] \quad (7)$$

where $c_1 = x (2/3)^{(3/2)} \Gamma(5/2x)^{(3/2)} / \Gamma(3/2x)^{(5/2)}$, $c_2 = (2/3)^x [\Gamma(5/2x) / \Gamma(3/2x)]^x$, and x is the shape factor ($x=1$ means the Maxwellian distribution and $x=2$ means the Druyvesteyn distribution).

The rate coefficients α^{ex} and α^{I} of the electron impact excitation and ionization can be obtained for EEDF $f_E(E) = E^{1/2} g_E(E)$ by the formula

$$\alpha = \langle \sigma v \rangle = \int_{E_{th}}^{\infty} \sqrt{\frac{2E}{m_e}} f(E) \sigma(E) dE \quad (8)$$

The spectral line intensity I_{ji} is given by

$$I_{ji}(n_e, T_e) = N_j \eta_{ji} A_{ji} \quad (9)$$

from the solutions N_j and η_{ji} of the sets of nonlinear equations, Eq. (1). The initial N_j values used in the non-linear matrix formulation are obtained from the solution of the linearized form of Eq. (1). The final self-consistent solution is then achieved through an iterative procedure in which the level population and escape factors are updated simultaneously, and the CR equations are solved repeatedly until convergence is attained.

3. Experimental setup

In order to check the validity of Ar neutral CR model developed by Chai and Kwon [1], plasma emission spectra of the PANTA experiment were measured by a HR 4000 spectrometer equipped with a lens tube and an optical fiber as shown in Fig. 2(a). In addition to Optical Emission Spectroscopy (OES), a multi-channel Langmuir probe array was installed and used to measure T_e and n_e in the PANTA experiment as depicted in Fig. 2(a). A photo of the PANTA experiment is shown in Fig. 2(b).

In the experiment, the plasmas were ignited with Ar gas and the input rf power to the helicon antenna coil was fixed at 4 kW. The Ar flow rate was varied from 10 sccm to 25 sccm while the axial magnetic field was varied from 300 G to 1500 G. The background pressures were 0.7 mtorr and 2.2 mtorr when

the flow rates were 10 sccm and 25 sccm, respectively.

The HR 4000 spectrometer measured plasma emission spectra from 400 nm to 850 nm with 0.4 nm spatial resolution. In the experiment, the exposure time was fixed at 100 ms and the spectra were obtained at 300 ms from the plasma ignition in each shot. And the intensity of the measured spectra was corrected by the calibration factor of the HR 4000 spectrometer.

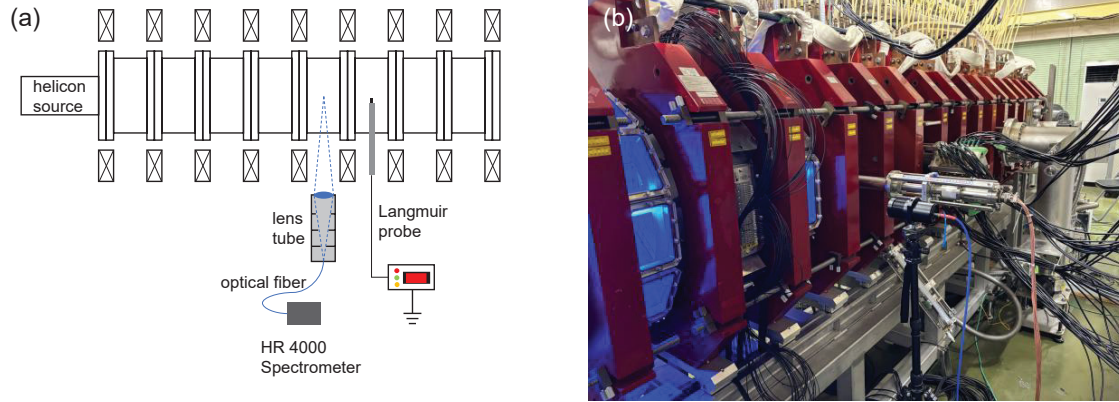


Figure 2. (a) A schematic diagram of diagnostics used in this work and (b) a photo of the PANTA experiment.

4. Results

The measured plasma emission spectra (calibrated) were shown in Figs. 3(a)-(c). Figure 3(a), (b), and (c) represent the case where the axial magnetic field of 300 G, 900 G, and 1500 G, respectively. As seen in the figures, as the magnetic field increases, emissions between 400 and 500 nm increases compared to emissions near 800 nm. In addition, emissions between 400 and 500 nm decreases as the flow rate increases from 10 sccm to 25 sccm. By the way, 400-500 nm emissions are mostly from singly ionized ions while emissions near 800 nm are from the neutral argon.

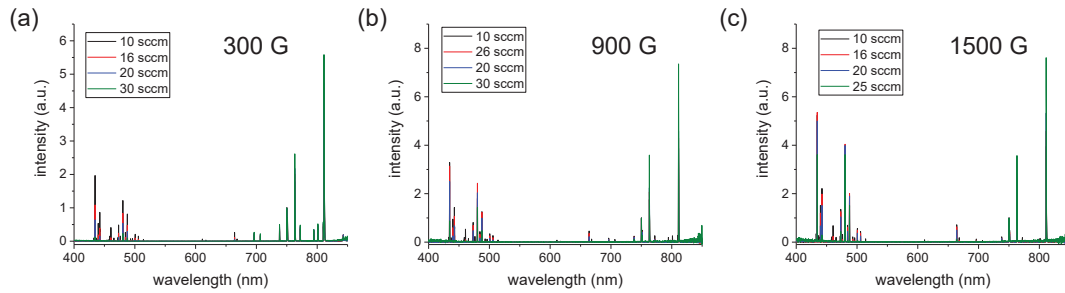


Figure 3. Plasma emission spectra from (a) $B_z = 300$ G, (b) $B_z = 900$ G, and (c) $B_z = 1500$ G.

Because we used the Ar neutral CR model and there was sufficient amount of neutral Ar particles in the PANTA experiment, we focused on the plasma emissions between 680 and 850 nm. Figures 4(a), (b), and (c) show the 650-850 nm spectra obtained at the Ar flow rate of 10 sccm with (a) $B_z = 300$ G,

(b) $B_z = 900$ G, and (c) $B_z = 1500$ G, respectively. As seen in the figures, we can identify 696, 704, 738, 750, 751, 763, 772, 794, 801, 810, 811 nm lines. They are all from the neutral Ar particles, specially from 2p to 1s levels (Paschen notation). By the wave, the obtained spectra were normalized by the intensity of 750.4 nm line.

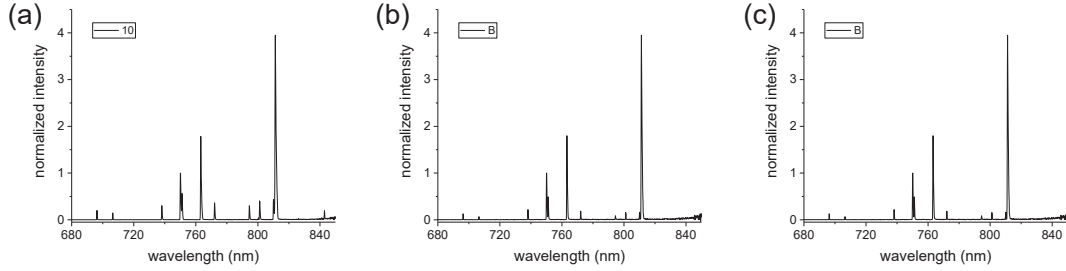


Figure 4. Plasma emission spectra between 680 and 850 nm measured at the 10 sccm Ar flow rate with (a) $B_z = 300$ G, (b) $B_z = 900$ G, and (c) $B_z = 1500$ G.

We integrated each peak over the wavelength to obtain the real intensity of each peak using the MATLAB's trapz function. The obtained peak intensities were shown in Figs. 5(a)-(c). Using the obtained integrated peak intensities, we tried to find the T_e and n_e which generate minimum loss function between the calculated and measured spectral intensities. The calculation of the Ar plasma emission spectra was done using the Ar neutral CR model described in Sec. 2 with the Maxwellian EEDF assumption. The loss function we used in this work is given by

$$f(T_e, n_e) = \sum [I_{CRM}(T_e, n_e) - I_{OES}(T_e, n_e)]^2 \quad (10)$$

where I_{CRM} is the calculated intensity and I_{OES} is the measured intensity.

The detailed calculation process is as follows. We first calculate the Ar emission spectra between 680 nm and 850 nm in various T_e and n_e . In this work T_e was varied from 0.5 eV to 5 eV while n_e was varied from 10^{11} to 10^{13} cm⁻³. The radius of plasma was fixed at 3 cm and Ar gas temperature was assumed at 600 K. Then, we calculated the loss function in each T_e and n_e . Some examples of the contour plot of the calculated loss function are shown in Figs. 6(a)-(c). From the obtained contour plot, we found T_e and n_e values that give minimum loss function. For instance, the optimum T_e and n_e are 2 eV and 3×10^{12} cm⁻³, respectively in Fig. 6(a).

As seen in Figs. 6(a)-(c), the optimum electron temperature and density did not significantly change among various B-field strengths. Figures 5(d)-(f) are the calculated spectral intensities with optimized T_e and n_e for (a) $B_z = 300$ G, (b) $B_z = 900$ G, and (c) $B_z = 1500$ G, respectively. It is seen that Figs. 5(a)-(c) are in good agreement with Figs. 5(d)-(f).

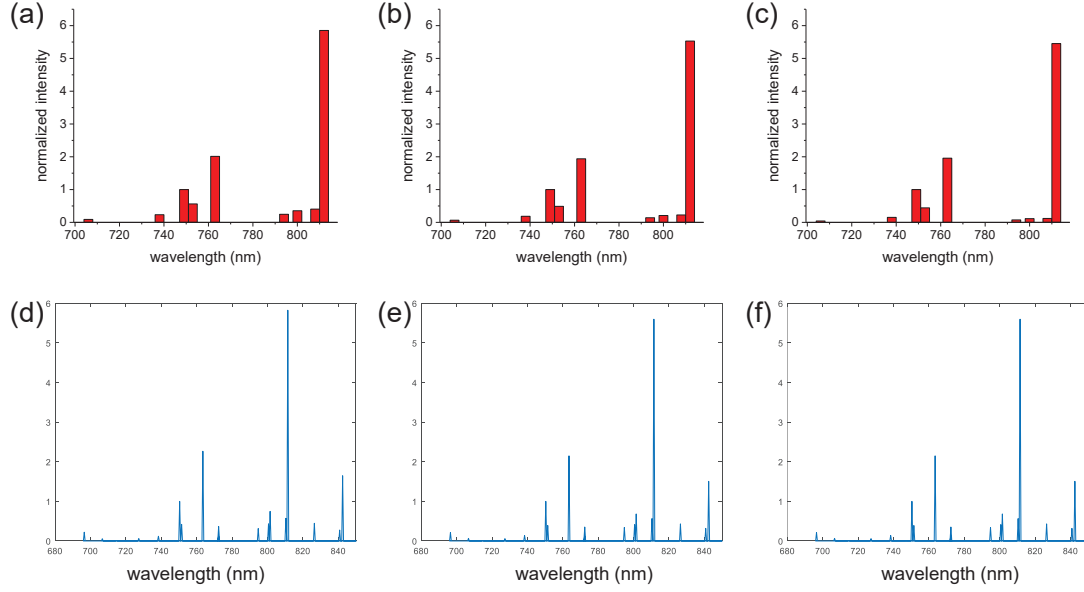


Figure 5. Integrated peak values of the measured spectra in (a) $B_z = 300$ G, (b) $B_z = 900$ G, and (c) $B_z = 1500$ G. Calculated spectra using the optimized T_e and n_e in (d) $B_z = 300$ G, (e) $B_z = 900$ G, and (f) $B_z = 1500$ G.

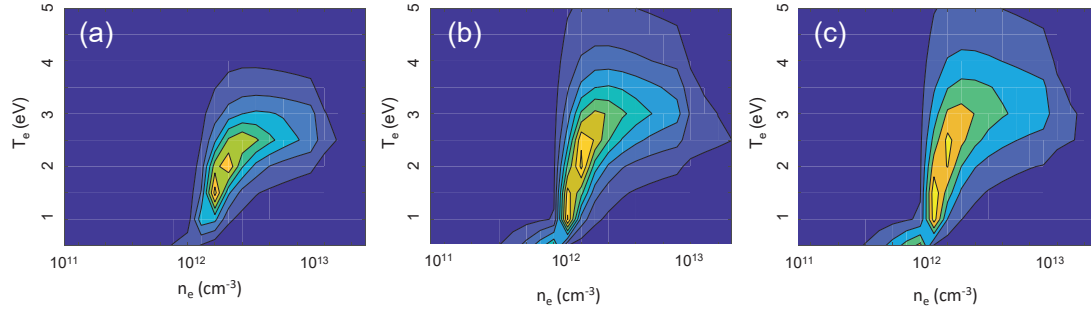


Figure 6. Contour plot of the loss function for (a) $B_z = 300$ G, (b) $B_z = 900$ G, and (c) $B_z = 1500$ G cases.

We fixed $B_z = 900$ G and varied the Ar flow rate from 10 sccm to 25 sccm. The measured plasma emission spectra between 680 and 850 nm are as shown in Figs. 7(a), (b), and (c) which were obtained at the Ar flow rate of (a) 10 sccm, (b) 20 sccm, and (c) 25 sccm, respectively. As seen in the figures, we can identify 696, 704, 738, 750, 751, 763, 772, 794, 801, 810, 811 nm lines when the flow rate was low while only 696, 738, 750, 751, 763, and 811 nm lines were clearly seen when the flow rate was high (20 and 25 sccm cases).

Similar to the previous analysis, we integrated each peak to obtain the real intensity of each peak using the MATLAB's trapz function. The obtained peak intensities were shown in Figs. 8(a)-(c). And we calculate the loss function using Eq. (1). In the calculation, T_e was varied from 0.5 eV to 5 eV while n_e was varied from 10^{11} to 10^{13} cm^{-3} . The radius of plasma was fixed at 3 cm and Ar gas temperature was assumed at 600 K. Then, we calculated the loss function in each T_e and n_e . Some

examples of the contour plot of the calculated loss function are shown in Figs. 9(a)-(c). From the obtained contour plot, we found T_e and n_e values that give minimum loss function. For instance, the optimum T_e and n_e are 2 eV and $3 \times 10^{12} \text{ cm}^{-3}$, respectively in Fig. 9(a).

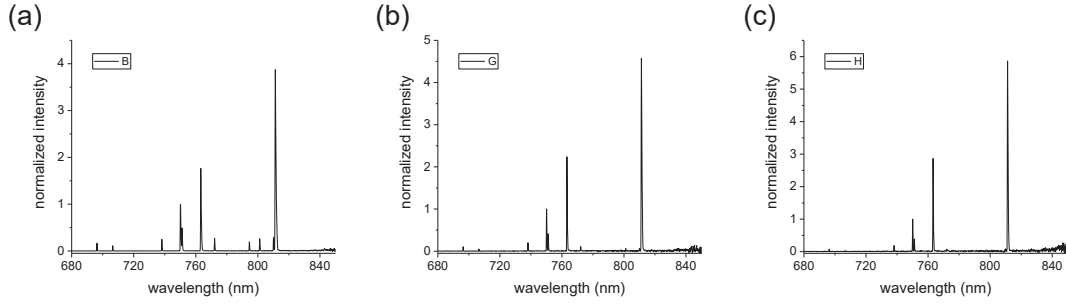


Figure 7. Plasma emission spectra between 680 and 850 nm measured at (a) 10 sccm, (b) 20 sccm, and (c) 25 sccm Ar flow rate with $B_z = 900 \text{ G}$.

As seen in Figs. 9(a)-(c), the optimum electron temperature decreased from 2 eV to 1 eV while the electron density increased from $3 \times 10^{12} \text{ cm}^{-3}$ to $4.5 \times 10^{12} \text{ cm}^{-3}$ as the Ar flow rate increased from 10 sccm to 25 sccm. Figures 8(d)-(f) are the calculated spectral intensities with optimized T_e and n_e for (a) 10 sccm, (b) 20 sccm, and (c) 25 sccm, respectively. It is seen that Figs. 8(a)-(c) are in good agreement with Figs. 8(d)-(f).

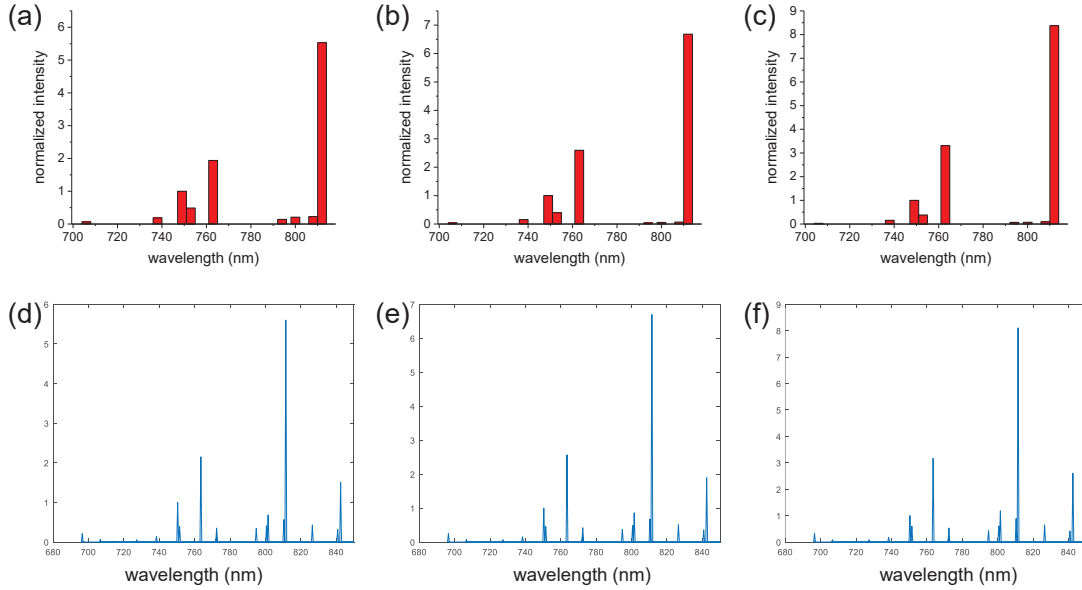


Figure 8. Integrated peak values of the measured spectra in (a) 10 sccm, (b) 20 sccm, and (c) 25 sccm. Calculated spectra using the optimized T_e and n_e in (d) 10 sccm, (e) 20 sccm, and (f) 25 sccm.

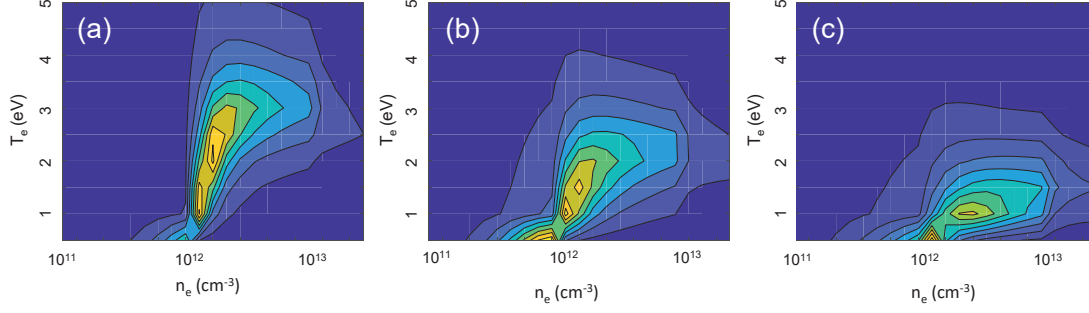


Figure 9. Contour plot of the loss function for (a) 10 sccm, (b) 20 sccm, and (c) 25 sccm flow rates.

5. Discussion

Figure 10 shows T_e and n_e obtained from the CR model-based OES in the PANTA experiment. The electron temperature decreased from 2 eV to 0.5 eV as the flow rate increased from 10 sccm (corresponds to 0.7 mTorr) to 25 sccm (corresponds to 2.2 mTorr) while the electron density increases from $3 \times 10^{12} \text{ cm}^{-3}$ to $5 \times 10^{12} \text{ cm}^{-3}$ as the flow rate increases. The electron temperature seems to weakly depend on the axial B-field while the electron density increased as the axial B-field increased.

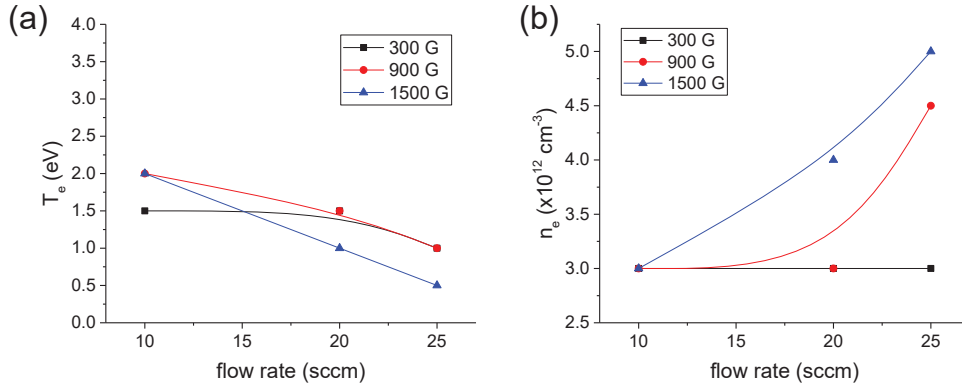


Figure. 10. T_e and n_e obtained from CR model-based OES method in the PANTA experiment.

The obtained T_e and n_e were compared with those measured by the Langmuir probe array. The measured T_e and n_e are shown in Fig. 11. As seen in the figure, the measured T_e decreased from 3 eV to 1 eV at the center as the pressure increased from 1 mTorr to 3 mTorr which is in good agreement with T_e obtained from OES. The measured n_e increases $3 \times 10^{12} \text{ cm}^{-3}$ to $5 \times 10^{12} \text{ cm}^{-3}$ which is also in good agreement with the values obtained from OES.

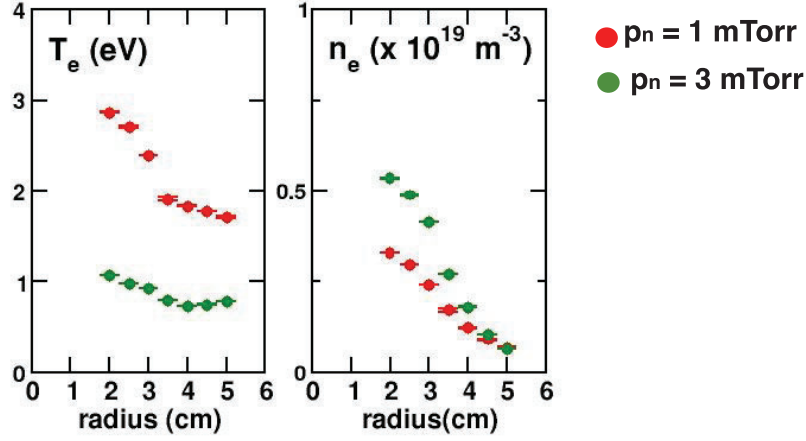


Figure 11. The electron temperature and density measured by the Langmuir probe array

The Ar neutral CR model developed by Chai and Kwon [1] was successfully validated against the Langmuir probe measurement in the PANTA experiment. Therefore, it is reasonable to use this model when finding the atomic line intensity ratios sensitive to T_e and n_e for the PANTA experiment. The purpose of finding the line ratios sensitive to T_e and n_e is to select optical bandpass filters for separating T_e and n_e fluctuations in the PANTA's 3D tomography system.

In order to find line ratios sensitive to T_e and n_e , we calculated several possible line ratios in various T_e and n_e . When we chose the line ratios, we excluded 750, 751, 772 nm lines because they have other lines nearby. We did not exclude 811 nm line because the intensity of the 810 nm line is very small compared to that of the 811 nm line in the PANTA experiment as shown in Figs. 4 and 7.

Among many combinations of two lines, we found that the intensity ratio of 811 nm to 763 nm is the most sensitive to T_e as shown in Fig. 12. As seen in the figure, the intensity ratio of 811 nm to 763 nm is monotonically increases from 1.5 to 2.5 as the T_e increases from 0.5 eV to 3 eV while it is insensitive to the change in n_e .

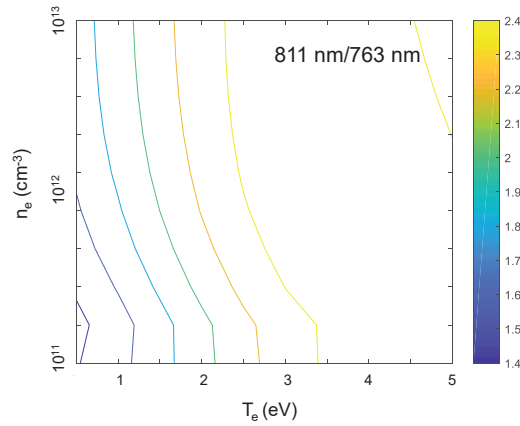


Figure 12. Intensity ratio of 811 nm to 763 nm in various T_e and n_e . It seems that 811 nm/763 nm is much sensitive to T_e compared to n_e .

It was also found that the intensity ratio of 794 nm to 763 nm is very sensitive to n_e as shown in Fig. 13. As seen in the figure, the intensity ratio of 794 nm to 763 nm is monotonically increases from 0.1 to 0.2 as the n_e increases from 10^{11} cm^{-3} to $5 \times 10^{12} \text{ cm}^{-3}$ while it is insensitive to the change in T_e below 4 eV.

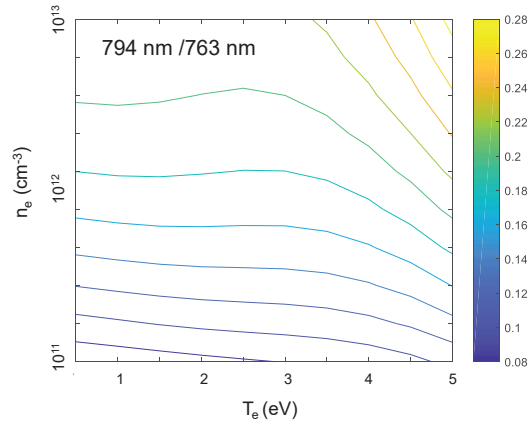


Figure 13. Intensity ratio of 794 nm to 763 nm in various T_e and n_e . It seems that 794 nm/763 nm is much sensitive to n_e compared to T_e .

6. Conclusion and future plan

In conclusion, we demonstrated that the Ar neutral CR model developed by Chai and Kwon [1] can predict plasma parameters such as T_e and n_e very close to those measured by the multi-channel Langmuir probe array. After the code validation, we deduced which intensity line ratios are sensitive to T_e and n_e and we found that the line ratio of 811 nm/763 is sensitive to T_e while the line ratio of 794 nm/763 nm is sensitive to n_e . Based on the obtained results, we will fabricate the optical bandpass filter centered at 763, 794, and 811 nm with a Full Width at Half Maximum (FWHM) of about 10 nm next year and will apply to the PANTA's 3D tomography system. It is expected that the temperature and density fluctuations can be separately obtained with new optical bandpass filters.

Acknowledgements

The author sincerely thanks Prof. Chanhoo Moon for many helpful discussions. This work was supported by RIAM International Joint Research funded by Kyushu University (25NU-7).

References

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国際化推進共同研究概要

〔採択番号〕 25NU-8

タイトル: Improvement of the plasma equilibrium reconstruction for SS0 operation on QUEST

研究代表者: Jinping Qian

所内世話人: HANADA Kazuaki

研究概要: 長年にわたって世界標準の平衡コードの一つであるEFITコードのQUESTへの導入を行い、多くの貢献をしていただいていた。今年度はIAEA会議の後、世話人がASIPPを訪問して共同研究の内容について議論をした。昨年からご本人がASIPPの副所長の立場となり、極めて多忙で来日しての共同研究ができないということで、EASTのデータを使った共同研究を行うこととし、ダイバータ熱負荷と磁場配位の関係を調べて結果をQUESTに適用する方針とした。EASTの長時間放電の熱負荷計測はこれまでの共同研究で実施した経験があり、熱負荷の上下非対称性を確認した。磁気配位も提供を受けたが、相互関係が明確にはならなかったため、今後の検討が必要な段階である。

RIAM JOINT RESEARCH REPORT SUMMARY (English Form)

1. Research ID: 25NU-8

2. Research Title: Develop and improve EFIT code of the plasma equilibrium reconstruction for SSO operation and advanced physical study on QUEST

3. Category: International

4. Applicant:

Affiliation: Institute of plasma physics, Chinese academy of sciences

Name: Jinping Qian

5. RIAM Attendant: Kazuaki Hanada

6. Summary (150~200 words in Japanese or 100~150 words in English):

This year, the RIAM attendant (K. Hanada) visited to ASIPP from October 20th to 24th to discuss this year's collaborative research. As a result, it was decided that the EFIT code would be used for power balance research during long pulse operation, particularly for divertor heat load control. At first, we decided to confirm the effectiveness of magnetic configuration control on the heat load using the results of previous EAST experiments.

Research subject.

The mission of QUEST is to develop the scientific basis for achieving a steady state condition at sufficiently high beta ($\sim 20\%$), with high confinement and low collisionality. For the understanding of magnetohydrodynamic (MHD) stability and operation of tokamak, it is essential to obtain information on the plasma equilibrium and the profiles. Also, it is especially important for steady state high-beta operations envisioned for advanced tokamaks (AT). By using EFIT code, the shape and profiles of the plasma flux surface can be reconstructed with external and internal constraints, which can provide useful information for further physical study, especially in high beta physical study on QUEST.

This project is to develop and improve the EFIT code of the plasma equilibrium reconstruction on QUEST. By using EFIT code, the reconstructed results using the external flux loops will be done. Benchmarking and test will be performed to estimate the overall uncertainties of the magnetic data. Meanwhile, a comprehensive method reconstructed the equilibrium current and q profiles with magnetic and internal iso-flux constraints will be tested. A double check of EFIT reconstruction results with other diagnostics will be carried out.

It was found that the most important issue in the QUEST side is to make and maintain a divertor configuration for long duration. The crucial point is how to reduce heat load to the divertor region. One of the candidates is magnetic field configuration control, especially diverter leg position control, which is being performed in EAST based on the EFIT code. The total heat load on the divertor region can be measured using calorimetry installed through previous collaborative research activities.

国際化推進共同研究概要

〔採択番号〕 25NU-9

タ イ ト ル： Joint study of long pulse high beta discharges and related edge turbulence transport in steady state operation (SSO) plasmas on QUEST and EAST

研究代表者： GAO Xiang

所内世話人： HANADA Kazuaki

研究 概 要： EASTで観測されたITBプラズマのELM penetrationに関してQUESTで同様の観測ができないかを検討した。EASTのELM penetrationではITB foot位置まで penetrationが進むとITBそのものを崩壊させる等の大きな影響が出ることが分かっている。現象としては大変興味深く、検討を行ったが、現在のQUESTで実験を行うことは難しいとの結論に至った。共同研究としてはEASTの結果に基づいて議論を行い、QUESTで開発している計測機器の導入等の可能性についても検討した。

RESEARCH REPORT

Date: FEB 12 2026

Visiting scientists: (name) Xiang Gao
(position) Professor
(university / institute) Institute of Plasma Physics,
Chinese Academy of Sciences

Host scientist: (name) Kazuaki Hanada
(position) Professor
(university / institute) Kyushu University

Research period: (from) April 1 2025 (to) March 31 2026

Research subject: **Joint study of long pulse high beta discharges and related edge turbulence transport in steady state operation (SSO) plasmas on QUEST and EAST**

Introduction

Steady state operation (SSO) of tokamak plasma is one of the basic requirements for future fusion reactors. Long pulse high beta operation is one of important missions for ITER. Joint study long pulse high beta discharges in SSO plasma research field on QUEST and EAST was strongly supporting ITER experiment from both experience and theory. In 2025, we focus on the ELM penetration in ITB plasma on EAST and some potential comparison with similar phenomenon with QUEST device.

I had visited QUEST building from December 10th to 16th, 2025. I gave a seminar and make a fruitful discussions in QUEST building meeting room. My presentation title is “ELM penetration in ITB plasmas on EAST tokamak”. I also have many discussions on student exchanges, joint new experimental proposals on QUEST and EAST.

New results in 2024-2025

The penetration of an edge-localized mode (ELM) into an internal transport barrier (ITB) plasma has been studied on the EAST tokamak with a flat central safety factor profile $q(0) \sim 1$ recently. The experiment indicates that when the ELM inward penetration radius reaches the ITB foot region, a significant influence on the ITB plasma is manifested, leading to the shrinking or collapse of the ITB on the EAST tokamak. Observations suggest that the onset of large ELM penetration, which extremely reduces the pedestal temperature and density, can trigger the collapse of the ITB, by means of the off-axis sawtooth on the EAST tokamak. The off-axis sawtooth events contribute to a further decrement in the core stored energy after a larger ELM crash in the pedestal region. The reversal surface of the off-axis sawtooth is situated around the ITB foot. The delay time between the ELM penetration reached to the ITB foot and the followed off-axis sawtooth collapse is about 2–3 ms. It is also found that the expanding of ITB is related to the net heating power. Mechanism of ITB collapse from ELM penetration to the off-axis sawtooth triggered is not yet clear. Experimental results for understanding ELM penetration in ITB plasmas are summarized and discussed.

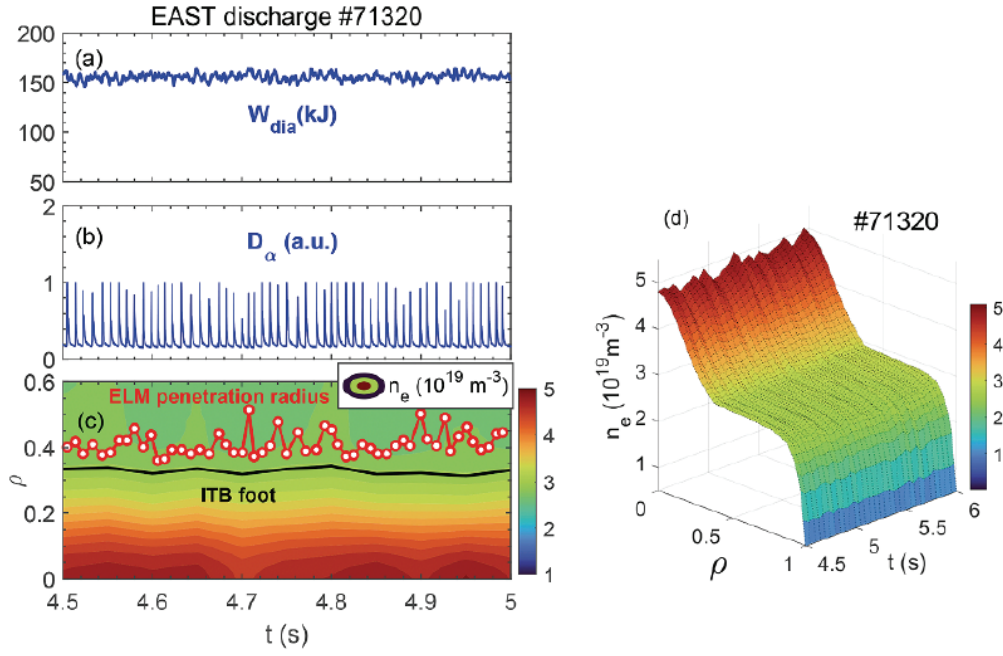


Figure 1. (a) Stored energy, (b) D_α emission, (c) contour of electron density, the location of pressure ITB foot (black solid line) as well as ELM penetration radius (red circle line). (d) Evolution of ne profile.

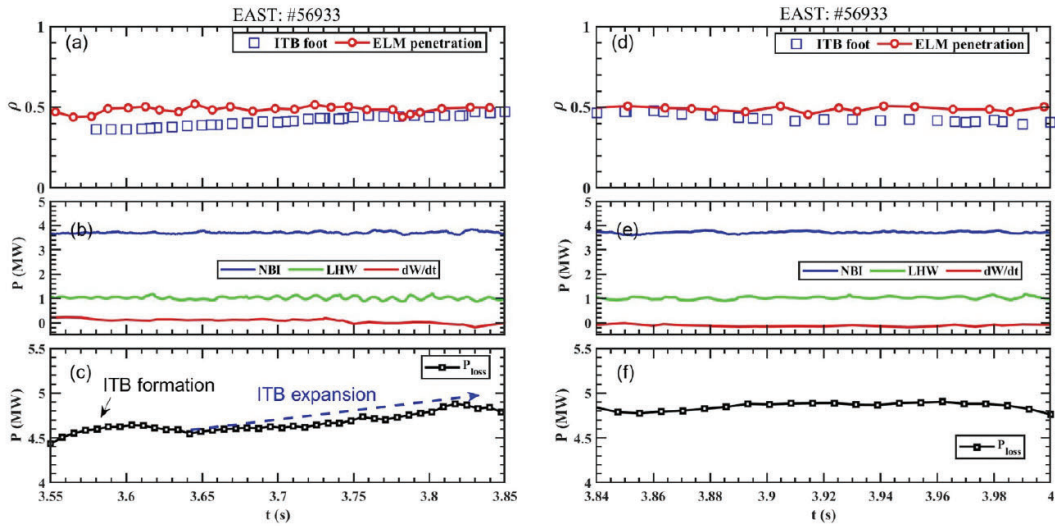


Figure 2. Evolution of (a) and (d): ITB foot and ELM penetration, (b) and (e): injected power and time derivative (dW/dt) of stored energy, (c) and (f): loss power P_{loss} .

Acknowledgement and comments:

Work supported by the international joint research at the Joint Usage of Research Centers for Applied Mechanics for 2025. I would like to thank our host, Professor K. Hanada. We hope that the international joint research at the Joint Usage of Research Centers for Applied Mechanics could continue to enhance China-Japan cooperation on fusion plasma research in the future.

My Co-Publications in 2025-2026:

- (1) X.Gao et al., "A summary of the 11th Asia-Pacific Transport Working Group (APTWG) meeting", Nuclear fusion, 66, 017001 (2025).
- (2) X.Gao et al., "ELM penetration in ITB plasma on EAST tokamak", Nuclear fusion, 65, 082001, (2025).
- (3) X. Gao et al., "Pedestal dynamics and turbulence in H-mode density ramp-up experiment on EAST", 45th ITPA-PEP meeting May. 19-22, 2025, Munich, Germany.

(Signature) _____

(Name in print) Xiang Gao

国際化推進共同研究概要

〔採択番号〕 25NU-10

タイトル: Joint study of calorimetric measurement of heat load and power balance estimation and measurement and simulation of energetic electrons loss in steady state operation (SSO) plasmas on QUEST and EAST

研究代表者: LIU Haiqing

所内世話人: HANADA Kazuaki

研究概要: プラズマ対向壁の熱負荷計測によって長時間維持プラズマのパワーバランスを計測することを試みている。今回はEASTでの長時間維持プラズマを対象に解析を行ったが、冷却水が放電中に一巡することで入水側の温度が上昇する現象が見られた。この影響を取り除くことで入力パワーの90%を検出することが可能となり、このことはコードを用いた解析でも確認できた。また来日中には中国で進められているBEST装置の計測に関するプレゼンをしていただき、貴重な情報を得ることができた。

RESEARCH REPORT

Date: FEB 14 2026

Visiting scientists: (name) **Haiqing LIU**

(position) **Professor**

(university / institute) **Institute of Plasma Physics,**

Chinese Academy of Sciences

Host scientist: (name) **Kazuaki Hanada**

(position) **Professor**

(university / institute) **Kyushu University**

Research period: (from) **April 1 2025** (to) **March 31 2026**

Research subject: Joint study of calorimetric measurement of heat load and power balance estimation and measurement and simulation of energetic electrons loss in steady state operation(SSO) plasma on QUEST and EAST

Introduction

The ability to sustain long-pulse steady-state plasma operation is a fundamental requirement for realizing commercial fusion energy in the near future. Both the QUEST and EAST tokamaks possess the capability to sustain plasma long-pulse steady-state operation, making them invaluable experimental platforms for advancing related research. One of this year's primary collaborative research efforts focuses on deepening the understanding of power balance in long-pulse steady-state plasmas. The research emphasizes two key aspects: (1) utilizing diagnostic data combined with code simulations to calculate the heat load on non-water-cooled plasma-facing components (PFCs), ultimately achieving over 90% measurement of injected power during long-pulse discharges on EAST; and (2) performing a power balance analysis and comparison of long-pulse discharge on EAST

Haiqing LIU gave a seminar and make a fruitful discussions in QUEST building meeting room. The presentation title is "Recent progress of plasma diagnostics on EAST and BEST". Prof. Handada and Prof. Liu had fruitful discussions on student exchanges, joint new experimental proposals on QUEST, EAST and BEST, etc.

Recent results in 2024-2025

The calorimetric diagnostic measures the heat load on PFCs during discharges by detecting the temperature of the PFC cooling water. This method avoids indirect measurement, providing accurate and reliable heat load data, making it a critical diagnostic system for power balance research. However, during the 1056 s discharge #106915, the cooling water temperature curves obtained from the calorimetric diagnostic became complex. This complexity arises because, in the EAST device, the cooling water flows in a closed loop, and the cooling tower cannot cool the water temperature back to its initial value after just one cycle. Therefore, when the discharge duration exceeds the cooling water circulation time, the heat carried by the water flowing out of EAST during the second cycle includes the total heat from cooling the PFC in the second cycle, as well as part of the heat from cooling in the first cycle. This situation complicates the cooling water analysis. To address this issue, a two-step correction method has been proposed: time calibration and data calibration. In this year, the two-step correction method had been used in analyzing data of EAST device.

After data correction, calorimetric diagnostic data can be used for heat load analysis in kilosecond-scale discharges. However, for non-water-cooled PFCs, the calorimetric method cannot be applied for heat load measurements. Instead, the Heat flux Engineering Analysis Toolkit (HEAT) code is utilized to simulate the heat flux and radiation on these PFCs, enabling the estimation of heat loads. By combining calorimetric diagnostics with code simulations, approximately 90% of the injected power can be measured, which is an important achievement in EAST. A more detailed power balance analysis is currently underway.

For further development of the joint research, the uncertainty quantification of the free boundary G-S plasma equilibrium calculation on Experimental Advanced Superconducting Tokamak (EAST) had been studied. The precision of plasma equilibrium is a pivotal issue in the field of magnetic confinement fusion plasma physics and the operation of tokamak plasmas. During the plasma equilibrium uncertainty quantification (UQ) assessment process, input parameters for the equilibrium solver were assigned default value ranges derived from Experimental Advanced Superconducting Tokamak experimental data. These input parameters were subsequently processed by an encoder, decoder, and analyzer uncertainty

assessment framework. The outcomes of the UQ assessment process provide insights into the calculated equilibrium output uncertainty and its sensitivity analysis. From sensitivity analysis results, the rankings of influence for equilibrium input parameters on the calculated safety factor q profile, plasma shape, toroidal cross-section magnetic field distribution, plasma pressure, and 0D outputs were presented. This result will support our joint research in near future.

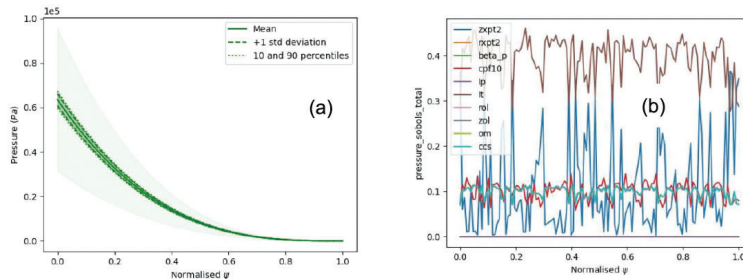


Figure 1. Plasma pressure uncertainty quantification (a) and sensitivity analysis (b).

Discussions

This year's collaborative research continued to focus on the long-pulse steady-state operation of plasmas and achieved significant results in two parts: (a) combining calorimetric diagnostic data with code simulations to achieve about 90% of the injected power measurement during EAST discharges, (b) A two-step correction method has been proposed: time calibration and data calibration. In this year, the two-step correction method had been used in analyzing data of EAST device.

During the stay, I had fruitful discussions with Prof. Hanada and colleagues and students of QUEST group. We will continue to study the power balance (new proposal in global particle balance) estimation in steady state operation (SSO) plasmas on QUEST and EAST.

Acknowledgement and comments:

Work supported by the international joint research at the Joint Usage of Research Centers for Applied Mechanics for 2025. We hope that the international joint research at the Joint Usage of Research Centers for Applied Mechanics could continue to enhance China-Japan cooperation on fusion plasma research in the future.

Co-publication list of the joint usage / research in 2025-2026:

N/A

(Signature) _____

(Name in print) Haiqing Liu

国際化推進共同研究概要

〔採択番号〕 25NU-11

タイトル: The research on the confinement and loss mechanism of alpha particle through the research of energetic electron on QUEST

研究代表者: JIE Yinxian

所内世話人: HANADA Kazuaki 研究

概要: 今年度は、QUESTのSOL領域に存在する高速電子を赤外線カメラで計測することを検討した。QUESTではポロイダル磁場が低いため、高速電子の軌道がエネルギーやピッチ角で大きく異なる。これは将来の核融合炉での α 粒子の振る舞いと類似していることから重要な研究である。SOLにリミタ等を挿入して熱負荷を計測することで軌道やピッチ角が確認できる可能性があるため、赤外線カメラの導入についての議論を実施した。

RIAM JOINT RESEARCH REPORT SUMMARY (English Form)

1. Research ID:

2. Research Title: The research on the confinement and loss mechanism of alpha particle through the research of energetic electron on QUEST

3. Category: International

4. Applicant

Affiliation: Institute of Plasma Physics, Chinese Academy of Sciences

Name: Yinxian Jie

5. RIAM Attendant: K. Hanada

6. Summary (150~200 words in Japanese or 100~150 words in English):

This year we worked on QUEST in site from December 10 2025 to December 16 2025. The main work was: Prof. Hanada, Prof. Gao, Prof Liu and I, discussing the measurement and analysis of heat load on the EAST Tokamak with Mr. Takeda Daichi, discussing the tempreture measurement by infarred camera on QUEST device with Mr. Shen Haobo.

We also dicussed the power balance on QUEST device. Long-duration, steady-state discharges with durations of up to 1000 s have been achieved in QUEST under predominantly electron cyclotron resonance heating (ECRH). Calorimetric measurements show that the heat loads on two limiters vary with the vertical plasma position. A combined analysis of experimental observations and electron orbit simulations indicates that ECRH produces a significant population of energetic electrons in the scrape-off layer (SOL), which well confined within the SOL region.

*) Submit either one of Japanese or English forms.

Research subject: The research on the confinement and loss mechanism of alpha particle through the research of energetic electron on QUEST

Prof. Hanada, Prof. Gao Prof Liu Miss.Yang and I, discussed the measurement and analysis of heat load on the EAST Tokamak in details with Mr. Takeda Daichi: How to get the data, how to check the data and how to analysis the date from EAST tokamak.

Long-duration, steady-state discharges with durations of up to 1000 s have been achieved in QUEST under predominantly electron cyclotron resonance heating (ECRH). A controlled vertical displacement of the plasma was obtained by modifying the current of a single poloidal field (PF) coil, while the overall plasma configuration remained nearly unchanged. Calorimetric measurements show that the heat loads on two limiters vary with the vertical plasma position. A combined analysis of experimental observations and electron orbit simulations indicates that ECRH produces a significant population of energetic electrons in the scrape-off layer (SOL), which well confined within the SOL region.

This effectiveness was quantitatively confirmed by magnetic field lines tracking simulation and calorimetric measurement of divertors in the experiment. Two-frequency power modulation of the lower hybrid wave (LHW) was conducted to evaluate power deposition on the scrape-off layer (SOL) during propagation from the LHW antenna to the main plasma. This experiment clarified that LHW-accelerated electrons in the SOL via collision damping deliver their energies to hot spots along the magnetic field line. These findings help alleviate or even eliminate the formation of hot spots and maintain the performance of plasma.

The findings of this study provide two primary insights. First, reduce the auxiliary heating power (such as LHW) deposition in the SOL. This part of the energy directly contributes to the heat load of related PFCs that are magnetically connected from the SOL. Therefore, efforts to increase the auxiliary heating power deposition in the core plasma for heating and current driving are needed.

This will improve the confinement performance of the plasma and reduce the cost-of-energy of the fusion device. Second, the heat load between different PFCs can be redistributed by slightly adjusting the magnetic configuration in SOL. This can be used to alleviate excessive heat load on a particular PFC, thus avoiding problems, such as impurity emission and subsequent plasma degradation. In the near future, the EAST aims to realize a higher performance plasma operation with higher power injection; therefore, it is important to achieve full FoV detection for PFCs on the EAST to monitor the condition of PFCs, including hot spots. Besides, the mechanism of association between the LHW and plasma should be further investigated to improve the efficiency of plasma heating and current driving through the LHW to achieve lengthier H-mode operations and noninductive current driving.

(Signature) Y. Jie

(Name in print) Yinxian Jie

国際化推進共同研究概要

25NU-12

タイトル： Plasma start-up and sustainment in spherical tokamak configuration
by RF

研究代表者： TAKASE Yuichi

所内世話人： 出射 浩

研究概要：

令和7年2月26、27日の2日間で国際WSをハイブリッド形式で開催した。英国から1名、米国から4名、国内から多数の参加があった。QUEST 研究計画での最近の進展・検討に加え、国内外実験研究の検討・進展、新たな理論・シミュレーション解析などが議論された。英国から1件、米国から4件、国内で15件の研究成果発表があり、球状トカマクでの研究展開につき、活発な議論があった。

Plasma start-up and sustainment in spherical tokamak configuration by RF

TAKASE Yuichi
(Tokamak Energy Ltd., United Kingdom)

An on-site/on-line hybrid workshop on “Plasma start-up and sustainment in spherical tokamak configuration by RF” was held on 26th and 27th February 2026 at Advanced Fusion Research Center in Research Institute for Applied Mechanics, Kyushu University. The agenda is shown below, followed by summaries of presentations. Lively in-depth discussions were held following each presentation.

Agenda

26th February AM

9:00 -9:10

Yuichi Takase / Hiroshi Idei

WS purpose and agenda

9:10 - 9:50

Yuichi Takase

Recent results from ST40 and future plans

9:50-10:30

Masayuki Ono

Dual utilization of X-I and O-I ECCD for fully solenoid-free operations for a fusion Reactor

10:30-11:10

Nicola Bertelli

EC heating/current drive scoping study for the SMART device

11:10 – 11:50

Luis Delgado-Aparicio

Soft and hard X-ray diagnostic development and possible applications to QUEST

11:50-12:50

Lunch

12:50-13:20

Hiroshi Idei

Progress on ECH/CD System and Research Plan on QUEST

13:20-13:40

Takumi Onchi

Power supply testing of a new current source for the toroidal coil of the QUEST spherical tokamak

13:40-14:10

Takahiro Yamaguchi

Initial results on X-I and X-2 EC plasma ramp-up experiments

14:10-14:40

Akira Ejiri

Development of Thomson scattering systems for QUEST, TST-2 and DEMO

14:40-15:10

Kengou Kuroda

CHI current drive by using FSB electrode configuration in QUEST

15:10-15:40

Taichi Shikama

Spectroscopic measurements of metallic impurities in CHI discharges

15:40-16:00

Yuya Otsuka

Observation of Sheet Structure During Coaxial Helicity Injection in the QUEST Spherical Tokamak

16:00-16:10

Coffee Break

16:10-16:40

Ryuya Ikezoe

Global RE-driven mode effects in QUEST and MHD-based studies of peak-load mitigation in RF-plugged divertors

16:40-17:10

Yoshihiko Nagashima

Experiments and Analyses on electrostatic fluctuations obtained by a SOL Langmuir probe in QUEST

17:10-17:40

Makoto Hasegawa

Prediction of Tokamak Plasma Parameters Using Machine Learning

Group Photo

27th February AM

9:00-9:30

Syunichi Shiraiwa

Application of discontinuous petrov galerkin discretization to radio-frequency wave simulation

9:30-10:00

Atsushi Fukuyama

Modeling of electron cyclotron current drive and heating in QUEST plasmas

10:00-10:30

Sadayoshi Murakami

Simulation study of ECH multiple resonance heating and energetic electron generation in the QUEST spherical tokamak

10:30-11:00

Kazuaki Hanada

EBW experiments by ECW injected from the high field side on QUEST

11:00-11:30

Shin Kubo

Progress in HCN laser scattering measurement on QUEST for EBW detection

11:30-12:00

Takeshi Ido

Present Status of HIBP on QUEST

12:00-12:30

Toshiki Kinoshita

Development and Initial Results of Doppler Backscattering on the QUEST Spherical Tokamak

12:30-13:30

Lunch

28th February PM

All suggested focus and output for this joint drafting session

Drafting of proposals for experiments, diagnosis, and analysis

26th February AM

Summary of Presentations

Y. Takase

ST40 is a compact high-field ST with copper coils. It operates with major radius 0.4 - 0.55 m, aspect ratios 1.6 - 1.9, and elongation up to 1.9. It is capable of B_t up to 2.1 T, I_p up to 1.0 MA, with two NB injectors (1 MW at 55 kV, and 0.8 MW at 24 kV). Ion temperatures of up to 100M °C have been achieved. Recently advancements were made in profile diagnostics, analysis, and interpretation. Vertical position control was improved dramatically by using the in-vessel merging-compression (MC) coils (after MC start-up is completed). SOPHIA, our tokamak simulator, is used for both real-time plasma control and for simulating scenarios in future devices. GSFit was developed as an open source equilibrium reconstruction code, and its real-time version, rfGSFit, is used to improve plasma control. L-mode to H-mode transition, as well as the intermediate I-phase, are being characterised. Energy confinement τ_E increases with B_t at low field, as found in other STs, but it saturates and becomes independent of B_t for > 1 T. The increase of τ_E with I_p is similar to other STs. Plasma operation has been extended to 1 MA, and the stored energy increased correspondingly. At $I_p = 0.2$ MA, plasmas with $\beta_p > 3$ with nearly full non-inductive current drive were achieved. Whereas the SOL power fall-off width λ_q in L-mode plasmas follows the Eich scaling, λ_q is typically an order of magnitude smaller in H-mode plasmas. First results were obtained with Li dropper, but little effect has been observed so far. ST40 is being upgraded to investigate low recycling regimes using Li evaporation under the LEAPS (Lithium Evaporations to Advance PFCs in ST40) programme, funded jointly by US DOE and UK DESNZ. The PFC will be converted to all-metal (Mo). 1 MW of EC (137/104 GHz) and a 4-barrel D pellet injector will also be installed.

M. Ono

The elimination of the need for an OH solenoid maybe the most impactful design driver for the realization of economical compact fusion tokamak reactor systems. This is particularly true for lower aspect ratio tokamaks such as spherical tokamaks (STs) to access higher beta regimes. As for the non-inductive start-up scenarios, the X-mode ECCD at fundamental resonance (X-I) was proposed due to the significantly higher ECCD efficiencies albite at lower density. While the current ramp-up scenarios at lower density is energetically favourable, an important question remains as to how to attain in the end the parameters consistent with the sustained plasma parameters where the plasma current, density, and temperature are simultaneously high. In the present work, in addition to the current circuit equation, we perform power balance analyses as the plasma losses such as radiative losses

tend to increase rapidly as the plasma density is increased. Due to a large density increase of $\times 10$, it is necessary to start the plasma with X-I but as the density is increased, the transition to the ordinary mode O-I is necessary. To control the radiative losses at high density, it was highly important to control the high-Z impurity levels such as that of tungsten to keep the plasma losses to a manageable level. As the density is increased, we find the transition to H-mode is essential from the plasma confinement and power balance point of view. Higher density and higher confinement leads to higher coulomb coupling between electrons and ions where ion temperature increases toward that of electrons. We find the D-T fusion alpha (α) heating increases with density which greatly helps the power balance at the high density. We also find applied vertical field (BV) which is necessary for the plasma equilibrium helps to provide necessary poloidal flux. With high $\beta_p \sim 1$, we find that it is feasible to ramp-up the plasma current and density simultaneously within ~ 50 sec is feasible without any OH solenoid flux.

N. Bertelli

This work presents a scoping study of electron cyclotron heating and current drive (EC H&CD) for the Small Aspect Ratio Tokamak (SMART), currently operated by the Plasma Science and Fusion Technology (PSFT) Laboratory at the University of Seville. The study utilized the ray-tracing codes GENRAY and TRAVIS to analyze two planned operational phases with magnetic field strengths of $B = 0.4$ T and 1 T. For the 0.4 T scenario, we performed a scan of poloidal and toroidal launching angles across three locations—mid-plane, off-mid-plane, and top-launcher—assuming extraordinary (X-mode) polarization. The results indicate that absorption occurs at the second harmonic, with the top-launcher achieving the highest power absorption. Additionally, we conducted a numerical analysis of the fundamental X-mode EC H&CD start-up regime for the 1.0 T scenario using wave frequencies of 28 and 35 GHz, both of which demonstrated high current drive efficiency. To validate these results, we performed a preliminary power scan using GENRAY coupled with the Fokker-Planck code CQL3D. A power injection of 1 kW shows a clear tail in the distribution function and approximately 0.4 kA of current, which is lower than the linear calculation predicted. Further study is necessary to fully evaluate the role of non-linear effects, which are particularly significant for a compact device like SMART.

L. Delgado-Aparicio

Soft and hard x-ray diagnostics are foundational tools in high-temperature plasma and fusion research, enabling measurements of MHD stability, energy confinement, impurity transport, runaway electron dynamics, radiated power, plasma-wall interactions and

disruptions. Traditional tomographic systems provide space-resolved but energy-integrated measurements, limiting access to local plasma parameters due to the lack of energy resolution. This talk traces one decade of progress in energy-sensitive x-ray diagnostics, highlighting the transition from single-energy filtered arrays to multi-energy, higher-resolution systems. To expand diagnostic capability significantly, a novel multi-energy x-ray camera has been developed and deployed at CMod, MST, WEST and TCV. It features independently adjustable energy thresholds for each “smart” pixel, enabling unprecedented mapping flexibility on a 2D sensor. Energy-threshold trimming and photon-energy calibration allow selective inclusion or suppression of radiative recombination and line emissions from medium- to high-Z species, enabling inference of a dozen plasma parameters from broadband or line-emission x-ray data alone. These systems enable direct emissivity measurements while also delivering real-time estimates of plasma centroid position, electron temperature, radiated power profiles, as well as indirect inference of impurity densities and two new methods for the effective charge (Z_{eff}). New applications include monitoring tungsten flushing during ICRH heating and sawteeth, diagnosing W-UFO events, detecting non-Maxwellian anisotropies, fast electron losses near strike points, and the evolution of slide-away and runaway electron populations for the first time. Finally, their integration with real-time control paves the way for non-magnetic equilibrium reconstructions and fast-acting RE alarms—pointing to a broader diagnostic paradigm for future fusion devices. Several applications for QUEST and opportunities for collaborations with PPPL will be outlined.

H. Idei

The #2 CW gyrotron was tested with the developed Kyushu University facility without and with CPD operation. The power of 360 kW which will be CW operation level was achieved. The transmission efficiency at the MOU is 95%. New transmission line for #2 CW gyrotron has been developed for the CW operation. At present, a long pulse dummy load is installed near the QUEST for the high-power test and aging. Relatively high transmission efficiency more than 85% is achieved at the transmission line. A quasi-optical polarizer has been developed to control incident polarizations of the selected mode for considered experimental scenarios. The polarizer is composed of $\lambda/4$ and $\lambda/8$ corrugated plates and coupling mirror. The coupling to a waveguide mode after controlling the polarization is good with a high mode purity of 98%. The polarizations are systematically scanned by rotation of $\lambda/4$ and $\lambda/8$ corrugated plates. The collaboration framework at NIFS is changed in this year. A new research program is accepted as the 3-year research up to 2027. Our center has been reorganized every 10 years. At 2027, the center will be reorganized again. A

research plan considered and proposed is introduced.

T. Onchi

Fundamental electron cyclotron heating and current-drive (ECH/CD) are planned in the QUEST spherical tokamak. To realize such fundamental ECH/CD experiment using 28 GHz radio frequency, toroidal magnetic field (TF) of 1 T in the vacuum vessel is a basic requirement. A new current source to increase TF has been developed and installed on QUEST TF coil. A module consists of a lithium ion capacitor and a DC-DC converter. All 125 modules are connected in parallel. A target of maximum current output is 100 kA. The tested output is up to 70 kA. In QUEST operation, the limit of the current is 60 kA presently, where the pulse width is 2 seconds. The new source has been applied to recent ECH/CD experiment. The output current is measured by a Rogowski coil. The overshoot and following 2 Hz oscillation with small amplitude (1 % of the target current) has been observed. The factor causing these oscillation has been unidentified yet.

T. Yamaguchi

Toroidal magnetic field at major radius increased from 0.25 T to 0.3 T. Although a fundamental resonance layer is located outside vessel, the energetic electrons with temperature of 60 keV can absorb the EC power in fundamental upshift resonance via Doppler-effect. Two type of non-inductive EC plasma ramp-up experiments were conducted to verify the multiple resonance effects. In the case of fixed $B_t = 0.3$ T, there are two types of discharges characterized by with or without temporal oscillation in the plasma current under the same operational conditions. In the discharge with the current oscillation, the inboard density increased up to the right-hand cutoff density at 2.7 s. The wave would be reflected due to the cutoff before propagating to the 1st absorption region. A transition from an effective current drive phase with the 1st absorption to efficient bulk electron heating phase without the 1st absorption was observed, depending on inboard density. In the case of varied B_t from 0.3 T in step of -0.01 T, the plasma start-up was impossible at $B_t < 0.28$ T. This result had good agreement with ray tracing analysis. At the critical field of $B_t = 0.28$ T, the plasma current and line-integrated density were clearly lower than that at the higher fields. A rapid increase in the hard X-ray counts associated with bremsstrahlung at the outer limiter before a formation of tokamak was observed several times at $B_t = 0.28$ T, indicating difficulty in formation of closed flux surface.

A. Ejiri

Thomson scattering (TS) systems for QUEST and TST-2 have been developed, and they are

used to measure various plasmas. Long pulse discharge is an interesting target in QUEST, and an automatic alignment system was developed, and a remote fiber movement system is under development. Development for DEMO is being carried out, and design studies and demonstration in TST-2 are conducted. Edge LITS and Core Forward TS were proposed for DEMO, and the feasibilities in terms of sensitivity and neutron irradiation are good.

K. Kuroda

The CHI current drive has been studied in QUEST, in which the CHI flux formation by using FSB electrode configuration has been achieved. The observation result of the distribution of injector current measured by magnetic sensor array and flux evolution shows that flux evolves largely and higher toroidal current is driven by the injector current flowing in the appropriate distribution. The similar CHI flux evolution was observed under different flux conditions on the identical flux configuration, in which the driven currents follow the CHI current scaling relation. The driven toroidal current was increased up to 210 kA under the flux condition of $\Psi_{inj} = 29.6$ mWb. We will remodel the electrode structure, in which we try to prevent the arcing discharge completely, and improve the CHI discharge by the optimized electrode.

T. Shikama

In CHI discharges, impurities originating from the electrodes degrade the electron temperature and plasma current. Therefore, understanding their generation and transport processes is essential. Previous studies have measured light elements released from the co-deposition layer on the electrode surface, whereas in this study chromium atoms and ions produced by sputtering of the electrode base material (SUS316L) were newly measured. Thirteen lines of sight were installed between the electrode and the equatorial plane, and Cr I and Cr II emission lines were observed at five time points during the 200 μ s period from plasma formation to bubble burst with an exposure time of 20 μ s. The Cr I emission was localized near the electrode at all times, while the Cr II emission was initially localized near the electrode and was extended toward the equatorial plane at the time of the bubble burst. This behavior can be understood as atoms being ionized near the electrode, followed by transport of the ions during the bubble burst.

Y. Otsuka

Coaxial Helicity Injection (CHI), a non-inductive current drive method, is performed on the QUEST spherical tokamak. In QUEST CHI discharges, sheet-like emission structures have often been observed in regions where magnetic reconnection occurs, as seen in fast camera

images. Magnetic measurements suggest that a high toroidal current exists at the location of the emission structure, which is similar to the Sweet–Parker-type sheet current reported in CHI simulations. In discharges with the sheet structure, the plasma current tends to be lower and the energy consumption of the capacitor bank tends to be faster. In addition, differences with and without the sheet structure also appear in probe measurements on the midplane. Since the CHI electrode has a finite radial thickness, this is considered to be due to whether the current path governing plasma formation is located more on the inner side or on the outer side. One possible reason for the difference in discharge paths is the spatial variation of neutral gas density caused by recycling from the vessel wall. In NSTX, where recycling is suppressed by lithium coating, variations such as those observed in QUEST have not been reported.

R. Ikezoe

QUEST experiments demonstrate that kinetic waves can suppress runaway electrons, as evidenced by modifications in global plasma current dynamics. In parallel, the RF-plugged divertor is investigated as an active transport control concept, where field-aligned RF-induced effective potentials create tunable barriers along the divertor leg. These potentials trigger localized supersonic transitions and enhance parallel confinement, thereby promoting radial transport broadening of the SOL. As a result, the SOL density decay length increases significantly, and the peak particle flux to the divertor target can be reduced by an order of magnitude for RF potentials of approximately three times the SOL plasma temperature.

Y. Nagashima

In this talk, preliminary results from edge plasma measurements using newly developed limiter-like Langmuir probe for QUEST are shown. By I-V characteristic measurements, existence of high temperature/energy electron tail components in SOL region inside the first wall is confirmed. At the same time, in some discharges, MHz range floating potential fluctuations are intermittently observed, and correlation between the high energy electron fluxes and envelope of the MHz range fluctuation is suggested. There are mainly two problems which should be overcome for future study. One is existence of positive spike, and the other is the frequency response of MHz range fluctuations. On existence of the positive spike, selective analysis on the negative spike phase is a solution. On the frequency response of MHz range fluctuations, artificial scanning experiment of the stray capacitance is a solution.

M. Hasegawa

This study proposes a method for real-time prediction of plasma position, shape, and internal parameters in QUEST using deep neural networks. Training was performed using equilibrium data generated based on the Grad–Shafranov equation, verifying whether internal parameters could be estimated solely from magnetic measurements. Furthermore, the improvement in prediction accuracy was evaluated by adding diamagnetic and pressure measurements to the input. Estimation with errors of approximately 10–20% is achievable for simple profiles, and accuracy improvements were confirmed for diverse profiles through additional measurements. This method contributes to future plasma control applications by accelerating equilibrium calculations.

S. Shiraiwa

Expanding the capabilities of full-wave simulations is a critical necessity for accurately capturing a wider range of physical phenomena in plasma wave and RF-heating applications. Specifically, enhancements are desirable to resolve short-wavelength modes for wave physics analysis in several key areas including high-frequency EC/LH waves, slow waves, surface waves. However, the current mainstream approach based on the finite element methods (FEM) faces significant challenges, when increasing the simulation domain size due to the indefiniteness of the linear system and the scalability of sparse linear solvers. In this work, we are investigating the feasibility of using the ultraweak discontinuous Petrov-Galerkin (UW-DPG) method for plasma wave simulations. UW-DPG is a generic framework that yields a symmetric positive definite (SPD) linear system, which is highly amenable to efficient, scalable iterative solvers. Because of this, UW-DPG may offer a transformative alternative to the conventional FEM. We are testing the UW-DPG method for various plasma wave simulations, and the initial results are encouraging. We showed (1) simulations of simple waveguide, which shows a convergence behavior unique to UW-DPG, (2) adaptive mesh refinement (AMR) capability, which is demonstrated in 2D Lower Hybrid (LH) simulations, and (3) initial ICRF (Ion Cyclotron Range of Frequencies) wave simulations, which shows excellent agreement with results obtained from the regular FEM solver.

A. Fukuyama

Recent results of modeling of heating and current drive by electron cyclotron (EC) waves in QUEST plasmas using the integrated modeling code TASK. Ray tracing analysis by TASK/WR+DP for EC heating and the Fokker-Planck analyses of electron momentum distribution function by TASK/FP for EC current drive have been performed. The Fokker-

Planck analysis provides accurate evaluation of ECCD efficiency, but requires computational resources. Future introduction of machine learning should be considered. Kinetic full wave analysis using integral form of dielectric tensor is powerful for hot inhomogeneous plasmas. It has been successfully applied to the magnetic shear heating near the electron cyclotron resonance and the excitation of electron Bernstein waves in QUEST configurations. Extension to the two-dimensional kinetic full wave analysis in the poloidal cross section of tokamak plasmas and incorporation of the relativistic effects are under way.

S. Murakami

We have performed the GNET simulation of the ECH electron distribution function, including the 3rd, 4th, and 5th harmonic resonances. It was found that the energetic electrons, generated by the 2nd resonance, were further accelerated by the 3rd, 4th, and 5th resonances. We have shown the critical role of higher-harmonic heating in the generation of energetic electrons in QUEST. We have also investigated the multi-resonance heating in QUEST with $B_0 = 0.5$ T.

K. Hanada

EBWH/CD is a good candidate for plasma start-up and a dedicated antenna and waveguides for HFS launch were installed on QUEST to conduct physical experiments. Numerical simulation using GENRAY predicted that a significant I_p could be expected on QUEST. To confirm the role of EBWCD in I_p start-up, four types of the magnetic configurations were examined. Considering the existence of L cutoff and the characteristics of EBWCD, a schematic model is proposed to explain the differences in I_p start-up. The magnetic signal was used to reconstruct the current profile, which was concentrated in the equilibrium region. The BR control was useful to regulate the I_p start-up. Positive area ratio resulted in a good I_p start-up.

S. Kubo

The history of EBW detection by the scattering project is reviewed. Initially, a 170 GHz gyrotron is considered as a scattering source, but a higher frequency is preferable for EBW detection. A 400 GHz gyrotron developed in Fukui University is loaned for the scattering project, and detection and optical systems are designed for 400 GHz. Due to the delay in the actual application, the loan term expired, and HCN laser (337 μm , 890 GHz) was selected in turn and transferred from Kyoto Univ. to QUEST in 2022. The detection system is redesigned for 890 GHz. The optical system is designed using the newly developed quasi-optical grating method. The detection system is redesigned to use a harmonic generator

and a sub-harmonic mixer originally prepared for 400 GHz.

T. Ido

A Heavy Ion Beam Probe (HIBP) system is being installed. In this fiscal year, we successfully achieved beam injection into the QUEST vacuum vessel. However, when the poloidal magnetic field required for plasma confinement is applied, the beam is deflected in the toroidal direction, resulting in a significant reduction in the injected beam current. For the plasma measurement, it is therefore necessary to compensate for beam deflection associated with variations in the magnetic field more precisely.

T. Kinoshita

Understanding the unique transport mechanisms in spherical tokamaks (STs) is critical for optimizing confinement and handling divertor heat loads, as conventional scaling laws often fail to describe ST behavior. To investigate these processes on the QUEST spherical tokamak, we have developed a low-frequency Doppler backscattering (DBS) diagnostic system. Optimized for QUEST's typical low-density plasmas ($n_e \sim 2 \times 10^{18} \text{ m}^{-3}$), the system operates in the 8–18 GHz range (X-band). A three-channel simultaneous measurement scheme allows for radial profile probing, while specialized focusing optics were designed to maintain beam integrity over the 1.5 m distance between the antenna and the plasma. Through multi-angle injection, the system captures ion-scale turbulence within the range of $k_{\perp} \sim 0.3\text{--}3.0 \text{ cm}^{-1}$ ($k_{\perp} \rho_i \sim 0.1\text{--}1.0$). Initial experimental results from ECRH-only discharges successfully identified the formation of a strong $\mathbf{E} \times \mathbf{B}$ flow shear in the core region ($\rho = 0.4\text{--}0.6$). This flow shear coincided with a significant suppression of turbulence levels, which likely facilitated the achievement and maintenance of higher electron temperatures ($T_e \sim 150 \text{ eV}$). Measured radial electric fields (E_r) ranged from -150 to $+50 \text{ V/m}$. Future work will focus on expanding measurement coverage through X-mode operation and performing high-fidelity quantitative analysis using the advanced beam-tracing code SCOTTY to account for complex 3D magnetic structures and diffraction effects.

国際化推進共同研究概要

〔採択番号〕 25NU-13

タ イ ト ル: Characteristics and instabilities of kinetic-scale flux ropes
driven by fast electrons

研究代表者: YOON Young Dae

所内世話人: MOON Chanhho

研究 概 要:

本研究は、線形磁化プラズマ装置PANTAを対象に、高速電子ビームによって駆動される運動論的不安定性と磁気フラックスロープ構造の形成機構を解明することを目的とした。数値シミュレーションを用いて、不安定性の発生から乱流への発展過程と、それが輸送特性に与える影響を明らかにする研究計画を策定した。本訪問では実験との比較・検証に向けた具体的な研究方針を共有し、今後の共同研究の実施体制を整えた。

Characteristic and instabilities of kinetic-scale flux ropes driven by fast electrons

Young Dae Yoon (Asia Pacific Center for Theoretical Physics)

I carried out an International Joint Research visit to the Research Institute for Applied Mechanics (RIAM), Kyushu University, from 11–14 January, hosted by Prof. Chanho Moon and the Fusion Plasma Group. The linear magnetized plasma device PANTA was the intended experimental platform and point of contact for validation.

Motivation and scientific rationale. The project was motivated by our recent Nature paper (Park et al., Nature 644, 59–63, 2025), which highlighted how non-equilibrium plasma dynamics can generate kinetic-scale magnetic structures (flux-rope-like bundles of field lines) and how their formation and relaxation can influence dissipation and transport. These results suggest that kinetic instabilities and the turbulence they drive can alter effective impedance and energy pathways inside current-carrying plasmas, potentially enabling or suppressing subsequent processes such as reconnection and rapid relaxation. A controlled linear device provides an attractive environment to isolate these cause-and-effect links with well-defined geometry, boundary conditions, and diagnostic access.

Aim of the planned joint research. The central aim at RIAM was to develop and apply simulations to study turbulence driven by beam-related kinetic instabilities in a linear magnetized plasma, and to connect the resulting turbulent transport and magnetic self-organization to the emergence and stability of kinetic-scale flux ropes. In practical terms, we intended to use simulations as a quantitative bridge between (i) injection of a fast-electron population (via electron guns), (ii) the onset and nonlinear saturation of kinetic instabilities, and (iii) measurable consequences in fluctuation spectra, transport levels, and inferred impedance.

Planned methodology. The proposed workflow comprised three steps: (1) establish a beam-free baseline model representative of PANTA conditions by matching key dimensionless parameters (magnetization, collisionality, and characteristic gradient scales) and by validating background fluctuations; (2) introduce an energetic-electron component representing the electron-gun source to map instability thresholds and dominant mode families, and to follow the transition into broadband turbulence; and (3) quantify how the turbulence modifies transport and effective impedance, while assessing whether flux-rope-like magnetic structures form, persist, or become unstable. The ultimate deliverable was a set of benchmarked simulation results and a clear set of experimentally testable signatures.

Activities during the visit and status. During the visit I presented a 30-minute overview of my recent research at the weekly Fusion Plasma Group meeting and discussed how the Nature results motivate beam-driven studies on PANTA. I also held technical discussions with RIAM

collaborators to refine feasible parameter ranges, identify the most informative diagnostics for comparison, and consolidate a staged plan for simulation–experiment benchmarking.

The planned research could not be carried out during this period because the power supply for the electron guns had not yet been installed and commissioned. Since the energetic-electron source is essential for defining realistic beam parameters and for validating beam-driven scenarios, the joint simulation campaign was deferred. Nonetheless, the visit established a shared roadmap for rapid initiation once the electron-gun system becomes operational during the next available period.

国際化推進共同研究概要

〔採択番号〕 25NU-14

タイトル: Development of Core-SOL-Divertor model for simulating tokamak with impurities

研究代表者: WISITSORASAK Apiwat

所内世話人: KASUYA Naohiro

研究概要:

トカマクプラズマにおける不純物輸送について統合的な解析を可能とするために、TASKコードへSOL・ダイバータ領域の効果を組み合わせるのが本研究の課題である。これまでに開発したSOL・ダイバータ領域の密度・温度の動的な変化を解く計算モデルをTASKコードのモジュールとして組み込み、計算を実施してデタッチメント現象を議論した。本年度は研究代表者が応研共同研究集会の実施時期にあわせて九大応力研を訪問し、研究発表を通じて九大をはじめ多くの日本の核融合研究者との研究交流を行うことができた。

Development of Impurity Transport Simulation for Detached Tokamak Plasmas in the SOL and Divertor Regions

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31 January 2026

1 Introduction

Impurities in tokamak plasma introduce several deleterious effects on the overall performance of the devices. A large amount of impurities can dilute the fuel and reduce the rate of fusion reactions. Furthermore, one of the most immediate effects is the loss of radiated power, which leads to lower plasma temperatures. Excessive edge cooling destabilizes the plasma and leads to plasma disruption, which can severely damage the wall and other structures. On the other hand, impurity ions from the plasma-facing components, such as tungsten, can travel farther from the edge and cause significant radiation in the core. This prevents the plasma from reaching a high enough temperature for ignition [1]. Hence, the concentration of impurities should be minimized.

Despite the downside effects, the radiation of plasma impurities nevertheless has some helpful consequences. Injection of noble gases such as argon or neon is intentionally used to increase radiation in the edge region of the plasma. A well-controlled amount of these seeded impurities helps to disperse the plasma power exhaust over wider surface areas and reduce the temperature in front of the plasma-facing components. This radiative cooling is the primary mechanism for accessing the detached plasma regime, a state where plasma pressure and particle flux to the divertor targets are significantly reduced, thereby protecting the wall materials from erosion and melting.

To accurately simulate this complex interplay between impurity transport and divertor physics, we have developed a new simulation module, TASK/CSD (Core-SOL-Divertor), within the integrated transport code TASK. This module extends the previous transport models by explicitly incorporating plasma detachment physics. Volumetric recombination (particle sink) and charge-exchange friction (momentum sink) terms have been added to the fluid equations. These improvements

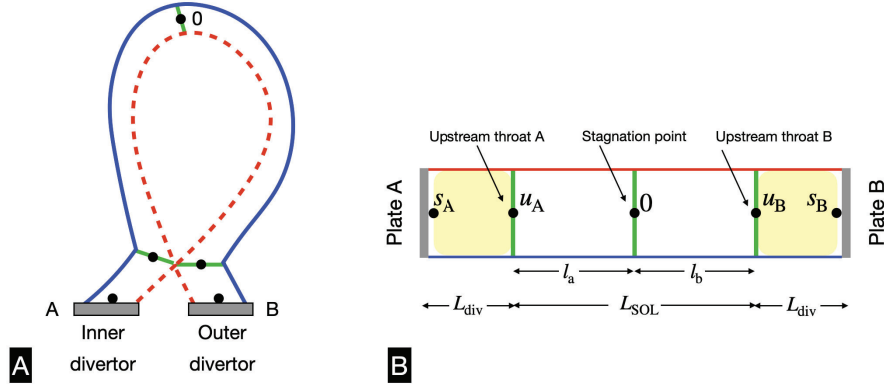


Fig. 1 Schematic diagram showing the geometry of the five-point model which considers the transport along the magnetic field.

allow the TASK/CSD code to investigate the transition from the attached to the detached state, capturing the characteristic flux rollover and temperature collapse driven by impurity radiation.

2 Methodology

To dynamically model the SOL and divertor plasma, one may reduce the complexity of the problem by considering only the transport along a magnetic field line. Instead of using a 1D or 2D transport model, one can focus on the relevant physical quantities of the plasma at specific points along the field line. The simplest model is the so-called two-point model, which considers only two points: the upstream (or stagnation point) and the target point. However, the two-point model does not account for asymmetric transport. A five-point model was originally proposed by Hayashi-san to study thermoelectric instability. It can also be used to model the dynamic response of SOL-divertor plasma during an ELM crash, which may induce thermoelectric instability and large SOL currents [2]. The model also only considers the transport of hydrogenic species without explicitly including impurities. In this work, we first describe the five-point model. The impurity transport will be solved in the background of the hydrogenic species and will be introduced later in this section.

The geometry of the five-point model is shown in Figure 1. The model considers the flux tube closest to the separatrix in single-null or double-null plasmas. The flux tube is divided into four regions. The fluid equations are integrated and reduced to a set of nonlinear algebraic equations with physical variables at the five positions.

2.1 Model Equations

The transport equations of the hydrogenic species governing the plasma dynamics in the SOL and divertor are given by:

$$L_{\text{SOL}} \frac{dn_0}{dt} = -\Gamma_{uB} - \Gamma_{uA} + S_0 L_{\text{SOL}}, \quad (1)$$

$$L_{\text{div}} \frac{dn_{sB}}{dt} = \Gamma_{uB} - \Gamma_{sB} + S_B L_{\text{div}}, \quad (2)$$

$$L_{\text{div}} \frac{dn_{sA}}{dt} = \Gamma_{uA} - \Gamma_{sA} + S_A L_{\text{div}}, \quad (3)$$

$$\frac{m_i}{2} (l_b + (1 + R_B) L_{\text{div}}) \frac{d\Gamma_{uB}}{dt} = n_0 (T_{e,0} + T_{i,0}) - n_{sB} (2T_{e,sB} + (1 + g) T_{i,sB}) - P_{\text{loss},B}, \quad (4)$$

$$\frac{m_i}{2} (l_a + (1 + R_A) L_{\text{div}}) \frac{d\Gamma_{uA}}{dt} = n_0 (T_{e,0} + T_{i,0}) - n_{sA} (2T_{e,sA} + (1 + g) T_{i,sA}) - P_{\text{loss},A}, \quad (5)$$

$$\begin{aligned} \frac{3}{2} \frac{dn_0 T_{e0}}{dt} &= -Q_{e,uB} - Q_{e,uA} - J(\phi_{uB} - \phi_{uA}) \\ &\quad + (W_{e0} + W_{e,eq,0}) L_{\text{SOL}}, \end{aligned} \quad (6)$$

$$\frac{3}{2} \frac{dn_0 T_{i0}}{dt} = -Q_{i,uB} - Q_{i,uA} + (W_{i0} + W_{i,eq,0}) L_{\text{SOL}}, \quad (7)$$

$$\begin{aligned} \frac{3}{2} \frac{dn_{sB} T_{e,sB}}{dt} &= Q_{e,uB} - Q_{e,sB} - J(\phi_{uB} - \phi_{sB}) \\ &\quad + (W_{e,B} + W_{e,eq,B}) L_{\text{SOL}}, \end{aligned} \quad (8)$$

$$\begin{aligned} \frac{3}{2} \frac{dn_{sA} T_{e,sA}}{dt} &= Q_{e,uA} - Q_{e,sA} - J(\phi_{uA} - \phi_{sA}) \\ &\quad + (W_{e,A} + W_{e,eq,A}) L_{\text{SOL}}, \end{aligned} \quad (9)$$

$$\frac{3}{2} \frac{dn_{sB} T_{i,sB}}{dt} = Q_{i,uB} - Q_{i,sB} + (W_{i,B} + W_{i,eq,B}) L_{\text{SOL}}, \quad (10)$$

$$\frac{3}{2} \frac{dn_{sA} T_{i,sA}}{dt} = Q_{i,uA} - Q_{i,sA} + (W_{i,A} + W_{i,eq,A}) L_{\text{SOL}}. \quad (11)$$

The equations for the impurity species are as follows, where $j = 1, 2, 3, \dots, z_{\text{max}}$ denotes the ionization states:

$$\begin{aligned} L_{\text{SOL}} \frac{dn_{j,0}}{dt} &= -\Gamma_{j,uB} - \Gamma_{j,uA} + L_{\text{SOL}} (n_{j-1,0} \alpha_{j-1,0} - n_{j,0} \alpha_{j,0} \\ &\quad + n_{j+1,0} \beta_{j+1,0} - n_{j,0} \beta_{j,0} + S_{j,0}), \end{aligned} \quad (12)$$

$$\begin{aligned} L_{\text{div}} \frac{dn_{j,sA}}{dt} &= \Gamma_{j,uA} - \Gamma_{j,sA} + L_{\text{div}} (n_{j-1,sA} \alpha_{j-1,sA} - n_{j,sA} \alpha_{j,sA} \\ &\quad + n_{j+1,sA} \beta_{j+1,sA} - n_{j,sA} \beta_{j,sA} + S_{j,sA}), \end{aligned} \quad (13)$$

$$\begin{aligned} L_{\text{div}} \frac{dn_{j,sB}}{dt} &= \Gamma_{j,uB} - \Gamma_{j,sB} + L_{\text{div}} (n_{j-1,sB} \alpha_{j-1,sB} - n_{j,sB} \alpha_{j,sB} \\ &\quad + n_{j+1,sB} \beta_{j+1,sB} - n_{j,sB} \beta_{j,sB} + S_{j,sB}), \end{aligned} \quad (14)$$

$$\begin{aligned}
\frac{m_Z}{2} (l_b + (R_j + 1)L_{\text{div}}) \frac{d\Gamma_{j,\text{uB}}}{dt} &= n_{j,0}T_{\text{H},0} - 2n_{j,\text{sB}}T_{\text{H},\text{sB}} \\
&\quad + \frac{m_Z}{\tau_j} \left[\frac{1}{2}n_{j,0}v_{\text{H},0} + \frac{1}{2}n_{j,\text{sB}}v_{\text{H},\text{sB}} + \frac{m_Z}{2} (l_b + (R_j + 1)L_{\text{div}}) \Gamma_{j,\text{uB}} \right] \\
&\quad + m_z (l_b + (R_j + 1)L_{\text{div}}) (\alpha_{j-1,\text{uB}}\Gamma_{j-1,\text{uB}} - \alpha_{j,\text{uB}}\Gamma_{j,\text{uB}}),
\end{aligned} \tag{15}$$

$$\begin{aligned}
\frac{m_Z}{2} (l_b + (R_j + 1)L_{\text{div}}) \frac{d\Gamma_{j,\text{uA}}}{dt} &= n_{j,0}T_{\text{H},0} - 2n_{j,\text{sA}}T_{\text{H},\text{sA}} \\
&\quad + \frac{m_Z}{\tau_j} \left[\frac{1}{2}n_{j,0}v_{\text{H},0} + \frac{1}{2}n_{j,\text{sA}}v_{\text{H},\text{sA}} + \frac{m_Z}{2} (l_b + (R_j + 1)L_{\text{div}}) \Gamma_{j,\text{uA}} \right] \\
&\quad + m_z (l_b + (R_j + 1)L_{\text{div}}) (\alpha_{j-1,\text{uA}}\Gamma_{j-1,\text{uA}} - \alpha_{j,\text{uA}}\Gamma_{j,\text{uA}}).
\end{aligned} \tag{16}$$

To simulate the impurity influx, we calculate the impurity neutral generation at the targets via physical sputtering. The neutral impurity flux $\Gamma_{0,p}$ leaving the target plate (where p denotes either target A or B) is given by:

$$\Gamma_{0,p} = \left(Y_H \Gamma_{H,p} + \sum_{j=1}^{z_{\text{max}}} Y_j \Gamma_{j,p} \right) \sin \Theta, \tag{17}$$

where Y_H and Y_j are the sputtering yields for hydrogen and impurity ions, respectively, and Θ is the incident angle of the magnetic field line. Assuming the neutrals are emitted with a thermal velocity v_0 and decay via ionization, the neutral density profile $n_0(z)$ near the target is modeled as:

$$n_0(z) = \frac{\Gamma_{0,p}}{v_0} e^{-z/\lambda_0}, \quad \text{where} \quad \lambda_0 = \frac{v_0}{n_e \alpha_0}. \tag{18}$$

These equations capture the key physics required for detachment studies: the source term S explicitly includes volumetric recombination (S_{rec}), acting as a particle sink at low temperatures (< 1.5 eV), and the momentum loss term P_{loss} accounts for friction due to charge exchange (S_{mom}) with neutrals.

To accurately capture the physics of plasma detachment, the model explicitly incorporates a momentum loss term, , which represents the dissipation of plasma momentum due to charge-exchange (CX) friction between the plasma ions and the neutral gas in the divertor region . This term is defined as the integrated drag force over the divertor leg length, L_{div} , and is calculated as

$$P_{\text{loss},A} = m_i n_{sA} n_{0,sA} \langle \sigma v \rangle_{\text{CX}} c_{sA} L_{\text{div}}, \tag{19}$$

where m_i is the ion mass, n_{sA} and $n_{0,sA}$ denote the plasma and neutral hydrogen densities at the target plate, respectively, c_{sA} is the ion sound speed, and $\langle \sigma v \rangle_{\text{CX}}$ is the charge-exchange rate coefficient evaluated at the local target temperature. Physically, this term quantifies the momentum transfer from the accelerating plasma flow to the background neutrals, serving as the primary mechanism for decoupling the downstream plasma pressure from the upstream pressure during high-recycling and detached conditions.

2.2 Algorithm

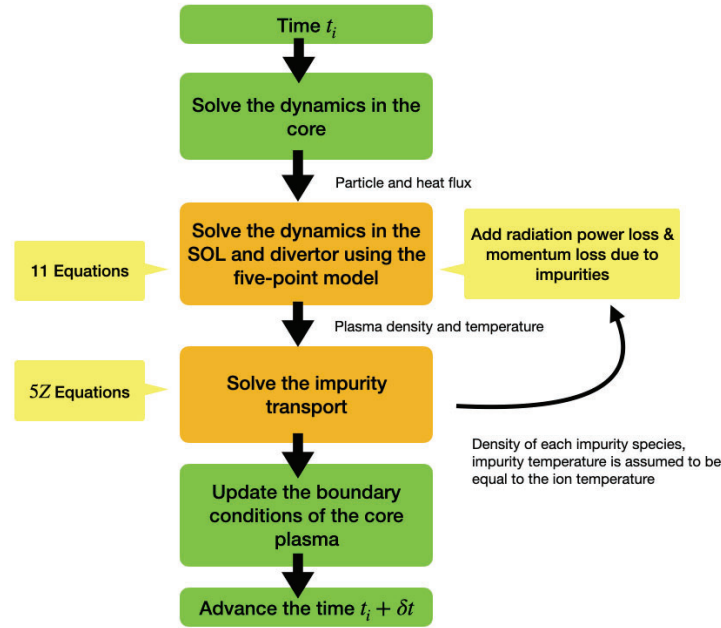


Fig. 2 Algorithm for solving the extended five-point model.

The impurity transport model can be coupled with the original five-point model to predict the densities and temperatures of both hydrogenic and impurity species. This combined model shall be named the SOL module. The SOL module can then be integrated into the main plasma simulation for the core region as follows (see Figure 2):

- At each time step, the main simulation numerically solves the plasma dynamics in the core and provides the particle and heat fluxes to the SOL module.
- In the SOL module, the original five-point model is first solved using the classical Runge-Kutta method (RK4), yielding the densities and temperatures at specific points along the field line.
- Assuming that the impurity ions share the same temperature as the main ions, the impurity transport model is then solved to determine the densities of the impurity species.
- These impurity densities are returned to the core simulation, updating the boundary conditions for the next time step.

The structure of the TASK/CSD module is designed as a hierarchical workflow centered around a main driver and a dedicated physics engine, see Figure 3. Execution begins with `csd_main`, which sequentially handles initialization (`csd_init`) and parameter loading (`csd_parm`) before entering the primary user interface, `csd_menu`. From this menu, the user can trigger the core solver, `csd_exec`, which manages the time-dependent evolution of the plasma. Within the physics kernel (`csdfunc`), the time loop is implemented using a 4th-order Runge-Kutta solver (RK4). This solver iteratively calls `ODE.Func` to evaluate the system of differential equations, relying on the `ComputerFluxSource` subroutine to calculate essential physical terms—such as atomic rates from OPEN-ADAS, particle sources, and momentum sinks. As shown in the data flow

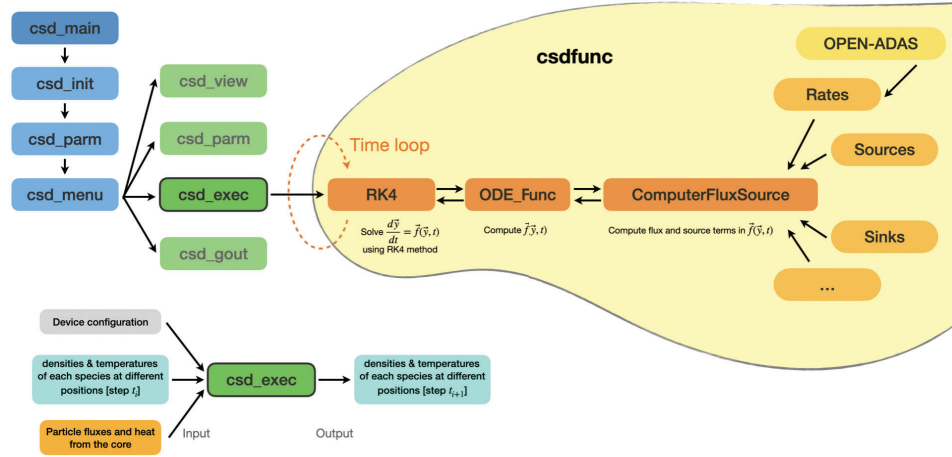


Fig. 3 Code structure and execution flow of the TASK/CSD module. The simulation is initiated by the main driver (`csd_main`), which handles parameter initialization (`csd_init`, `csd_parm`) before entering the user control interface (`csd_menu`). The core physics engine (`csd_exec`) advances the plasma state in time using a 4th-order Runge-Kutta solver (RK4), which iteratively calls the derivative function (`ODE_Func`) and the flux calculator (`ComputerFluxSource`) to evaluate atomic rates, source terms, and transport fluxes.

schematic, `csd_exec` functions as a state-transition operator, taking the device configuration, core fluxes, and plasma state at time t_i as inputs to compute the evolved densities and temperatures for the subsequent time step t_{i+1} .

3 Results and Discussion

In this section, we present the simulation results obtained using the newly developed TASK/CSD module. To illustrate the model's capability in reproducing the transition from attached to detached divertor regimes, we employed a set of parameters representative of a medium-sized tokamak device. The simulation configuration is defined by a major radius of $R = 3.0$ m and a total separatrix surface area of $S_{\text{sep}} = 120$ m². The computational domain along the magnetic field line is divided into a main Scrape-Off Layer (SOL) with a connection length of $L_{\text{SOL}} = 50$ m and a divertor leg with a length of $L_{\text{div}} = 2$ m. Carbon ($Z = 6$) was selected as the impurity species to investigate the impact of radiative cooling on plasma detachment. For the initial attached conditions, the upstream electron density and temperature were initialized at $n_0 = 1.0 \times 10^{19}$ m⁻³ and $T_{e,0} = T_{i,0} = 60$ eV, respectively, with a recycling amplification factor set to 2.0.

We first examine the plasma dynamics in the sheath-limited regime, configured with an input power of $P_{\text{SOL}} = 1.5$ MW and a low recycling amplification factor to simulate a pumped divertor. As illustrated in the simulation results in Figure 4, the target particle flux (Γ_s) exhibits a linear increase proportional to the rising upstream density, with no indication of flux rollover. This linear response confirms that the plasma remains in the attached state. Consistently, the electron temperature at the divertor targets ($T_{e,s}$) stabilizes at approximately 25 eV, which is significantly higher than the 1.5 eV threshold required to trigger volumetric recombination. Regarding impurity transport, the core impurity densities demonstrate a stable linear rise, indicating continuous accumulation in the upstream region. Although the strong plasma flow generates a friction force that flushes impurities toward the targets, the impurity source term is sufficient to maintain a positive and physically consistent

density profile throughout the simulation.

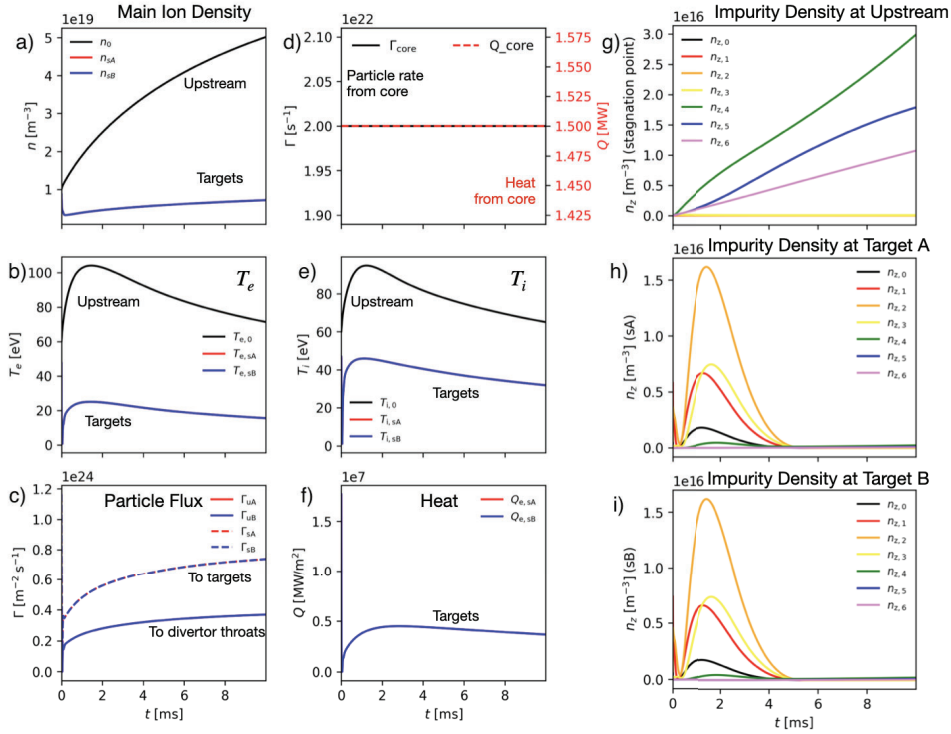


Fig. 4 Temporal evolution of SOL and divertor plasma parameters in the sheath-limited regime ($P_{\text{SOL}} = 1.5$ MW). The panels illustrate: (a) the main ion densities at the upstream stagnation point (n_0) and the divertor targets (n_{sA} , n_{sB}); (b) electron and (e) ion temperatures at corresponding locations; (c) the parallel particle fluxes; (g) charge-state resolved impurity densities ($n_{z,j}$) for Carbon ($Z = 0 \dots 6$) at the upstream interface; (h-i) impurity densities at the inner (A) and outer (B) divertor targets. The results demonstrate an attached plasma state, characterized by the linear rise of target fluxes and stable target temperatures ($T_{e,s} \approx 25$ eV) well above the recombination threshold.

Subsequently, we investigated the transition to the detached plasma regime by actively controlling the heat flux and particle flux from the core. Through this systematic variation of boundary conditions, the detached plasma state was successfully observed. A definitive signature of detachment, the “flux rollover,” is clearly evident in the simulation results, Figure 5. As the upstream density (n_0) increases, the particle flux to the targets (Γ_s) initially rises, reaches a peak, and subsequently decreases, diverging sharply from the linear behavior observed in the attached case. This rollover is driven by a precipitous collapse in the target electron temperature ($T_{e,s}$) to values below 2 eV, the threshold necessary to activate strong volumetric recombination. The simulation reveals that this recombination acts as a dominant particle sink, extinguishing over 80% of the plasma flux before it reaches the divertor plates. Furthermore, the momentum loss fraction rises to approximately 90%, confirming that charge-exchange friction has effectively decoupled the target plasma pressure from the upstream pressure. This transition is primarily initiated by radiative cooling from Carbon impurities, which lowers the divertor temperature sufficiently to trigger the recombination-dominated feedback loop.

Based on the simulation results illustrating the transition to detachment, the graphs in Figures 6 depict the non-linear response of the divertor plasma to increasing upstream density (n_0). Initially, the particle flux to the targets (Γ_s) rises linearly, characteristic of the high-recycling regime. However, as n_0 exceeds a critical threshold, the target electron temperature

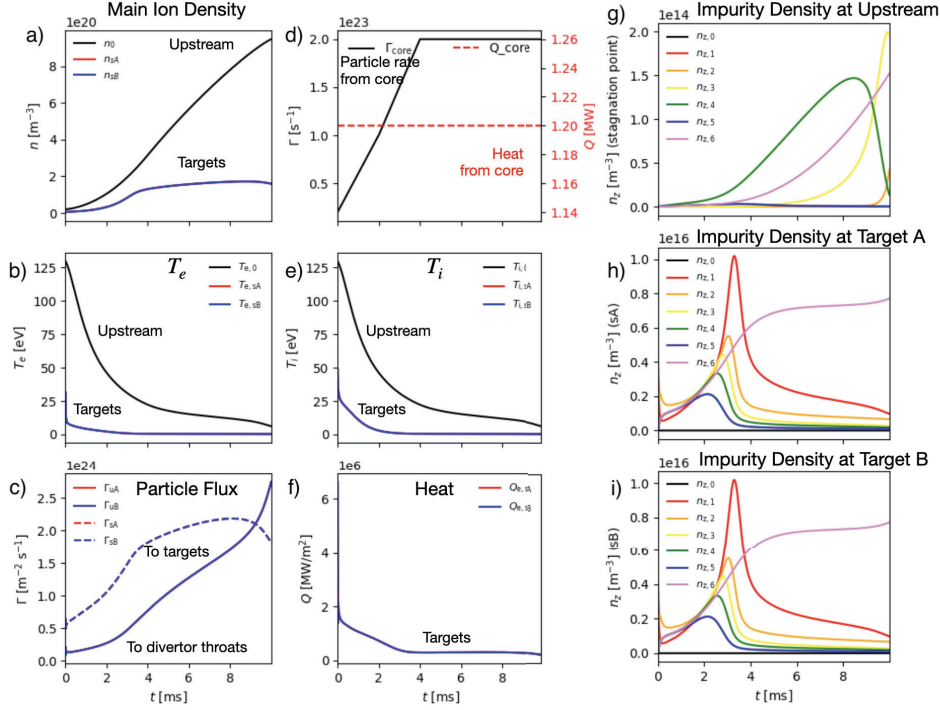


Fig. 5 Temporal evolution of SOL and divertor plasma parameters during the transition to the detached regime. The panels show: (a) the upstream main ion density (n_0) and target densities (n_{sA} , n_{sB}); (b, e) electron and ion temperatures at the upstream and target locations; (c) the parallel particle fluxes; (f) the heat fluxes; (g) carbon impurity densities at the upstream stagnation point; (h, i) impurity densities at the inner (A) and outer (B) divertor targets.

($T_{e,s}$) collapses below 2 eV, triggering the onset of volumetric recombination. This cooling leads to a sharp "rollover" in the particle flux, where Γ_s decreases despite the rising upstream density. Simultaneously, the momentum and particle loss fractions increase rapidly to approximately 90% and 80%, respectively, confirming that charge-exchange friction and recombination have effectively decoupled the target plasma from the upstream pressure and particle sources.

4 Summary

In this study, we have developed a time-dependent Core-SOL-Divertor transport module, named TASK/CSD, designed to simulate the dynamic behavior of tokamak boundary plasmas in the presence of impurities. The model solves a comprehensive set of 11 fluid equations governing the hydrogenic plasma species, fully coupled with transport equations for impurity ions.

A key feature of this module is the explicit integration of atomic and molecular processes essential for reproducing plasma detachment. We have incorporated volumetric recombination as a particle sink and charge-exchange friction as a momentum loss mechanism. Additionally, the model accounts for impurity-induced radiative cooling, using Carbon ($Z = 6$) as a test species, which serves as the primary trigger for the temperature collapse necessary to access the detached regime.

Simulation results successfully demonstrated the validity of the model across distinct operating regimes. In the sheath-

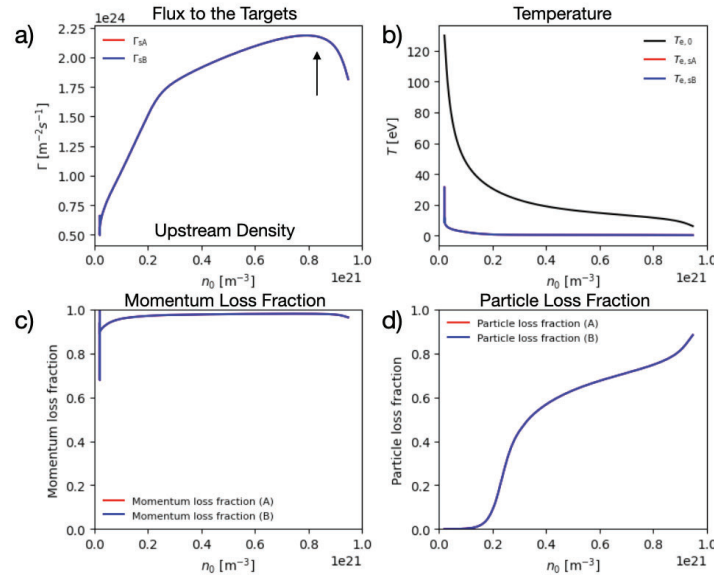


Fig. 6 Plasma parameters plotted against upstream density (n_0) during the transition to detachment. (a) The target particle flux (Γ_s) rolls over, deviating from the attached linear trend. This behavior is driven by (b) the collapse of target temperature ($T_{e,s} < 2$ eV), which triggers (d) massive volumetric recombination ($> 80\%$ particle loss) and (c) significant momentum loss ($\sim 90\%$) due to charge-exchange friction, effectively decoupling the target pressure.

limited regime, the code exhibited stable, attached plasma conditions with target particle fluxes scaling linearly with upstream density. Furthermore, by increasing the upstream density, we successfully reproduced the transition to the detached state. Key signatures of detachment, including the characteristic particle flux rollover and a precipitous drop in target electron temperature below 2 eV, were clearly observed. These results confirm that the interplay between impurity radiation, volumetric recombination, and momentum loss is correctly captured by the model.

Future work will focus on the full integration of the TASK/CSD module into the comprehensive TASK transport suite to provide self-consistent boundary conditions for core plasma simulations. We also plan to validate the model and incorporate it with the TASK/SOL module to fully integrate with the solver in the core region.

Acknowledgement

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国際化推進共同研究概要

25NU-15

タイトル: Active high power mm wave transmission line technology for advanced fusion devices

研究代表者: LECHTE Carsten

所内世話人: 出射 浩

研究概要: 大電力ミリ波によるプラズマの不安定性抑制に向けた高速スイッチシステム(FADIS)の開発を進めている。これまでに方形コルゲート導波管(SCW)スプリッターを用いたFADISの概念設計を進めてきた。2方向に分割されたビームの一方は出力1となり、もう一方は反射鏡を用いてSCW共振器に結合され、さらには2方向に分割されたビームの一方は出力2となり、もう一方は再びSCW共振器に結合される。動作周波数をわずかに変えることで出力1・2が切り替わる。2方向に分割されるビームはガウスビームとして扱えず、反射鏡後の反射ビームを適切に評価する必要がある。九州大学では反射ビームを扱うために拡張キルヒホッフコードを開発した。Stuttgart 大学では別途、物理光学コードを開発しており、ガウスビームを用いたベンチマークで、ほぼ完全な一致をみた。2方向に分割されたビームの反射では、若干の差があるものの、良好な一致を見た。

Report of international collaboration 25NU-15 between RIAM and IGVP in FY2025: High power mm wave transmission line technology for advanced fusion devices

Mr. Dr. Carsten Lechte

Introduction: A Fast Directional Switch (FADIS) for high-power millimeter waves that works at two different frequencies (110 and 138 GHz) has been in development at RIAM. It uses two beam splitters that are realized as square corrugated waveguides (SCW). Interference between the partial beams depends on small frequency changes (10 of MHz), leading to destructive interference either at output port A or B and corresponding beam output to the opposite port. The beam is coupled between the SCWs via phase inverting mirrors. Due to the working principle of the SCW beam splitters, the output beams are not pure Gaussian beams, and the angle they exit the splitters at deviates from the input angle.

The task for the collaboration is to develop tools and methods to optimize the coupling mirrors for the expected beams. Both RIAM and IGVP (University of Stuttgart) have their on wave propagation simulation codes developed at their respective institutes. The simpler and faster spectral method uses FFT for decomposition into plane waves. They can only propagate scalar waves between parallel planes. The more physically correct code uses the Kirchhoff integrals to propagate a beam between arbitrary surfaces in space.

RIAM's "extended KI" code: The Kirchhoff integral is formulated as an integral equation of the wave field—rather than a differential equation (wave equation)—by applying the Helmholtz equation and Green's second identity. It integrates the contributions to the observation point from spherical waves originating at each point on the aperture, which acts as a point source with its own complex amplitude. Furthermore, the aperture defining the boundary conditions is not restricted to a flat plane; any continuous (differentiable) surface is applicable. Therefore, when a beam is incident on a quasi-optical mirror, the reflected wave can be determined by treating the complex electric field distribution on the mirror surface as a curved aperture.

IGVP's "PROFUSION physical optics" or "PO" code: The code uses the general Kirchhoff integrals for the E and H field of the (vacuum) wave. It has provisions for propagating between any combination of planes and general triangular meshes. In this project, the beam source, target, and intermediate planes are simple planar objects, whereas the curved mirrors are meshes. A general Gaussian beam fit procedure is used on all the beam planes. A graphical presentation of the test case is shown in figure 1.

The phase reversing test case mirror is designed with the phase matching method: The input beam is propagated to the mirror plane by the fast FFT method. The desired output beam at the output plane is back-propagated to the mirror. The phases of both beams are subtracted to determine the phase shift Φ that is necessary for phase matching. The mirror elevation is $\lambda\Phi/(2\pi)$ with some scaling factors depending on the angle of incidence. This approach is a good approximation, assuming that the mirror "thickness" is negligible compared to all other dimensions in the beam path.

The PO and KI codes could be used to generate a higher order correction to the FFT result. Both beams are propagated onto the real mirror and the phase matching is performed again. This time, the residual phase mismatch is used to correct the existing mirror. This step can be iterated.

Benchmarking of the PO and KI codes on a test case with a phase reversing mirror with 45° incidence was performed. One measure of correctness is the beam at the output plane and how much it differs from the perfect Gaussian input beam. The PO code fits a Gaussian beam on the input and output fields.

The result from the PO code reproduces the input beam with 99.778 % purity. The losses to beam distortion (HOM) and cross polarization agree with theory. The result for the extended KI code do not consider cross polarization, but they do consider the HOM losses.

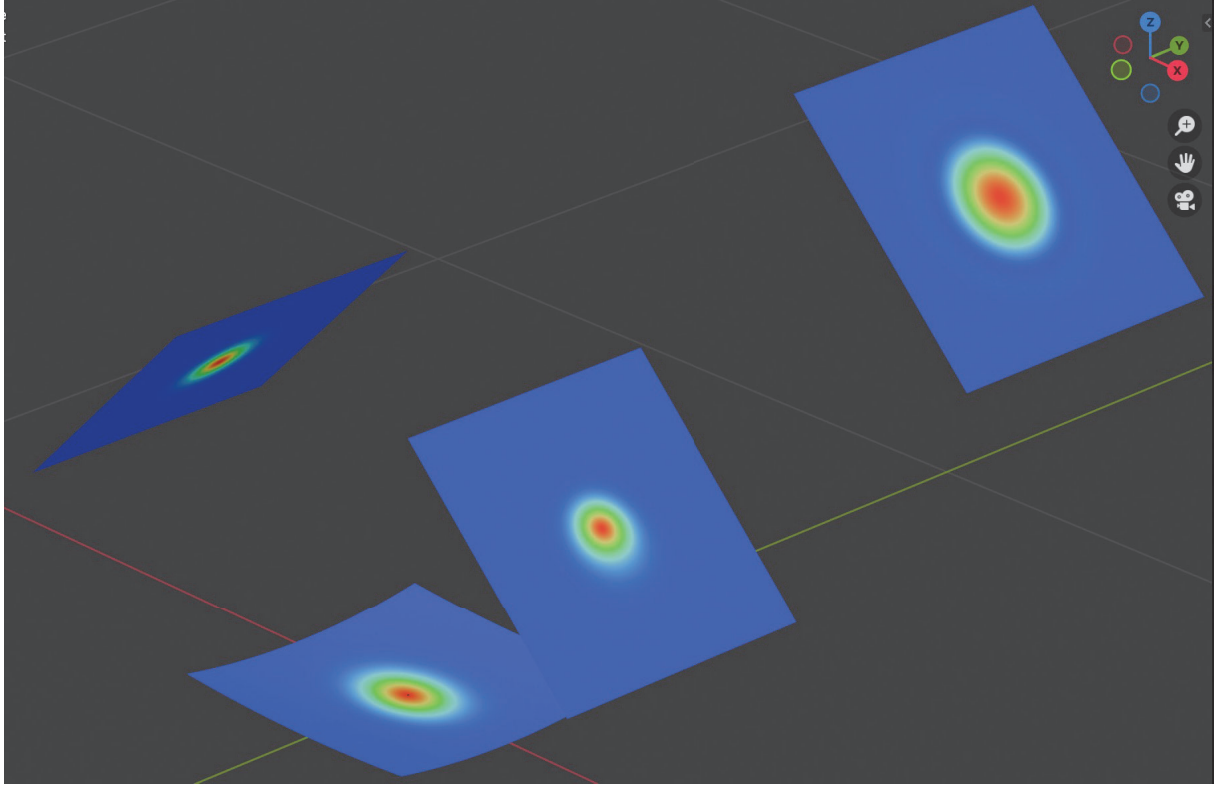


Figure 1: View of Gaussian beam cross sections of the test case, calculated with the PO code of IGVP Uni Stuttgart and visualized with Blender. The source plane is on the left, the phase reversing mirror is at the bottom. Two output planes shown are at distance 0.5 m, recovering the input beam, and at 1.41 m, showing the beam divergence.

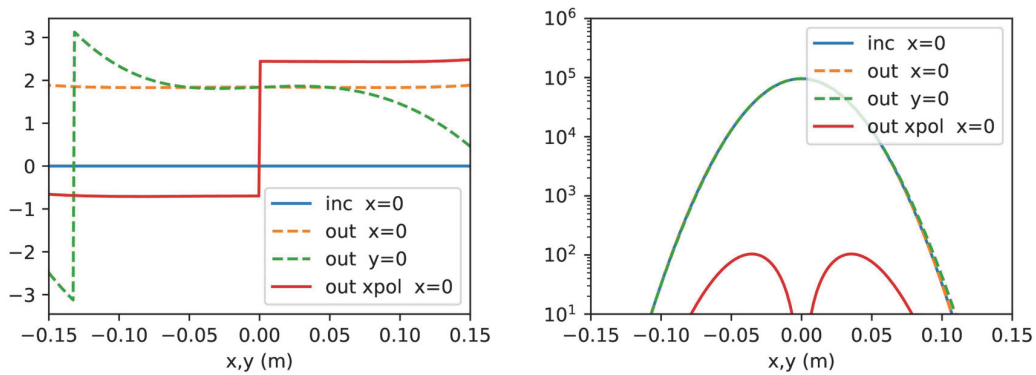


Figure 2: Plots of phase and power of the output beam compared to the input beam. The cross polarization is shown in red. The asymmetric deformation of the beam is evident at $x \approx 0.10$ m.

The FADIS coupling mirror: Finally, we consider the case of the coupling mirror between the two SCW beam splitters. The field pattern at the output aperture of the first SCW and the mirror shape are

provided by RIAM. The output beam is an 98+ % pure Gaussian beam. After the reflection, the beam is propagated to the input aperture of the second SCW. The PO and KI results show good agreement (see figure 3). While the phase matches perfectly between the two codes, there is a small difference in beam shape.

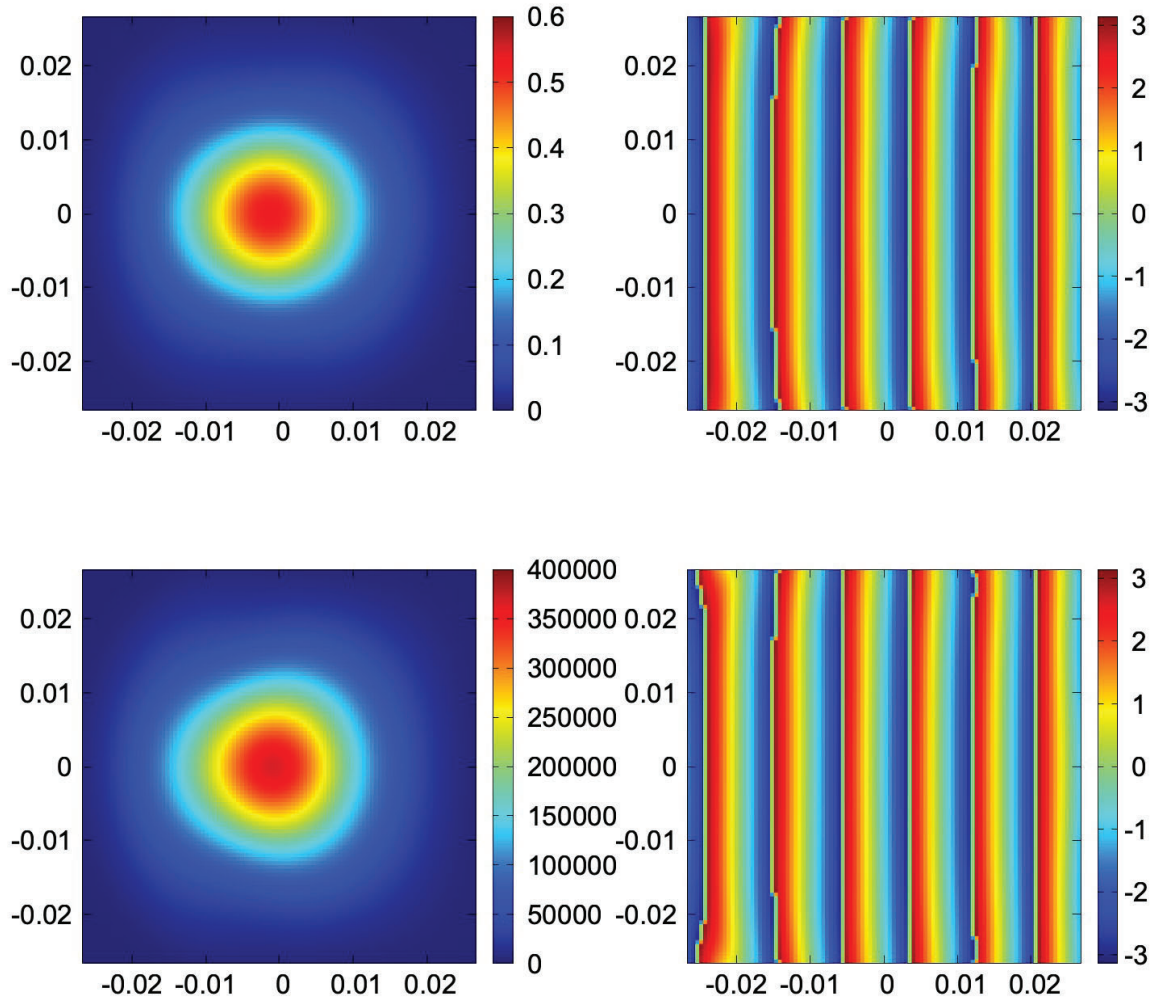


Figure 3: Output beam intensity and phase of the KI method (top) and the PO method (bottom).

Summary: We have used two codes from both institutes to tackle a mirror optimization problem that is relevant to sophisticated high power millimeter wave transmission lines. The codes show good agreement, and the performance of the component was shown to be suited to the application.

国際化推進共同研究概要

〔採択番号〕 25NU-16

タ イ ト ル: Investigating MHD-Scale Turbulence and Fluctuations using Magnetic Probes on PANTA

研究代表者: YUN Gunsu

所内世話人: MOON Chanhho

研究 概 要:

本研究は、PANTA線形プラズマ装置において高感度磁気プローブを用い、MHDスケールのプラズマ乱流および揺動特性を定量的に評価することを目的とした。磁気プローブとラングミュアプローブを併用して磁場揺動と密度揺動を同時測定し、プラズマコア領域において低周波揺動と非線形波動相互作用が強く現れることを明らかにした。これにより、磁気プローブを用いた乱流診断の有効性を実証し、磁場揺動の詳細解析に向けた基盤を確立した。

Investigating MHD-Scale Turbulence and Fluctuations using Magnetic Probes on PANTA

Affiliation: POSTECH
Applicant: Gunsu Yun

Abstract

This study aims to quantitatively investigate MHD-scale plasma turbulence and fluctuations using magnetic probes in the PANTA linear plasma device operated at the Research Institute for Applied Mechanics (RIAM), Kyushu University, Japan. A diagnostic system combining high-sensitivity magnetic probes and Langmuir probes was constructed to simultaneously measure magnetic and electrostatic fluctuations. Experimental results reveal strong nonlinear turbulence characteristics in the plasma core, identified through magnetic fluctuation spectra, phase differences, coherence, and bicoherence in specific frequency ranges. This work validates the effectiveness of magnetic-probe-based turbulence diagnostics and demonstrates its potential for extension to fusion and plasma application systems.

1. Purpose of the Research

Plasma turbulence and fluctuations play a crucial role in governing energy and particle transport and directly affect the performance and stability of fusion plasmas. In particular, MHD-scale magnetic fluctuations are closely related to plasma structure formation and mode interactions; however, precise experimental measurement and interpretation of these fluctuations remain challenging.

The purpose of this research is to quantitatively measure MHD-scale turbulence and fluctuations in the PANTA linear plasma device using high-sensitivity magnetic probes, and to analyze the correlation between magnetic and electrostatic fluctuations. Through this study, differences in turbulence characteristics between the plasma core and edge regions are identified, and the experimental validity of magnetic-probe-based diagnostics is demonstrated.

2. Experimental Method

2.1 Equipment and Environment

The experiments were conducted on the PANTA linear plasma device installed at RIAM, Kyushu University, Japan. PANTA generates low-energy plasma using a helicon source and provides a relatively simple magnetic field configuration, which is suitable for fundamental

studies of plasma turbulence and transport. An axial magnetic field of approximately 900 G was applied during the experiments.

PANTA experiment parameter

B-field strength : 900G
Amp. : Differential Amp. (Gain factor 10)
Spatial resolution: 0.5 cm (0~12cm)
Low pass filter : 100 kHz from ADC
Source : Helicon antenna (3kW, 7MHz)
ADC Resistance : 20 Ohm

Bias for ion density fluctuation : -33.75V
Bias for electron density fluctuation : 33.74V

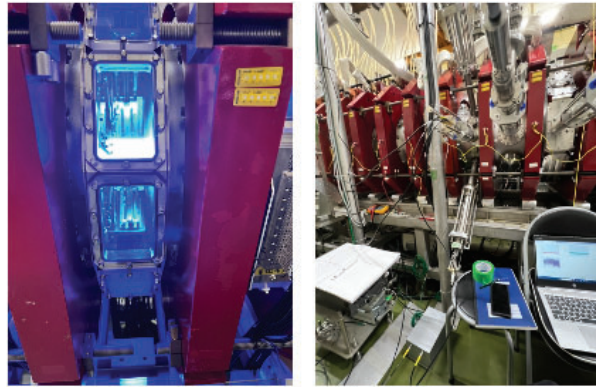


Fig.1 PANTA experiment parameter

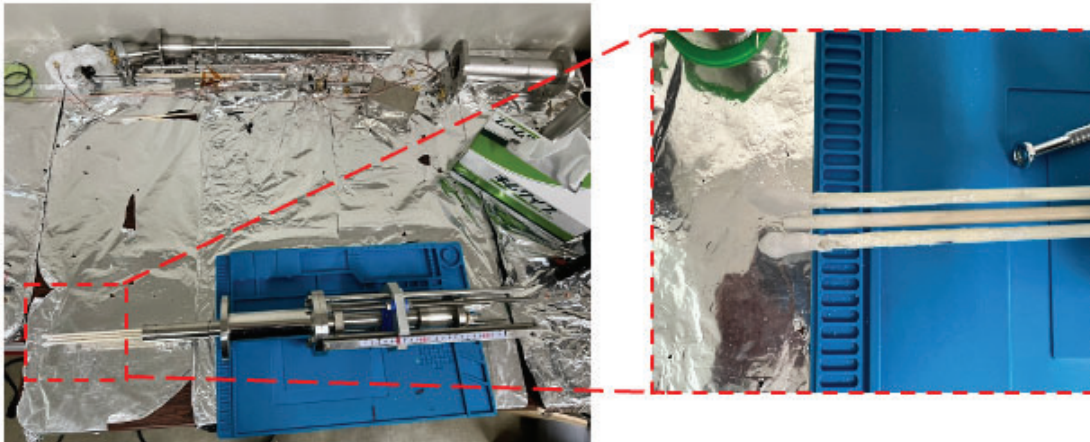


Fig.2 Magnetic probes and Langmuir probe array

2.2 Data Collection Methods

A diagnostic system consisting of high-sensitivity magnetic probes and a Langmuir probe array was employed. The magnetic probes utilize approximately 300-turn coils, providing significantly enhanced sensitivity compared to conventional magnetic probes. The probes were installed both parallel and perpendicular to the magnetic field lines, enabling simultaneous measurement of axial and azimuthal magnetic fluctuations.

The acquired signals were processed using differential amplifiers to suppress low-frequency noise and were recorded as time-domain data using a data acquisition system.

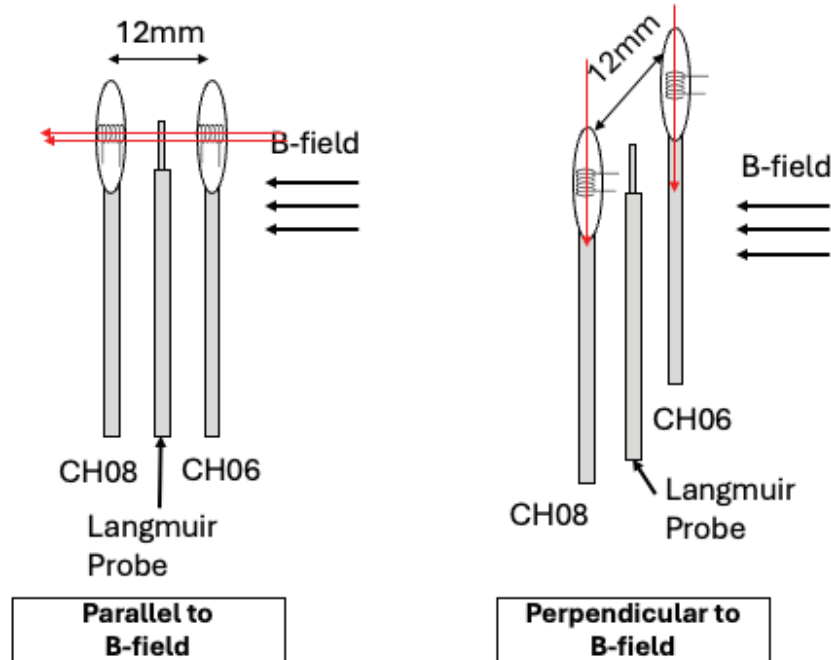


Fig.3 Experiment plan for different direction to B-field with Magnetic Probe

2.3 Analysis Techniques

The measured magnetic and electrostatic fluctuation signals were analyzed using the following techniques:

- Fast Fourier Transform (FFT) and Power Spectral Density (PSD) analysis
- Radial-profile analysis of fluctuation amplitude and spectral characteristics
- Phase difference and coherence analysis for spatial structure investigation
- Bicoherence analysis for quantitative evaluation of nonlinear interactions

3. Experimental Results

Electron temperature and electron density profiles were obtained using the Langmuir probe array. Current–voltage (I–V) characteristics were measured at different radial positions, and plasma parameters were extracted through fitting of the ion and electron saturation current regions. The results show systematic radial variations of both electron temperature and density, with higher values observed toward the plasma core and gradual decreases toward the edge region. These profiles indicate clear spatial inhomogeneity of the plasma and provide a reference for interpreting fluctuation characteristics.

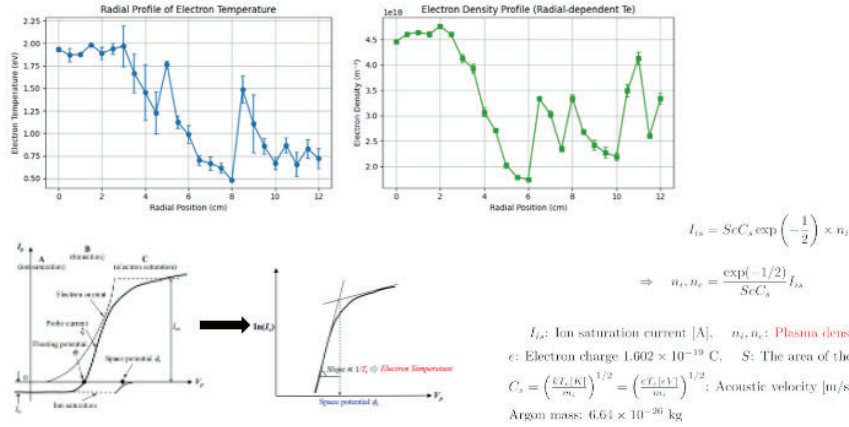


Fig.4 Radial profile of electron temperature and density from Langmuir Probe

Magnetic probe measurements were analyzed by evaluating the voltage signals as a function of radial position. For each position, the mean value and standard deviation (error bar) of the magnetic probe voltage were calculated. The mean voltage level represents the relative strength of the magnetic fluctuation signal, while the magnitude of the error bar reflects the level of temporal fluctuations.

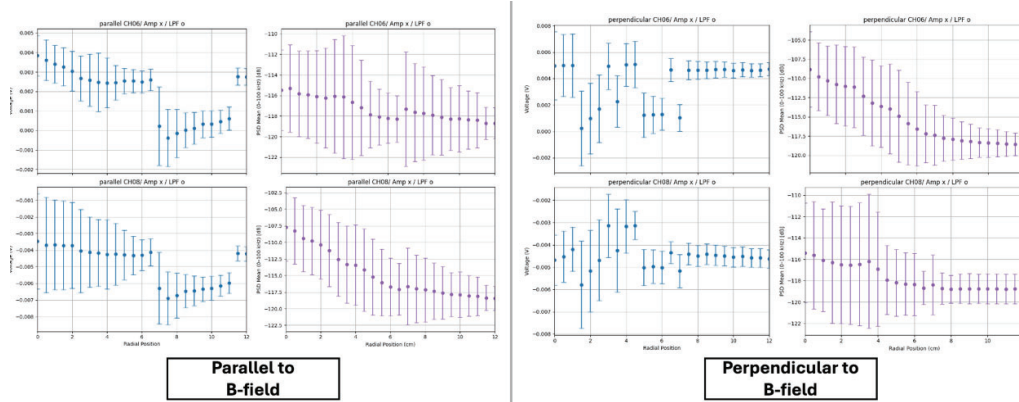
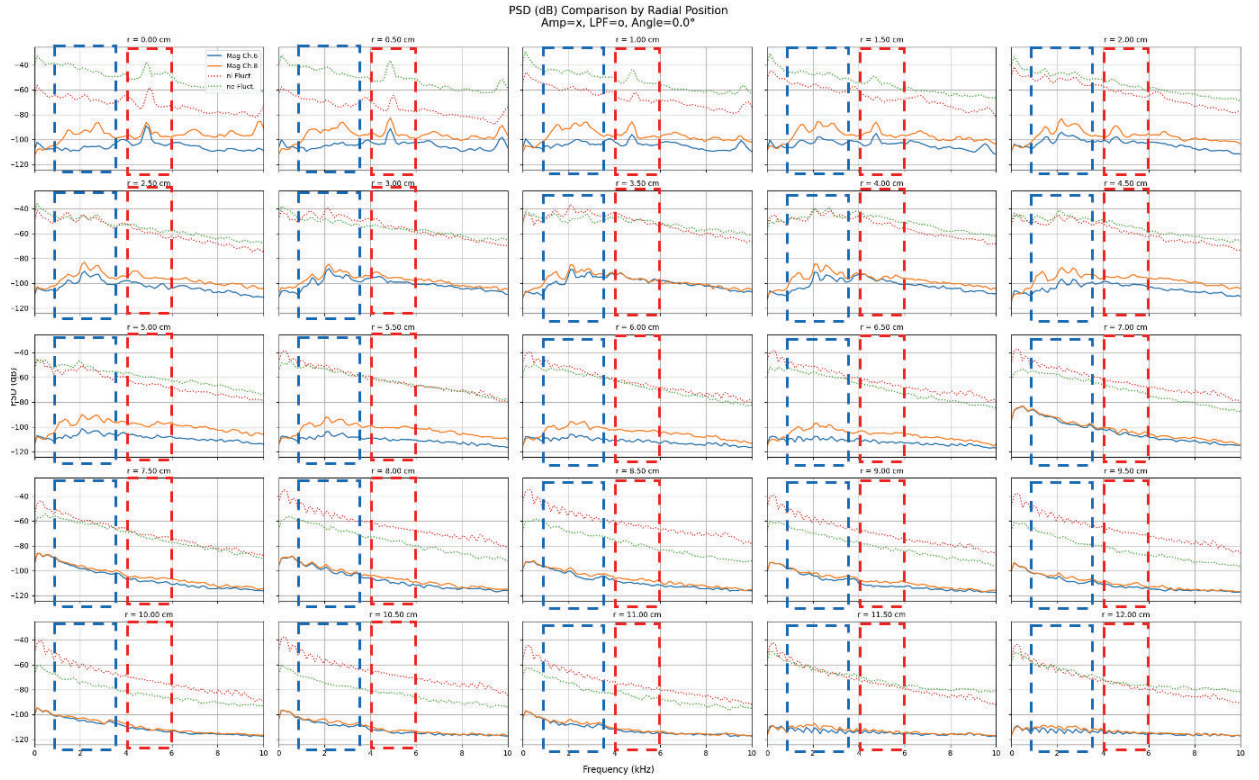


Fig.5 Radial value of magnetic probe's raw data and PSD mean + Std.

The analysis shows that regions with larger mean voltage values correspond to stronger magnetic fluctuation signals, whereas larger error bars indicate enhanced fluctuation activity and increased instability. In particular, the plasma core region exhibits both higher average signal levels and larger fluctuation amplitudes compared to the edge region, suggesting more intense and dynamically active turbulence near the core.

Power spectral density (PSD) analysis of the magnetic probe signals further reveals distinct spectral peaks in the kHz frequency range (approximately 2–5 kHz). These peaks are strongest in the plasma core and gradually weaken with increasing radial position. Moreover, major spectral peaks observed in ion and electron density fluctuations measured by the Langmuir probe are also detected in the magnetic fluctuation spectra, indicating a strong correlation between electrostatic and electromagnetic fluctuations.



Parallel to
B-field

Fig.6 Power Spectral Density of Langmuir probe and Magnetic probe

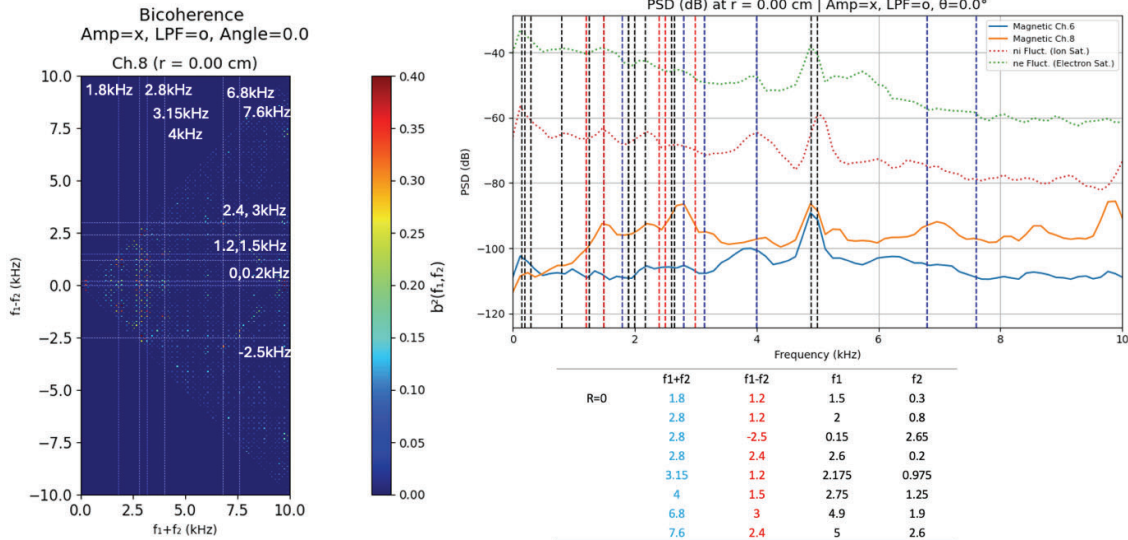


Fig.7 Bicoherence analysis from Magnetic probe data

4. Discussion

The combined analysis of Langmuir probe and magnetic probe measurements provides a consistent physical picture of MHD-scale turbulence in the PANTA plasma. Radial profiles of

electron temperature and electron density obtained from Langmuir probe I–V characteristics indicate that the plasma core is characterized by higher temperature and density, while both parameters decrease toward the edge region. These background profiles strongly influence the spatial structure and intensity of plasma fluctuations.

Magnetic probe voltage signals were analyzed using mean values and standard deviations as a function of radial position. The mean voltage level reflects the relative strength of magnetic fluctuation signals, whereas larger error bars represent increased temporal variability and enhanced fluctuation activity. The observation that both the average signal level and the fluctuation amplitude are larger in the plasma core suggests that the core region is more dynamically active and unstable compared to the edge region.

Power spectral density analysis further reveals that kHz-range magnetic fluctuations are most pronounced in the plasma core and weaken with increasing radial position. The simultaneous observation of common spectral peaks in both magnetic probe signals and Langmuir probe density fluctuations indicates strong coupling between electromagnetic and electrostatic fluctuations.

Bicoherence analysis provides clear evidence of nonlinear wave–wave interactions in the plasma. Frequency combinations exhibiting bicoherence values exceeding 0.3 coincide with dominant PSD peaks, confirming that these fluctuations arise from nonlinear processes rather than independent linear modes. The systematic decrease of bicoherence with radial position implies that nonlinear interactions are strongest in the core region, while edge fluctuations are more linear or noise-dominated.

Overall, these results demonstrate that high-sensitivity magnetic probes are an effective diagnostic tool for investigating MHD-scale turbulence and nonlinear dynamics in linear plasma devices. The ability to simultaneously resolve electromagnetic and electrostatic fluctuations provides a robust framework for studying plasma turbulence, with potential applicability to fusion devices and plasma-based energy systems.

5. List of Publications

Conference Presentations

- S. Hong et al., “RF diagnostics with In-vessel B-dot probe for measurement of low ion cyclotron harmonics emission on KSTAR,” 1st Asian School on Advanced Plasma Diagnostics for Magnetic Fusion Experiments, NIFS, Japan.
- S. Hong et al., “Sub-Alfvénic harmonic ICEs modulated by He beam injection in LHD,” IFPC 2025, Daejeon, Korea.

国際化推進共同研究概要

〔採択番号〕 25NU-17

タイトル: Theoretical understanding of nonlinear wave physics of PANTA
helicon plasma

研究代表者: CHOI Gyungjin

所内世話人: KOSUGA Yusuke

研究 概 要:

PANTAヘリコンプラズマにおけるドリフト波乱流と帯状流の相互作用を理論的に解析し、 $E \times B$ ステアケース構造との関連について研究を推進した。波動運動論に基づき安定性条件を導出し、構造維持には臨界 $E \times B$ シアが必要であり、その強度は流れの波数に依存することを示した。今後は中性粒子との相互作用を取り入れ、実験との整合性向上を目指す。

Theoretical understanding of nonlinear wave physics of PANTA helicon plasma

Gyungjin Choi

Department of Nuclear and Quantum Engineering, KAIST, Daejeon 34141, Republic of Korea

The PANTA device provides an ideal experimental platform for investigating fundamental nonlinear drift wave dynamics. Due to its excellent accessibility and controlled environment, PANTA allows for the rigorous validation of complex turbulence theories. This report presents an advanced nonlinear theoretical framework developed to understand the structural sustainability of E×B staircases in such linear magnetized plasma systems, which can be formed near marginality of drift wave turbulence onset. While these structures are known to regulate transport, their long-term stability against structural collapse—driven by the growth of bump-hole pairs—remains a critical area of study. This research aims to provide a robust theoretical foundation for PANTA experiments, with broader impacts on fundamental plasma physics.

The interaction between broadband drift wave turbulence and zonal flows in PANTA is modeled using a wave kinetic framework. This approach describes the evolution of wave packet populations under the influence of shear flows. The dispersion relation for zonal flows (Ω, q) , which governs the self-consistent feedback between the turbulence intensity and the flow, is expressed as:

$$1 + \frac{\gamma_{\text{mod}}^2}{\Omega^2} \left(1 - \frac{q\bar{v}_{gx}}{\Omega} - \frac{\Delta_{\text{mm}}^2 - (q\bar{v}_{gx})^2}{\Omega^2} \right)^{-1} + \text{Res} \int d^2\mathbf{k} \frac{qk_y^2}{2} \frac{qv_{gx}}{\Omega - qv_{gx}} \frac{\partial N_0}{\partial k_x} = 0.$$

This equation captures the underlying physics of how modulated wave action density N supports the maintenance of the staircase structure.

The sustainability of the staircase is determined by its resistance to the growth of phase-space structures. We identify a structural stability criterion based on the spectral width of the turbulence Δk_y . To prevent the collapse of the staircase, the E×B shearing rate must exceed a critical threshold $(\omega_{\text{E×B}}^{\text{crit}})$, which scales with the flow wavenumber q :

$$\omega_{\text{E×B}}^{\text{crit}} = c(w)\bar{k}_x |n'_0| \Delta_{\text{mm}}^2(q) \propto q^2.$$

This suggests that maintaining finer-scale staircase structures requires a higher level of E×B shear, providing a predictive guideline for PANTA's experimental observations.

The current model focuses on the nonlinear interactions within the plasma species. However, in linear devices like PANTA, the interaction between ionized plasma and background neutral particles can significantly influence turbulence damping and flow formation. As a future work, we plan to extend this theoretical framework to include the effects of neutral particles. This extension will allow for a more comprehensive understanding of how neutral-plasma coupling modifies the structural stability of E×B staircases, further bridging the gap between theory and experimental reality in PANTA.

国際化推進共同研究概要

〔採択番号〕 25NU-18

タイトル: Multi-line-of-sight tomography measurement with evaluation of reflected light

研究代表者: MUNECHIKA Koyo

所内世話人: FUJISAWA Akihide

研究概要: 宗近さん（現在ITER機構に所属）はトモグラフィーの再構成トモグラフィーの専門家である。特に可視光の反射を取り入れた再構成アルゴリズムを開発し、その有用性を東京科学大学（旧東京工業大学）飯尾研究室所有のPHIXトカマクにおいて実証してみせた。現在、応用力学研究所核融合力学部門所有のPLATOトカマクでは多波長トモグラフィー（ $H\alpha$ 、UV、軟X線）には現在 $H\alpha$ 、UV部分が設置され、現在 $H\alpha$ のトモグラフィーが稼働している。今回の国際化推進研究においては可視光である $H\alpha$ 光のトモグラフィーの再構成アルゴリズムについてPLATOの設計図および真空容器の材質などを含めてその反射の取り扱いについて議論を行った。今後 $H\alpha$ 光の局所発光を推定するためのアルゴリズムの開発によって有意義な知見が得られた。

Multi-line-of-sight tomography measurement with evaluation of reflected light

Koyo MUNECHIKA, ITER Organization

Purpose

To ensure reliable and safe operation of fusion devices, it is essential to understand the instabilities and anomalous transport occurring within the plasma and develop control strategies to mitigate them.

Photodetection is a critical technique for measuring detailed plasma properties as it offers high-speed, non-invasive measurements. By employing multiple lines of sight and tomography techniques, we can reconstruct the spatial distribution of plasma emission. However, visible light measurements are compromised by reflections from device walls, which reduce measurement accuracy. To address this challenge, we employ ray-tracing simulations to develop accurate optical models that account for the device geometry and material properties. This approach enables us to suppress reflected light and achieve precise reconstruction of the actual plasma emission distribution.

In this study, simultaneous optical measurements with multiple lines of sight will be performed using the PANTA and PLATO at the RIAM, Kyushu University. In particular, the PLATO system has high spatial resolution fiber measurement and provides an ideal environment for improving measurement accuracy through reflected light correction. The results of this study will enable detailed analysis of instabilities and transport phenomena in fusion plasmas and provide important knowledge for the realization of fusion power generation.

Method

For the evaluation of reflectance characteristics, we develop a new device-specific library based on the Python open-source ray-tracing library raysect and its extension cherab. Measurement simulations of actual light sources are performed using material properties such as refractive index derived from information about the device wall materials. The reflective characteristics of the actual device walls are also measured through experiments using point light sources to evaluate differences between the experimental results and numerical models.

For the tomography analysis, geometric matrices representing the relationship between detectors and spatial mesh voxels are constructed with and without accounting for reflections. The reconstruction method is compared with other reconstruction methods to establish an accurate and reliable method that considers the effects of reflections.

Discussion

The development of a machine-dependent PLATO cherab library has been successfully completed, enabling synthetic diagnostics measurements based on 2-D phantom radiation distribution. The contribution of reflections has been accounted for through material properties and CAD information of device wall surfaces.

For tomography analysis, inversion methods employing MLEM (Maximum Likelihood Expectation Maximization) and MFR (Minimum Fisher Reconstruction) were used to reconstruct simulation data. Additionally, GPT (Gaussian Process Tomography) was tested to compare the effectiveness of each reconstruction method.

Future work will focus on applying the developed reconstruction methods to experimental data and validating their effectiveness in improving diagnostic accuracy.

国際化推進共同研究概要

〔採択番号〕 25NU-19

タ イ ト ル: Multiscale flux rope experiment: Developing and commissioning flux rope discharge system

研究代表者: PARK, JongYoon

所内世話人: MOON Chanhoo

研究 概 要:

本研究は、PANTA装置において多重スケール磁気フラックスロープ実験を実現するため、アークプラズマガンを用いた放電システムの設計・開発を行った。単一電源構成を採用し、スパーク回路およびパルス形成回路を含む高出力電源系を設計することで、安定したフラックスロープ生成条件を確立した。本システムの構築により、多重スケールの乱流揺動を詳細に研究できる実験基盤を整備した。

JongYoon Park (Seoul National University, Seoul, South Korea)

Figure 2 Selected Capacitor: 1.8 mF, 1.3 kV

The system utilizes 14 units of 1.8 mF, 1.3 kV capacitors currently in stock at RIAM. The design ensures that the pulse width and current levels are optimized for the PANTA environment.

2. Sparker Circuit

To overcome the limited charging voltage of the main PFN and effectively initiate the arc, a separate sparker circuit was designed based on transformer principles. This circuit applies a momentary high-voltage pulse between the anode and cathode to trigger the breakdown. Once the discharge is initiated, the main PFN naturally "takes over" to maintain the arc. This circuit employs six capacitors (configured in series-parallel to allow up to 2.6 kV and 2.7 mF), providing sufficient time for the takeover process. A ferrite core will be used to enhance induction, and following precedents in similar devices, a simplified design without a hysteresis reset circuit was adopted.

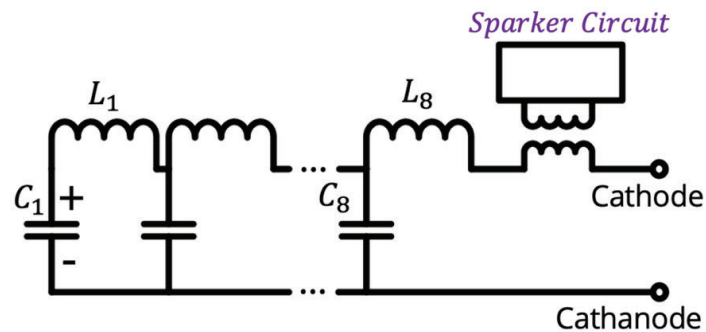


Figure 3 Circuit diagram of the single power configuration including the sparker circuit and PFN

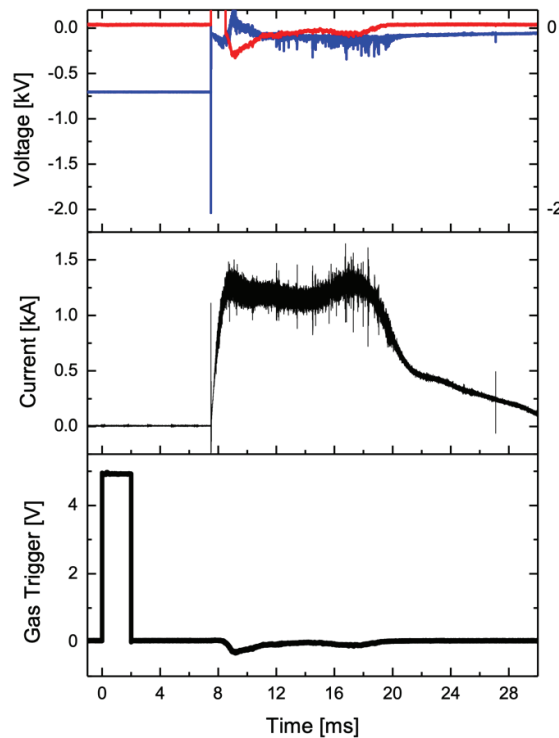


Figure 4 Example of discharge for the single power configuration including the sparker circuit and PFN

3. Pulse Forming Network (PFN) for Single Power Configuration

An 8-stage PFN was designed using the available capacitor bank to achieve a pulse width of under a matching condition. The critical component of this PFN is the inductor, which must withstand loads—specs that are unavailable in commercial products. Consequently, a lab-made air-core inductor was designed with a 15 cm diameter and dual 10 m parallel windings. Based on prior fabrication experience achieving approximately , this inductor will facilitate the customized single power configuration for PANTA. SPICE simulations confirm the expected discharge characteristics under the matching condition.

Table 1 Specifications of the Custom-Designed PFN for PANTA

Parameters	Value	
C_N (~1.3 kV)	1.8	mF
L_N	62	μH
N	8	
τ_p	5.34	ms
Spark Voltage	~ 2	kV

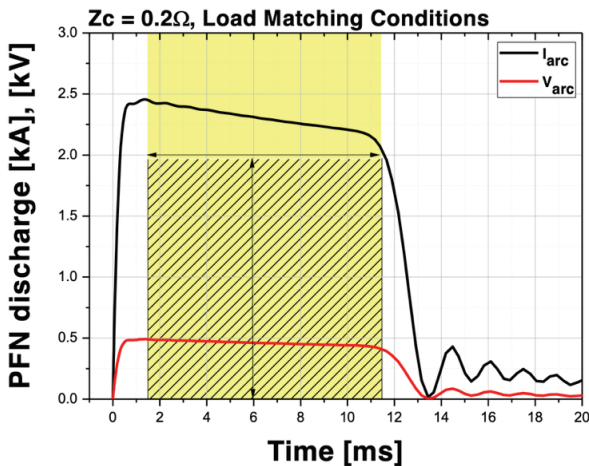


Figure 5 Expected discharge results of the designed PFN (SPICE simulation results)

Discussion

While the current Single Power Configuration was designed within time and budget constraints, it remains forward-compatible for expansion into a Dual Power System. Operating the single-source setup will provide empirical data to refine the requirements for the second stage. Based on preliminary calculations—specifically targeting a 100 V voltage droop for a 5 ms, 1 kA pulse—the projected specification for an auxiliary source is approximately 50 mF at 1 kV, derived from the fundamental relation: $C = \frac{I\Delta t}{\Delta V}$

Future Work: Upcoming Project

The next phase of this research involves transitioning from conceptual design to hardware realization. The primary objectives are the manufacturing, installation, and commissioning of the flux rope discharge system within PANTA. Once operational, systematic experiments will be conducted to explore regimes ranging from quasi-ideal kink modes to strong turbulence. By leveraging PANTA's high-resolution diagnostics, this project aims to provide the first three-dimensional and four-dimensional benchmarks of flux rope dynamics, establishing a unique facility for quantitative multiscale plasma research.

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国際化推進共同研究概要

25RE-1

タイトル : Investigations on Land-Fixed Oscillating Water Column Wave Energy Converter Based on HAMS Model and OpenFOAM Model

研究代表者 : GAO, JUNLIANG

所内世話人 : 劉 盈溢

研究概要 : 沿岸部における波浪エネルギーの開発・利用が注目されている。中でも固定式沖合波浪エネルギー変換器 (WEC) は、効率性と構造の簡潔さから最も実用的とされる。しかし、沿岸海域は波浪条件が複雑で、強非線形波が生じやすい。WEC が最大効率に達する共振時には流体粘性が重要となるが、先行研究では線形波および非粘性流体のみが対象であった。本研究では、強非線形波を含む多様な条件下で数値実験を行い、エネルギー変換効率と波浪荷重をシミュレーションする。これにより、粘性と非線形性が顕著な場合における予測精度の向上を目指す。

雑誌論文 :

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- [4] Zhou, Q., Gong, S.K., Mi, C.L. & Gao, J.L. (2024). Numerical study on the influence of terrain on the energy capture efficiency of oscillating water column wave energy converters. *Proceedings of the 21st China Ocean (Coastal) Engineering Symposium*. Qingdao, China. Oct. 18-21, 2024. (In Chinese)

Introduction

Marine energy boasts numerous advantages, including its eco-friendliness, abundant reserves, and a long effective development window, presenting immense utilization potential. Among various marine energies, wave energy, as a renewable source characterized by high energy quality, wide energy flow density, and a large usable area, has garnered significant attention. Consequently, the effective development and utilization of wave energy are crucial for the further advancement of China's offshore economy. In recent years, various types of wave energy converters have emerged. Among them, the Oscillating Water Column (OWC) wave energy converter has gained widespread application in the field of wave energy generation due to its high reliability and simple structure.

Regarding the OWC (Oscillating Water Column) wave energy conversion device, scholars both domestically and internationally have conducted numerous physical model experiments and numerical simulation studies. In terms of physical experiments, Ashlin et al. (2016) investigated the hydrodynamic characteristics of OWC devices with different bottom structures under various irregular wave actions, finding that a circular arc-shaped bottom structure significantly enhances wave energy conversion efficiency. Ning et al. (2016) studied the impact of different structural parameters on the wave energy conversion performance of OWC devices, revealing that the wave energy conversion efficiency of the OWC device is highest when the porosity is 0.66%. In terms of numerical simulations, Zhang et al. (2012) found that increasing the aperture of the OWC device significantly reduces the pressure in the air chamber. Bouali and Larbi (2017) explored the influence of incident wave parameters and the geometric shape of the OWC device on wave energy conversion efficiency using CFX software.

In previous physical model experiments and numerical studies on OWC devices, the focus was typically on exploring the structural parameters of the devices themselves, with a lack of research on the impact of different external topographies on the energy capture efficiency of the OWC device's air chamber. On the other hand, in actual coastal and offshore waters, the seabed topography is often not flat, but rather filled with various complex terrains such as slopes and submerged breakwaters. Based on these two reasons, this paper adopts a numerical simulation method based on STAR-CCM+, considering an isosceles trapezoidal submerged breakwater seabed topography, and studies the impact of the height of the terrain and the distance between the terrain and the OWC device on the energy capture efficiency of the air chamber from the perspective of wave energy conversion efficiency.

Methodology

Governing equations

The governing equations used in this numerical model are the continuity equation and the Navier-Stokes equation, which are respectively:

$$\nabla \cdot \mathbf{v} = 0 \quad (1)$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = \mathbf{g} - \frac{1}{\rho} \nabla P + \frac{\mu}{\rho} \nabla^2 \mathbf{v} \quad (2)$$

In the equations, $\mathbf{v}$ represents the velocity vector, ρ denotes the density of the fluid, t stands for time, $\mathbf{g}$ is the

acceleration of gravity, μ signifies the dynamic viscosity coefficient, and P is the dynamic pressure.

The energy capture efficiency within the air chamber of the OWC wave energy conversion device is measured by the wave-to-kinetic energy conversion efficiency η_e , expressed as:

$$\eta_e = E_0 / E, \quad (3)$$

where E_0 represents the kinetic energy of air within one wave period at the air outlet, and E denotes the total wave energy within one wavelength range.

In the gas chamber, gas-liquid interaction occurs, converting wave energy into kinetic energy of the air. The kinetic energy E_0 of the air within one wave period at the gas outlet is given by

$$E_0 = \frac{1}{2} \rho_k D T V^3. \quad (4)$$

In the equation, ρ_k represents the gas density, V denotes the gas velocity, D signifies the width of the gas chamber outlet, and T stands for the incident wave period.

The total wave energy E within a wavelength range is given by:

$$E = E_k + E_p, \quad (5)$$

where the wave kinetic energy E_k and wave potential energy E_p per unit width of the wave crest line length are respectively: :

$$E_k = \int_0^L \int_{-h}^0 \frac{\rho}{2} (u^2 + w^2) dx dz = \frac{1}{4} \rho g A_i^2 L \quad (6)$$

$$E_p = \int_0^L \int_0^\eta \rho g z dx dz = \int_0^L \frac{\rho g}{2} \eta^2 dx = \frac{1}{4} \rho g A_i^2 L \quad (7)$$

In the formulas, u represents the horizontal velocity component, w represents the vertical velocity component, h represents the water depth, L represents the wavelength, and ρ represents the liquid density. The free surface height is denoted as $A_i = H_i/2$, where A_i is the amplitude of the incident wave and H_i is the incident wave height.

Numerical wave flume

This article employs STAR-CCM+ software to establish a two-dimensional viscous flow numerical wave tank. As shown in Fig. 1a, the wave tank has a length of 6 times the wavelength, a height of 1.60 m, and a width of 0.01 m in the y direction, corresponding to the width of one computational cell. The still water depth h is 0.80 m. Relaxation zones with a length of 1.5 times the wavelength are set up at both ends of the tank to absorb transmitted and reflected waves. The OWC device is arranged in the middle of the tank. VS in the figure represents a velocity measurement point located at the midpoint of the air chamber outlet, and PS represents a pressure measurement point located on the top surface of the air chamber, 0.02 m away from the inner wall of the rear wall. The wave gauge G_1 is also arranged at the midpoint of the air chamber to record the wave surface elevation inside the chamber.

The structural parameters of the OWC device and the submerged breakwater topography (SBT) are shown in Fig. 1b. The width of the OWC device's air chamber B is 0.34 m, the thickness of the front wall of the air chamber C is 0.02 m, the width of the air hole inside the air chamber D is 0.009 m, the draft depth of

the air chamber d is 0.20 m, and the height of the air chamber h_c is 0.15 m. The actual SBT is simplified to an isosceles trapezoid with an upper base length a , a lower base length b , a base angle θ , and a slope $i = 2h_1/(b-a)$. The horizontal distance between the OWC device and the SBT is Δx . The incident waves in this article are regular waves with an amplitude A_i of 0.02 m, a period T ranging from 1.00 to 2.05 s, and an incident wavelength L ranging from 1.60 to 5.00 m. The incident wave period is normalized using the following formula:

$$f^* = \frac{1}{T} \cdot \frac{h}{\sqrt{gB}}, \quad (8)$$

resulting in a normalized wave frequency f^* ranging from 0.21 to 0.44.

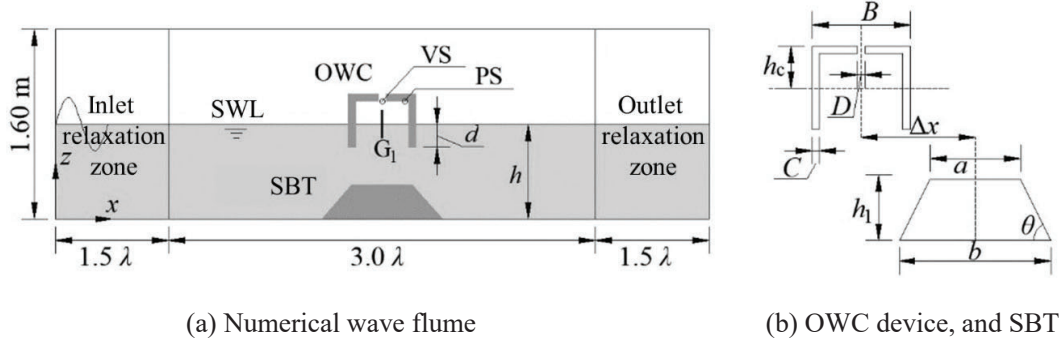


Fig. 1 Schematic diagram of numerical wave flume, OWC device, and SBT

This paper maintains the structural parameters of the OWC device unchanged, only altering the structural parameters of the SBT and the horizontal distance between them, and designs multiple operating conditions (see Table 1). Operating conditions 1, 2, and 3 maintain the slope and horizontal distance of the SBT unchanged to study the impact of changes in topography height; operating conditions 3, 4, 5, and 6 maintain the slope and height of the SBT unchanged to study the impact of changes in its relative position to the OWC device. Operating condition 0 (i.e., without SBT) is set as the control group to study the impact of having or not having a SBT on the OWC device.

Table 1 Parameters of different SBTs

Case	i	h_1 (m)	Δx (m)
0	0	0	0
1	1	0.2	0
2	1	0.3	0
3	1	0.4	0
4	1	0.4	0.5
5	1	0.4	1.0
6	1	0.4	1.5

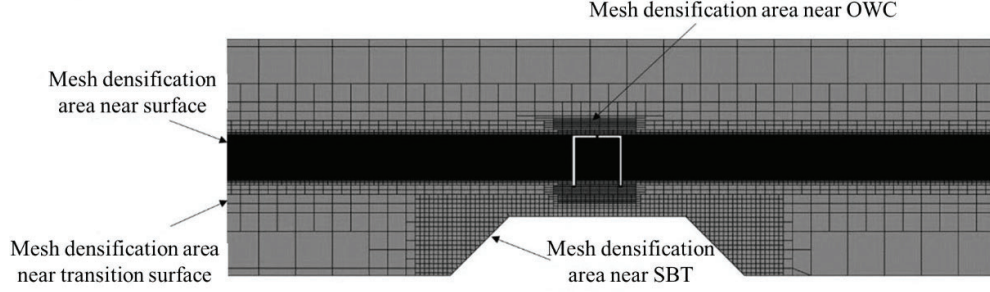


Fig. 2. Typical mesh configuration around the OWC device and the SBT

Results

Fig. 3 presents the varying trend of wave energy conversion efficiency η_e of the OWC device with incident wave frequency f^* under different SBT heights when $\Delta x = 0$ and $i = 1$. Two distinct phenomena can be observed. Firstly, under different topography heights, the energy conversion efficiency of the OWC device first increases and then decreases with f^* , reaching a maximum at $f^* = 0.36$. In the conditions considered in this section, the wave energy conversion efficiency of the OWC device is the highest without topography, reaching 0.362. Secondly, in the low-frequency range ($f^* \leq 0.32$), the higher the topography height, the higher the energy conversion efficiency, which is higher than that without topography; in the high-frequency range ($f^* > 0.32$), the lower the topography height, the higher the energy conversion efficiency, but it is lower than that without topography. This is because the presence of topography leads to the wave shallow water effect, i.e., the wave height increases when the water depth becomes shallower, which is beneficial for the OWC device to extract wave energy. Additionally, the presence of topography also results in the reflection of some energy, which is detrimental to the OWC device extracting wave energy. In the low-frequency range, the wavelength is longer, and for long waves, the reflection of wave energy by topography is limited, with the increase in wave height due to the shallow water effect playing a dominant role. Therefore, the energy conversion efficiency of the OWC device increases within this frequency range. In the high-frequency range, the presence of topography leads to a larger loss of reflected wave energy, while the increase in wave height due to the shallow water effect is limited, resulting in a decrease in energy conversion efficiency.

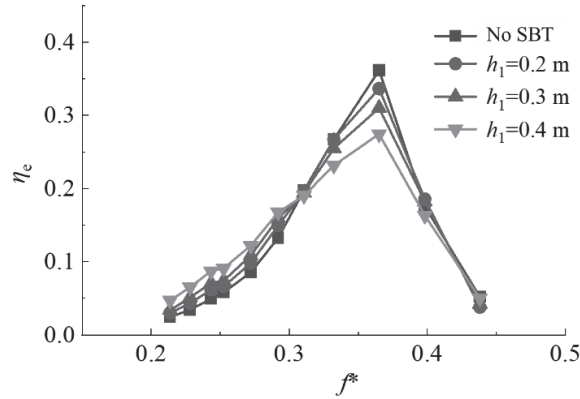


Fig. 3. Energy conversion efficiency under different SBT heights when $\Delta x = 0$ and $i = 1$.

Fig. 4 presents the trend of energy conversion efficiency η_e of the OWC device's air chamber as a function of incident wave frequency f^* under different relative positions between the SBT and the OWC device when $h_1 = 0.4$ m and $i = 1$. Two phenomena can be observed from the figure. Firstly, under different relative position conditions, the energy conversion efficiency of the OWC device first increases and then decreases with f^* , and reaches a maximum at $f^* = 0.36$. When the horizontal distance Δx between the SBT and the OWC device is 1.5 m, the maximum energy conversion efficiency of the OWC device can reach 0.364, which is basically consistent with the maximum energy conversion efficiency of the OWC device without topography, which is 0.362. When $\Delta x = 0, 0.5$ m, and 1.0 m, the maximum energy conversion efficiency of the device is generally lower than that without topography. Secondly, in the low-frequency band ($f^* \leq 0.26$), the smaller Δx , the higher the energy conversion efficiency, and it is higher than that without topography. However, in the high-frequency band ($f^* > 0.35$), the larger Δx , the higher the energy conversion efficiency, but it is lower than that without topography.

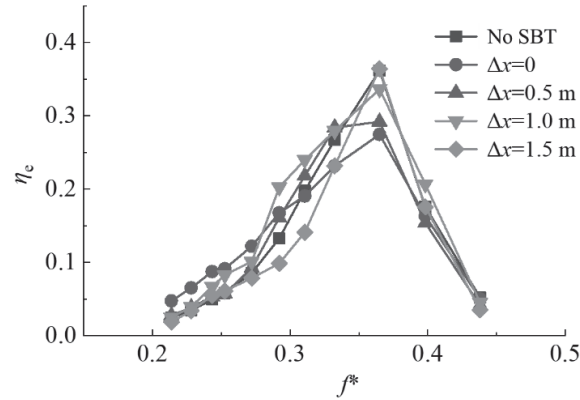


Fig. 4. Energy conversion efficiency under different relative positions between SBT and OWC device when $h_1 = 0.4$ m and $i = 1$.

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国際化推進共同研究概要

〔採択番号〕 25RE-2

タイトル: New Oxides/GaN Interfaces for Next-Generation Power Electronics
Technology

研究代表者: BOERO Mauro

所内世話人: KANGAWA Yoshihiro

研究概要:

本研究では、アモルファスナノ材料における量子トンネル効果と熱輸送を第一原理計算、強化サンプリング、機械学習によって調査した。多様なサイズと形状のSiNおよびGaN系を正確に記述・再現する計算プロトコルを開発した。熱特性および関連する伝導度は実験結果と顕著な一致をもって計算可能であることを確認した。機械学習（ML）および関連する原子間ポテンシャル（MLIP）のためのデータベースをSiN向けに生成・評価し、第一原理計算手法に匹敵する信頼性と精度を達成した。さらに、経路積分分子動力学法を用いて量子効果を扱えることが判明し、主に軽原子で発生する重要なトンネル効果を実証するとともに、システムに双安定性を付与することを明らかにした。

New Oxides/GaN Interfaces for Next-Generation Power Electronics Technology

BOERO Mauro

(University of Strasbourg-CNRS, ICUBE laboratory UMR7357, France)

In this research, it was investigated that amorphous nanomaterials in qubits and pcmems: quantum tunneling and thermal transport by first-principles, enhanced sampling, and machine learning.

We report a computational protocol that accurately describes and reproduces SiN and GaN systems of a wide variety of sizes and shapes. The thermal properties and related conductivities can be computed with remarkable agreement with experimental results. A database for machine learning (ML) and related interatomic potential (MLIP) has been generated and assessed for SiN, achieving reliability and accuracy comparable to first-principles approaches. Moreover, quantum effects can be treated using the path-integral molecular dynamics approach, which evidences important tunneling effects that occur mostly for light atoms and confer bistability to the system.

Paper list:

1. M. Boero, K. Shiraishi, T. Nagahasi, F. Nanataki, A. Oshiyama, Space-induced floating electronic states in non-stoichiometric amorphous silicon nitride for memory devices applications, *Phys. Rev. Materials*, 9, 084601, 2025.
DOI: 10.1103/mc16-76ck
2. Y. Kangawa, A. Kusaba, T. Kawamura, P.I Kempisty, K. Ishisone, M. Boero, Influence of intrinsic point defects incorporated from growth surface on atomic interdiffusion and unintentional compositional gradient in AlGa_N/AlN heterointerfaces, *Crystal Growth & Design*, 25, 740, 2025.
DOI: 10.1021/acs.cgd.4c01542

Conference presentation:

1. Mauro Boero, Amorphous nanomaterials in qubits and pcmems: quantum tunneling and thermal transport by first-principles, enhanced sampling and machine learning, ITI QMat – QuanTEdu Scientific Day, Strasbourg, France, 2025.06.06.

国際化推進共同研究概要

〔採択番号〕 25RE-3

タ イ ト ル : Buckling analysis and lightweight design for ultra-long composite blades of wind turbines

研究代表者 : Xiaoming Zhang

所内世話人 : 劉 盈溢

研究概要 : 洋上風力発電機の大型化とロータ径の増大に伴い、せん断ウェブコアによって支持される円筒曲面シェルで構成された超長尺ブレードのスパークャップにおいて、局所座屈が発生しやすくなっている。従来の解析では、コアを単純支持として理想化することが一般的であり、曲面シェルの端部における回転拘束が無視されているため、座屈安定性が過小評価され、過剰な材料使用を招いている。本研究では、フルサンディッチ構造の概念に基づき、無次元化されたコア・シェル厚さパラメータ(β)を導入した。ABAQUS を用いた線形摂動解析の結果、 β と曲率パラメータ(Z)が曲面シェルの座屈耐性を共同で制御しており、いずれかのパラメータの増加に伴い弾性局所座屈荷重が向上することが明らかになった。さらに、軽量ブレード設計のために甲虫の鞘翅の内部構造を応用したバイオミメティック(仿生)コアを開発し、新しい無次元パラメータ(η)を用いて曲面シェルへの回転拘束を定式化した。パラメータシミュレーションの結果、 η の増加に伴い曲面シェルの座屈荷重が向上し、従来の $\eta = 0$ のケースと比較して最大 85%の向上が確認された。これらの結果は、 β 、 Z 、および η に基づく超長尺風車ブレードの設計フレームワークを定義するものであり、洋上風力発電において構造的完全性を維持しつつ材料使用量を削減するための明確な戦略を提供するものである。

国際化推進共同研究報告書

25RE-3

タイトル: Buckling analysis and lightweight design for ultra-long composite blades of wind turbines

研究代表者: Xiaoming Zhang

所内世話人: 劉 盈溢

Introduction

As offshore wind energy expands and rotor diameters grow, the design of ultra-long wind turbine blades faces increasing challenges. The spar caps of blades, consisting of cylindrically curved shells supported by shear-web cores, are particularly susceptible to local buckling under wind loads [1,2]. Traditional design methods often treat the core as a simple support and ignore the rotational constraint it provides to the curved shell. This simplification can underestimate the actual buckling resistance and lead to overly conservative, heavier designs.

Previous studies have demonstrated that rotational constraints, induced by boundary conditions, significantly enhance the buckling strength of shells. For example, flat shells, which exhibit buckling behaviour similar to curved shells, can develop up to 2.5 times higher buckling strength when their edges are clamped rather than simply supported [3,4]. This underscores the importance of explicitly accounting for rotational constraints in buckling analysis. Izzuddin et al. [5] further showed that, considering the same core thickness, flat shells can experience a 50% increase in the buckling load. These observations indicate that the rotational constraints provided by the shear-web core is a key factor in buckling stability and should be explicitly included when evaluating the buckling resistance of curved shells with flexible core supports.

Accounting for the rotational constraint provided by flexible core supports can increase the predicted buckling strength; however, this tends to be a marginal refinement to standard design practice. Greater gains in buckling resistance can be achieved more effectively by optimizing the core structural layout. A biomimetic structure is introduced in this study, in which ultra-long wind turbine blades are equipped with a trabecular core inspired by beetle elytron. Existing studies suggest that trabecular cores can substantially improve the buckling resistance of shells. For instance, Chen et al. [6,7] reported up to a twofold increase in buckling load when trabecular cores replace conventional cores, owing to edge rotational constraints that approaches clamped boundary conditions. Combined experimental and finite-element evidence consistently show that trabecular cores markedly increase the buckling strength of shells, leading to higher load-carrying capacity than shells with conventional cores [8-10]. Therefore, integrating trabecular cores offers a promising approach to improve the structural performance of ultra-long wind turbine blades, enhancing both efficiency and stability under demanding operating conditions.

Accordingly, this study has two main objectives: (1) to quantify how flexible core support influences the local buckling behaviour of spar-cap curved shells; and (2) to introduce a biomimetic core into the sandwich design of blades and evaluate its effectiveness in enhancing buckling resistance, enabling a more efficient structural solution for ultra-long wind turbine blades.

Methodology

Blades with flexible core supports

In this study, a full sandwich-structure concept is adopted to evaluate the buckling behaviour of curved shells (Fig. 1), with the analysis expressed in terms of two dimensionless parameters: the core-to-shell thickness parameter (β), which captures the flexible core support, and the curvature parameter (Z), as given in Eq. (1) and Eq. (2), respectively.

$$Z = b^2/Rt_s \quad (1)$$

$$\beta = t_c/t_s \quad (2)$$

Here, b is the curved-shell width, R is the shell radius of curvature, t_s and t_c are the thicknesses of the curved shell and the core, respectively.

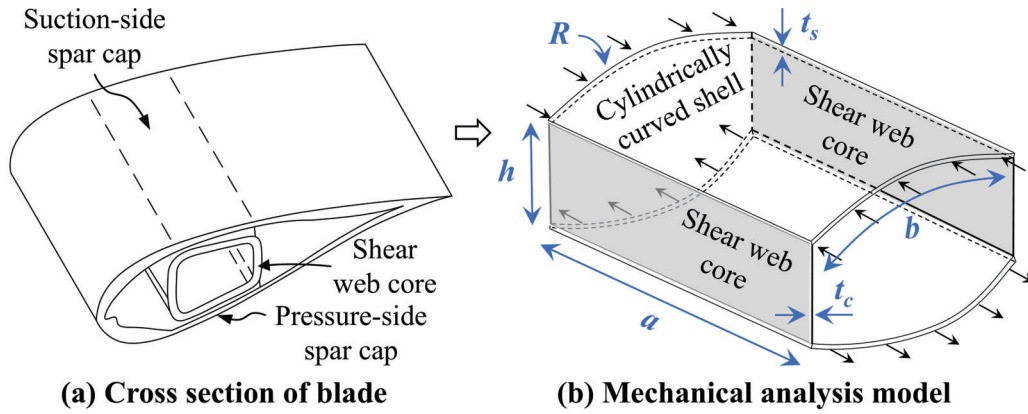


Fig. 1 Wind turbine blade structural configuration and its mechanical modelling [11]

Linear eigenvalue buckling analyses are carried out in ABAQUS over a parametric range of the curvature parameter (Z) and the core-to-shell thickness parameter (β). The buckling coefficient (k_c) is extracted from the eigenvalue of the first buckling mode and evaluated in normalized form, as defined in Eq. (3).

$$k_c = \frac{\text{eigenvalue}}{t_s \sigma_E} \quad (3)$$

Here, σ_E denotes the classic Euler critical stress [12,13], as defined in Eq. (4), and E and ν are the elastic modulus and Poisson's ratio of the composite material, respectively.

$$\sigma_E = \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t_s}{b} \right)^2 \quad (4)$$

As shown in Fig. 2(a), for a fixed Z , the buckling coefficient (k_c) increases with β , indicating that a thicker core relative to the curved shell provides stronger rotational constraint at the shell–core interface, which enhances the local buckling stability. This trend reflects a progressive transition in the effective boundary

condition from nearly simply supported (Sine-type mode shape) at low β to near clamped (Cosine-type mode shape) as β increases [8,11]. However, when $\beta \geq 2.0$, the rotational constraint approaches the clamped limit, and further increases in β yield only marginal gains in buckling strength.

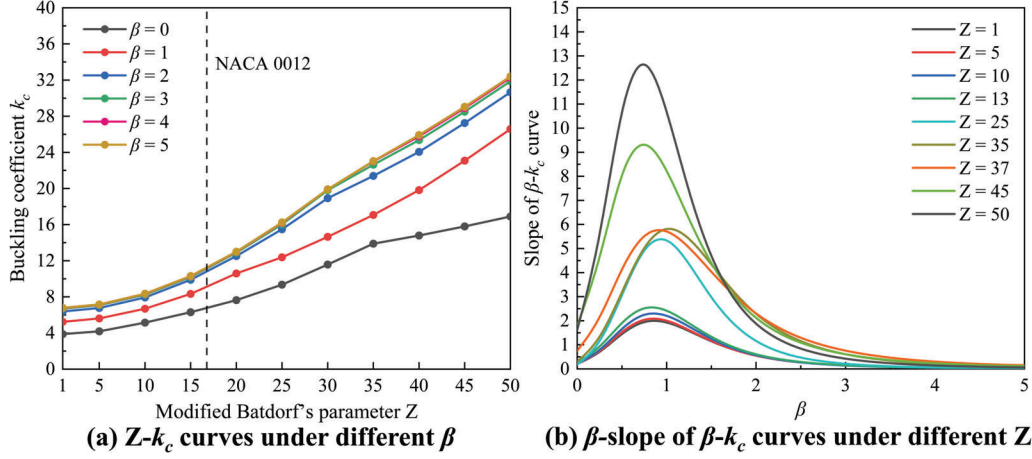


Fig. 2 Buckling coefficient k_c for curved shells with flexible core supports [11]

For each value of Z , there is an optimal β that yields the maximum increase in buckling loads. As shown in Fig. 2(b), the β that maximizes the buckling load gain is approximately 0.85 for $0 \leq Z \leq 13$, 1.10 for $13 < Z \leq 37$, and 0.75 for $Z > 37$, which shows that the sensitivity of buckling performance to flexible core support depends on shell curvature. In practice, selecting β above its efficient value increases core thickness without a commensurate improvement in buckling stability. By contrast, using the recommended β values achieves a better balance between buckling resistance and material usage, allowing a 19.56% reduction in total mass relative to the current design while still satisfying stability requirements [11].

Blades with biomimetic core supports

A beetle elytron-inspired trabecular core, comprising a lattice web with cylindrical trabeculae (Fig. 3), is proposed for lightweight blade design. The associated rotational constraint is quantified using a new dimensionless parameter (η), as given in Eq. (5).

$$\eta = r_t/l \quad (5)$$

Here, r_t is the trabecular radius and l is the unit-cell length.

Following Zhang et al. [8], the dimensionless parameter (η) is varied from 0 to 0.25, and is used as the design range in the present parametric study. The buckling coefficient (k_c) is obtained using the same eigenvalue buckling procedure used for the curved shells with flexible core support. The key difference in this part is that core thickness is not parameterized explicitly. Instead, the trabecular core is introduced into the numerical model as an equivalent boundary condition, allowing the added edge rotational constraint to be examined independently through η (Eq. (5)). The combined effect of the core-to-shell thickness parameter (β) and the trabecular core will be examined in future work.

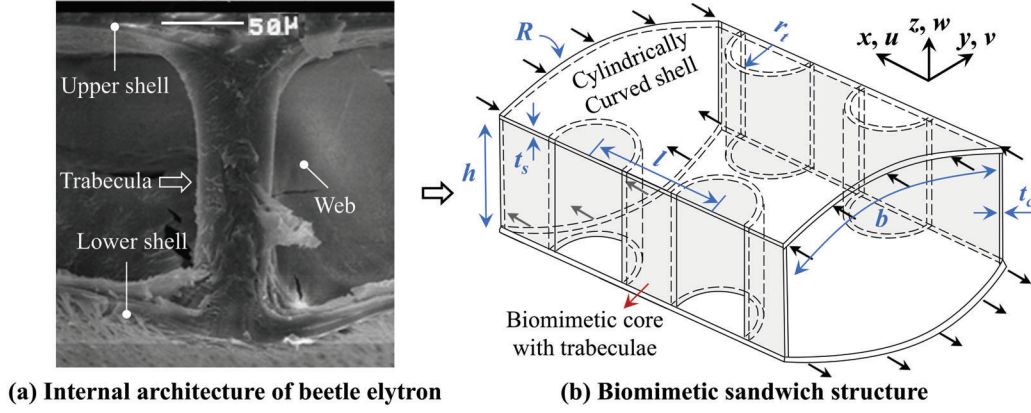


Fig. 3 Wind turbine blade bio-inspired by beetle elytron [14]

As shown in Fig. 4, for a given η , the buckling coefficient (k_c) increases with the curvature parameter (Z), following the same overall trend as the conventional-core baseline ($\eta = 0$). This suggests that η does not change the monotonic dependence of k_c on Z ; instead, it raises the buckling level relative to the baseline.

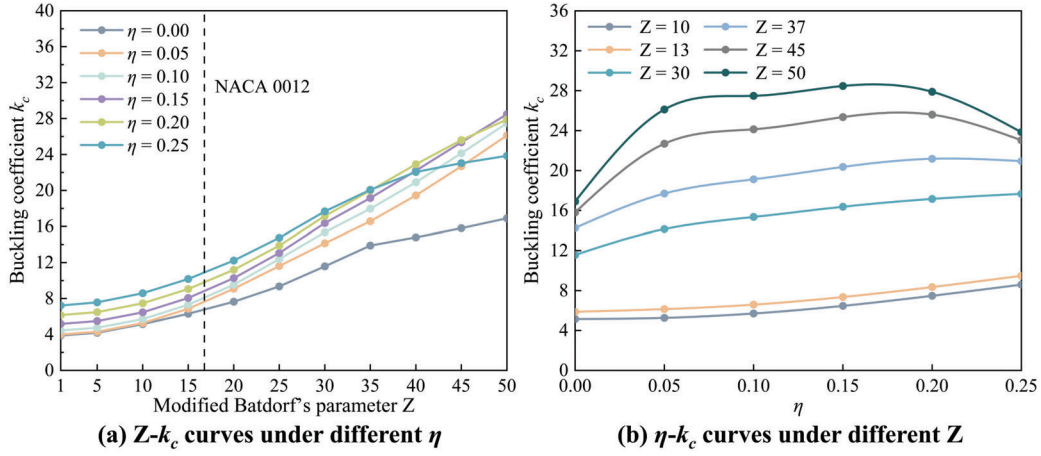


Fig. 4 Buckling coefficient k_c for curved shells with trabecular core supports

For a fixed Z , increasing η generally increases buckling strength, reflecting the added stability from greater rotational constraint. The improvement can be substantial, with a maximum gain of up to 85% relative to $\eta = 0$ (conventional design). However, at high curvature and large trabecular radius, the governing buckling pattern changes: when $Z > 35$ and $\eta > 0.20$, a circular buckling mode localized within the trabecular region becomes dominant, which can reduce the buckling load [8]. This mode transition indicates that instability is no longer governed by buckling of the curved shell between trabeculae. Instead, deformation localizes in the trabecular zone. As a result, further increases in η do not necessarily improve the overall buckling resistance and may activate a less favourable local mode.

Results

This study advances the lightweight design of ultra-long wind turbine blades by accounting for flexible core support and introducing a biomimetic trabecular core. The main conclusions are summarised as follows:

(1) With flexible core support, buckling resistance of curved shells increases with the core-to-shell thickness parameter (β), but it approaches a plateau as the edge rotational constraint nears a clamped condition.

Efficient β values are recommended for different Z ranges. Using these values improves the balance between buckling resistance and material usage, enabling a 19.56% reduction in total mass relative to the current design while meeting the buckling requirement.

(2) The biomimetic trabecular core increases buckling resistance as η increases, achieving up to 85% higher buckling load than the conventional design ($\eta = 0$). However, when $Z > 35$ and $\eta > 0.20$, the governing instability changes to a circular buckling mode localized in the trabecular region, which reduces the buckling load.

Overall, the proposed Z - β - η framework allows substantial material savings without compromising blade buckling resistance. However, these findings are based on linear eigenvalue buckling analyses. Future work should incorporate nonlinear buckling and post-buckling behaviour to capture the stability response of ultra-long wind turbine blades more realistically.

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国際化推進共同研究概要

〔採択番号〕 25RE-4

タ イ ト ル : Design of the pre-stressed concrete-filled steel tubular lattice wind turbine tower

研究代表者 : Yuhang Wang

所内世話人 : 劉 盈溢

研究概要 : 低風速かつ高シアーな陸上地域における風力資源の効率的な利用を促進し、風力発電所の開発・建設コストを削減するため、大容量かつ高ハブ化された風力タービン専用の革新的な「プレストレスト鋼管コンクリート(CFST)ラチス風車タワー」が開発された。本プロジェクトでは、ハブ高さ 160 メートル、単機出力 4MW を有する世界初の CFST ラチスタワーのプロトタイプが 2023 年初頭に完成した。本構造は主に、上部(円形鋼管タワー)、下部(プレストレスト CFST ラチス部)、および中間部(鋼・コンクリート合成遷移セクション)の 3 つの部分で構成されている。本報では、当該構造の特徴と設計の詳細を明らかにし、このような革新的構造の設計および適用におけるリファレンスを提供することを目的とする。

国際化推進共同研究報告書

25RE-4

タイトル: Design of the pre-stressed concrete-filled steel tubular lattice wind turbine tower

研究代表者: Yuhang Wang

所内世話人: 劉 盈溢

Introduction

Currently, onshore wind power is experiencing several trends, including an increase in individual turbine capacity, significant elevation of hub height, and continuous growth in blade length. The tower structure plays a critical role in ensuring the safe operation of wind turbines. This necessitates meeting higher demands in terms of performance, size limitations, and cost control of the tower structure. However, as the hub height of wind turbines surpasses 160 meters, traditional tower structures become impractical due to their large size, heavy weight, and high cost. Consequently, alternative solutions are sought to address these limitations and make the tower structure more suitable for such applications.

In 2018, a new type of wind turbine structure called pre-stressed concrete-filled steel tube (CFST) lattice wind turbine tower was proposed for large-capacity, high-hub height wind turbines. The four-year academic research was conducted to develop this innovative wind power structure. In 2021, the construction of the world's first prototype of pre-stressed CFST lattice tower with a hub height of 160 meters and a single unit capacity of 4MW was initiated. The project is led by CSIC HaiZhuang Wind power Co.,Ltd. and developed and designed by Chongqing University. The foundation construction began in October 2022, and the overall structure was completed in January 2023 (Fig. 1). The wind turbine was connected to the grid and put into operation in June 2023.



Fig. 1 Photo of the new tower and its surroundings

The design, manufacturing, and construction of this new structure presented challenging technical issues due to the absence of established design codes and sufficient practical experience for reference. Consequently, this paper aims to present the structural performance and key technical research associated with this innovative structure. Close collaboration between structural designers and university researchers was crucial in overcoming these challenges and achieving successful completion during the design and construction process.

Methodology

Structural selection

The lattice tower (Fig. 2) is designed to convert the overall bending mode of the tower structure into an axial force mode in the corner components. For the tower columns designed using hollow sections, the tube wall thickness would have had to be more than 25 mm to meet the requirements of both strength and stability. From a manufacturing perspective, a special machine for plate-bending would have been necessary to achieve sufficient accuracy. Moreover, special attention would have been needed to ensure the welding quality at joints. This increases the cost of the structure. In recent years, CFST concrete columns have been widely used in various structural applications such as building structures, bridges, transmission towers, and offshore structures due to their advantages of easy manufacturing, high load-bearing capacity, good economic benefits, and excellent ductility [1-6]. This has contributed to increased cost-effectiveness in structural design and construction.

The tensile strength of concrete is relatively low, and the steel tube in CFST structures primarily bears the tensile resistance, which often requires a significant amount of steel. To address this issue, the concept of prestressed CFST lattice structures (Fig. 2) is proposed. By applying prestressing forces, the CFST columns predominantly experience compression during wind turbine operation. This approach allows the CFST column to effectively utilize its high compressive load-bearing capacity while reducing the tensile force on the member. By increasing the concrete area instead of the steel tube wall thickness to enhance the load-carrying capacity of the members, the required amount of steel can be significantly reduced, resulting in cost savings.

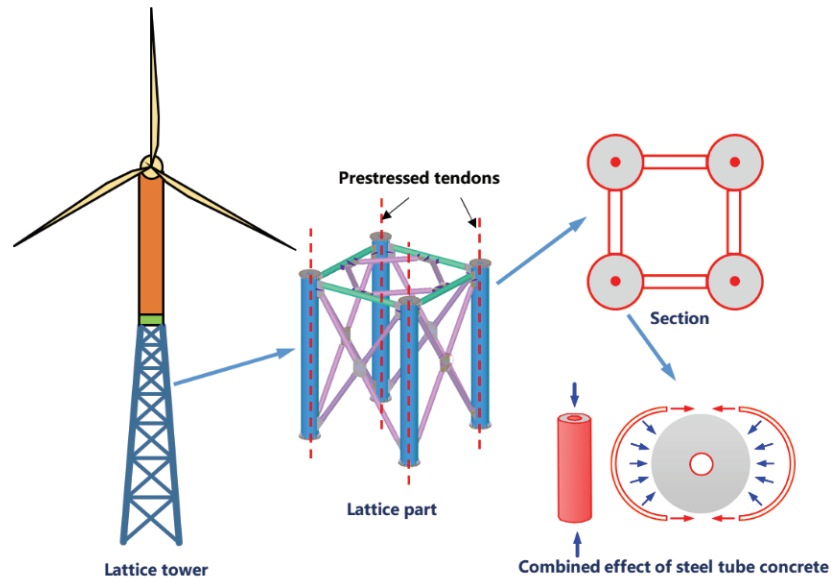


Fig. 2 Mechanical Analysis of the lattice tower

Q355 steel is used as the steel material with a nominal yield strength of 355 MPa. The steel tube diameter is 1150 mm, and the wall thickness is 10 mm. The concrete strength is specified as C60 with a nominal cubic compressive strength of 60 MPa.

The lower section of the tower structure is designed with a lattice configuration to withstand higher loads. It is connected to the upper steel tower through a transition piece (Fig. 3).



Fig. 3 Structural members and connections of the lattice wind turbine tower

Pre-stressed system design

In the lattice tower structure, the corner columns are constructed using concrete-filled double-skin steel tubular (CFDST) columns (as shown in Fig. 2), where the hollow part serves as a prestressing duct and is prestressed longitudinally along the entire height. The magnitude of prestressing determines the design control strategy for the overall structure, and the effects of prestressing are mainly reflected in the following three aspects: (1) Allowing the components to primarily bear compressive forces to fully utilize the high compressive load-carrying capacity of CFST column. (2) Preventing cracking in the internal concrete of the components during normal operation of the wind turbine to maintain the load-carrying capacity of the structure. (3) Increasing the overall structural stiffness and stability.

Additionally, according to the concrete fatigue design code [7], the fatigue performance of concrete under high compressive stress levels tends to weaken. Therefore, it is necessary to optimize the structural design principles to reduce material costs. Based on the structural load characteristics and performance, each corner column in this project is prestressed with a value of 6900 kN (considering a loss of 570 kN in prestressing over the design service life), ensuring that the internal concrete of the components does not exceed the tensile strength of concrete (no cracking) during normal operation of the wind turbine. 33 strands of 15.2 mm diameter steel prestressing tendons were selected based on the prestress of 6900kN.

In addition, the diameter of the prestressing duct inside the corner column should be larger than the diameter of the prestressing bars to avoid any collision between the prestressing tendons and the inner tube wall in case of nonlinear deformation of the tower during operation. For this project, the diameter and wall thickness of the internal steel tube (prestressed duct) of the corner column are selected as 340 mm and 5 mm, respectively.

Joint design

The diagonal braces and horizontal braces are connected to the corner columns through gusset plates (Fig. 4c). The adjacent columns are connected using flanges (Fig. 4e). The components are joined together using ring groove rivets.

At the end of the corner columns, internal stiffeners are used to provide positioning for the inner steel tubes and improve the load-bearing performance of the joint region, as shown in Fig. 4(d). The gusset plates at the end of the angle columns extend into the interior of the concrete and are welded to the inner steel tubes, with studs arranged on both sides of the gusset plate within the concrete. This construction form ensures clear load transmission, allowing a portion of the load to be directly transferred to the concrete and inner steel tubes through the node plate, preventing the outer steel tubes from buckling under tension. This enhances the fatigue performance and load-bearing capacity of the joint.

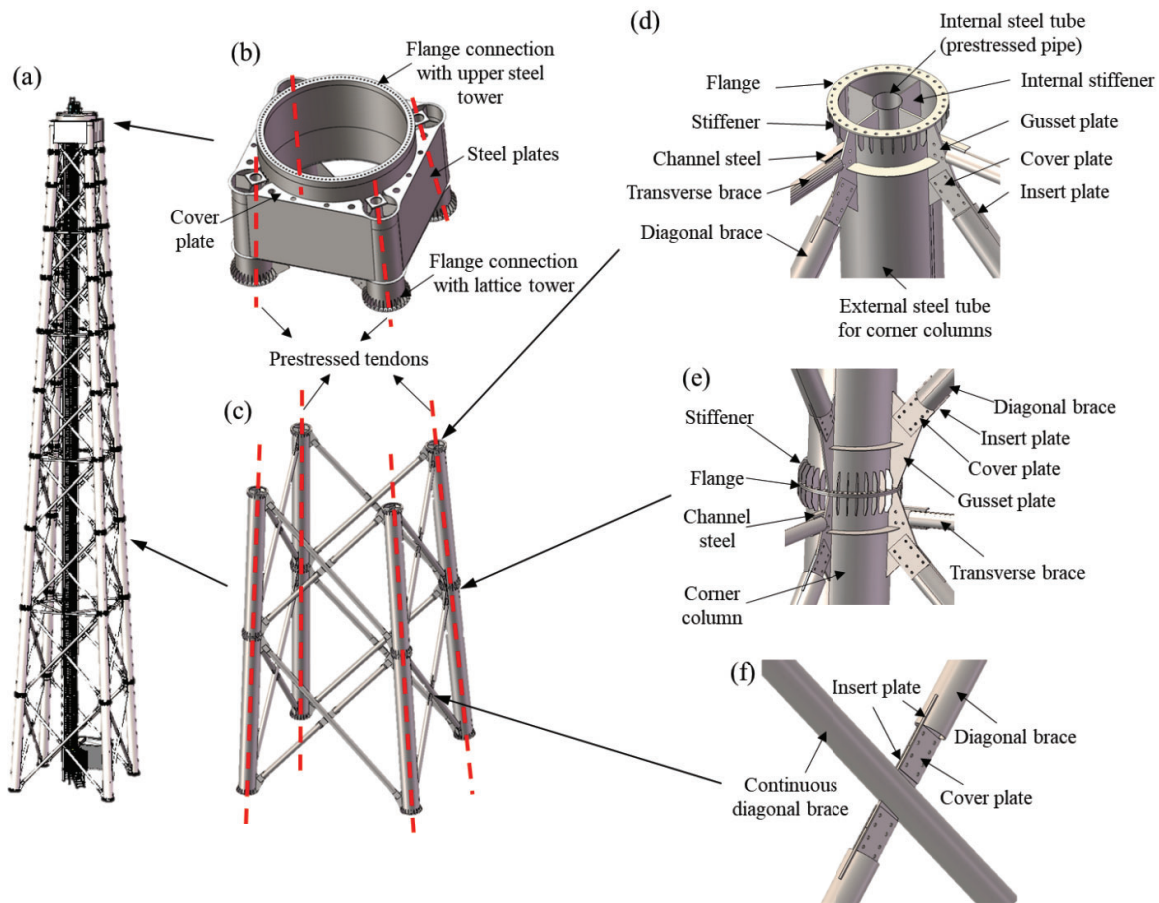


Fig. 4 Schematic diagram of lattice part and transition piece

The determination of flange bolt dimensions and quantities should follow the principle that the flange surfaces of the wind turbine are not detached during normal operation (the flange surfaces are always under compression). The flanges between the columns are connected using 32 pieces of M30 grade 10.9 bolts with grooved rivets. It is important to note that when designing flange bolts without stiffeners, the additional bending moment caused by flange deformation under load should be considered [8].

Transition piece design

The transition piece, serving as the connection structure between the steel tower and the lattice part, is crucial for the safe and reliable operation of the entire wind turbine. It allows for a reliable connection between the upper steel tower and the lower lattice part, enabling them to work together well. The commonly used form of the transition piece is the reinforced concrete transition piece (RCT), which is technologically mature and widely applied. However, the RCT still has the following disadvantages: 1) complex manufacturing and challenging assembly of densely placed steel reinforcements, 2) potential cracks that may affect the service life of the tower, and 3) relatively low load-bearing capacity. Therefore, there is an urgent need to improve the structural performance of the transition piece to address these issues.

To improve the mechanical performance of RCT, a new type of steel-concrete composite transition piece (SCCT) has been proposed. The SCCT consists of steel components and a sandwiched concrete core (Fig. 4b). The four corner columns of the lattice part extend to the top of the transition piece, while the steel tube of the upper steel tower extends downward to the bottom of the transition piece. The four corner columns are positioned on the outer side of the steel tube, and several conventional stiffeners are evenly distributed between them. Additionally, cover plates are installed on the outer side, top, and bottom of the transition piece, and several reinforcing plates are uniformly welded between the outer cover plate and the steel tube. Finally, the cavities are filled with concrete to enhance the composite effect.

It is important to note that under bending moments, the steel plates on the tension side of the transition piece are prone to detachment from the concrete and concrete cracking. To prevent these issues, studs are uniformly distributed on the inner side of the steel components within the transition segment. This further enhances the overall connection between steel and concrete. The upper end of SCCT is connected to the steel tower through flanges, while the lower end is connected to the lattice part through flanges on the four corner columns. The width of the side of SCCT is chosen as 5m, taking into consideration the width limits for transportation on land.

The SCCT provides enhanced load-bearing capacity due to the synergistic effect between steel and concrete. Furthermore, by utilizing steel tubes, the amount of steel reinforcement required is reduced. This eliminates the need for traditional formwork construction and steel reinforcement assembly processes associated with conventional RCT, thereby improving manufacturing efficiency. Additionally, SCCT helps prevent concrete cracking, which extends the service life of the wind turbine.

Due to the limited application of SCCT in wind turbine structures, there has been relatively little research conducted on this topic. The structural configuration of SCCT used in this project is similar to that of CFST, especially CFDST. Therefore, previous research on the compressive performance of CFST [9] and CFDST [10-15] can provide valuable information for studying SCCT.

While previous research on CFST and CFDST structures can provide valuable guidance for this study, the geometric characteristics of the research objects are not identical to SCCT. Therefore, in order to fill this research gap in wind turbine structures and provide a theoretical basis for the application of SCCT in wind turbine structures, experimental and theoretical investigations on the compressive performance of SCCT were conducted [16]. Through validated finite element models, parameter analysis of the structure was carried out to

identify the sensitive parameters that affect the ultimate bearing capacity of SCCT. Structural optimization was performed to reduce the overall cost.

Installation design

The segmented length of the lattice column is determined by the inclination angle of the diagonal braces. Through parametric analysis using the finite element software ABAQUS for lattice parts with different inclination angles of the diagonal braces, it was found that the structure exhibits optimal load-carrying efficiency when the inclination angle is 45 degrees. Therefore, in this project, an inclination angle of 45 degrees is adopted for the diagonal braces, with a length of 11m for the bottom lattice column and 3.6m for the top lattice column. The structure is assembled using full bolts. As this new structural system is being applied for the first time, to ensure the installation accuracy on-site pre-assembly of the lattice part and transition piece (Fig. 5a) is conducted after the completion of the manufacturing for each steel component. Once the measurement accuracy at various locations meets the requirements, the concrete pouring is carried out for the lattice columns (Fig. 5c) and transition piece (Fig. 5b).

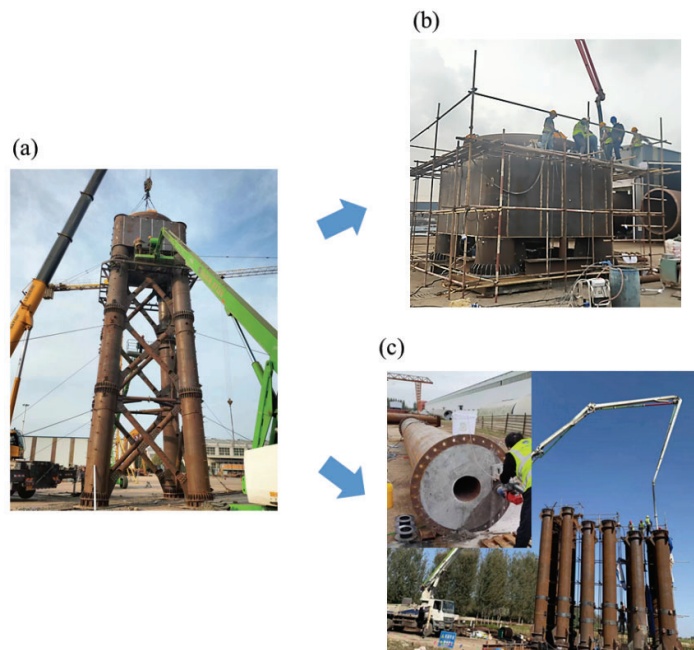


Fig. 5 Pre-assembly and concrete pouring

When the concrete strength meets the requirements, it is transported to the turbine site for lifting. After the installation of each level of lattice columns (Fig. 6a) and diagonal braces, horizontal braces (Fig. 6b), the horizontal level, height difference, and root opening of the top end of the four lattice columns are measured. Adjustments are made using guy ropes, and once the adjustments are completed, the horizontal level of that level is installed along with the elevator shaft. Subsequently, the installation of the 10 tower sections and elevator attachments is carried out, followed by the lifting of the transition piece (Fig. 6e). Pre-tensioning is applied at the top of the transition piece to increase the integrity and stability of the lattice tower. The prestressed tendons should be symmetrically, synchronously, and uniformly tensioned in batches. After the tensioning is completed, the bolts of the entire lattice part are finally tightened to prevent the loss of bolt preload.

Results

The key points of innovative pre-stressed CFST lattice wind turbine tower can be summarized as follows:

(1) The application of concrete-filled steel tube enhances the load-bearing capacity of columns while reducing steel consumption. Additionally, the application of prestressing technology prevents concrete cracking in the cross-section of the columns.

(2) The steel-concrete composite transition piece provides an effective and cost-effective load transfer mechanism for the structure.

(3) Only one small independent concrete foundation is installed under each column, compared with the foundation of traditional tower structures, the amount of concrete consumption is reduced by 28%, and the cost is significantly reduced.

(4) All components are manufactured in the factory to ensure their quality and enable standardized production. This approach facilitates the transportation of individual components to the site, reducing transportation difficulties and increasing efficiency. The final assembly of the structure is performed on-site with the individual components.

(5) All the key technologies employed in structural design aim to achieve safe, reliable, and sustainable infrastructure. Furthermore, compared to traditional steel-concrete hybrid tower, the prestressed CFST lattice tower can save 10% in construction costs. The techniques utilized in this project can enhance the performance and constructability of large-span transmission towers worldwide in the future.

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国際化推進共同研究概要

〔採択番号〕 25RE-5

タイトル： Design and analysis of the sharing mooring/cable system for the co-located floating offshore wave and wind energy systems

研究代表者： Yang, Shun-Han

所内世話人： 劉 盈溢

研究概要：

洋上風力発電の開発が深海域へと進展する中、従来のカテナリー式チェーン係留システムは、コストおよび海底占有面積の観点から次第に制約を受けるようになっている。一方、浮体式洋上風力発電機（FOWT）と波力発電装置（WEC）を組み合わせた風力・波力統合発電システムは、発電量の向上および海域利用効率の改善が期待されている。以上の背景を踏まえ、本研究では、浮体式風力プラットフォームに点吸収型 WEC を搭載した統合型風力・波力発電システムを対象とし、チェーン-繊維-チェーンの分割構成を有するハイブリッド・タウト係留システムについて検討を行った。係留用繊維材料としては、柔軟性および剛性特性の異なる代表例として、ナイロンロープおよび高弾性ポリエチレン（HMPE）ロープを採用した。解析は三段階で実施した。まず、DNV WADAM を用いて、FOWT-WEC 連成系の周波数領域における流体力応答解析を行った。次に、NREL WEC-Sim を用いて、極端外力条件下における完全連成の時間領域シミュレーションを実施した。最後に、BV 船級協会の基準に基づき、終局限界状態におけるプラットフォーム運動、係留索張力、および発電性能の評価を行った。

その結果、係留索の剛性がシステム全体の動的挙動を支配する主要因であることが明らかとなった。HMPE ロープは、プラットフォーム変位の抑制および WEC のエネルギー取得効率の向上に有効である一方、高い軸剛性によりピーク張力の増大やスナップ荷重発生リスクを伴うことが示された。これに対し、ナイロンロープは優れた荷重吸収性能を示し、プラットフォーム運動を低周波ドリフト成分へと移行させる効果が確認されたが、その代償として許容変位量の増加が必要となる。最終的に、水深 200 m 条件下において、最小破断荷重の 10%を初期張力とし、アンカー半径 370 m とするナイロンロープを用いた 3×2 冗長係留構成が、統合型風力・波力発電システムに対する有効な設計案であることが示された。

国際化推進共同研究報告書

25RE-5

タイトル: Design and analysis of the sharing mooring/cable system for the co-located floating offshore wave and wind energy systems.

研究代表者: Yang, Shun-Han

所内世話人: 劉 盈溢

Introduction

In response to global initiatives aimed at reducing greenhouse gas emissions, offshore renewable energy has attracted increasing attention in recent years. Along the pathway toward decarbonization, offshore wind energy has experienced rapid expansion [1], while wave energy is widely regarded as one of the marine renewable resources with the highest energy potential [2]. Wind and wave resources also exhibit complementary characteristics in both temporal and spatial domains. Ocean waves are primarily generated by wind but propagate with a time lag, such that wave energy can remain significant even after wind speeds decrease. This complementary behavior has the potential to smooth power output, reduce short-term fluctuations, and enhance the stability of renewable energy supply.

To improve energy utilization efficiency per unit sea area, integrated wind-wave energy systems that combine floating offshore wind turbines (FOWTs) with wave energy converters (WECs) have been proposed as a promising solution. By sharing offshore infrastructure—including mooring systems, anchors, power cables, and substations—such hybrid systems can increase total energy yield while reducing the levelized cost of energy and improving sea-area utilization efficiency [3].

Despite their widespread application and proven reliability, conventional catenary mooring systems exhibit inherent scalability limitations when deployed in deeper waters (typically exceeding 70 m) for marine renewable energy applications. As water depth increases, the required mooring line length and weight grow substantially, leading to increased material and installation costs, expanded seabed footprints, constraints on turbine spacing [4], and potential adverse impacts on the seabed environment. To address these challenges, taut mooring systems employing synthetic fiber ropes—such as polyester, nylon, and high-modulus polyethylene (HMPE)—have emerged as promising alternatives for deep-water applications. These systems offer significant reductions in structural weight and seabed footprint, as well as lower installation costs. However, the application of synthetic taut moorings to integrated wind-wave platforms introduces new design challenges, particularly the trade-off between limiting platform offsets to protect dynamic export cables and mitigating peak mooring tensions to avoid rope failure. In addition, the nonlinear mechanical behavior of synthetic fibers may introduce modeling

uncertainties, and current design practices for synthetic mooring systems in marine renewable energy applications remain limited [5].

Hybrid mooring systems, which combine multiple mooring components such as steel chains, synthetic fiber ropes, buoys, and clump weights, have been proposed to leverage the advantages of different materials within a single configuration [6]. A three-segment hybrid design is commonly adopted, in which steel chain segments are installed at both the anchor and fairlead ends. These chain segments provide sufficient pretension and restoring force due to their weight, enhance abrasion resistance at seabed and platform contact points, and ensure durability in the upper water column by resisting ultraviolet degradation in the photic zone [7]. The central segment typically consists of a lightweight and elastic synthetic fiber rope with superior load-absorption capability. This hybrid configuration not only reduces overall system weight and cost, but also improves the ability of the mooring system to mitigate snap loads and fatigue damage commonly observed in conventional all-chain mooring systems [7].

The primary objective of this research is to propose and evaluate a taut hybrid mooring configuration suitable for integrated wind–wave energy systems deployed in deep-water environments. This objective is addressed through three specific research goals. First, a hybrid taut-mooring system incorporating multiple mooring materials within each mooring line is designed for extreme environmental conditions at a water depth of 200 m. Second, based on the proposed mooring configuration, the hydrodynamic interaction effects between the FOWT and the WECs are quantified. Third, a fully coupled numerical model of the integrated wind–wave energy system is established to evaluate system performance with respect to the ultimate limit state. By systematically addressing these objectives, this study aims to provide a comprehensive understanding of fiber-based mooring systems for integrated wind–wave energy platforms, thereby supporting their reliable and cost-effective deployment in deep-water marine renewable energy applications.

Methodology

Simulation framework

In this study, WEC-Sim (Wave Energy Converter SIMulator), developed by the National Renewable Energy Laboratory (NREL), is employed as the primary time-domain simulation tool. Based on the WEC-Sim framework, the simulations are further coupled with MoorDyn for mooring system dynamics and MOST for wind turbine modeling. This integrated framework provides a fully coupled aero–hydro–servo–elastic simulation environment for the floating wind–wave energy system. The hydrodynamic coefficients required by WEC-Sim are obtained through potential-flow analysis using DNV WADAM, and subsequently converted into a WEC-Sim-compatible format via BEMRosetta. This workflow ensures consistency from hydrodynamic characterization to fully coupled time-domain simulations. Within the coupled model, the floating platform, wind turbine, WECs, and mooring system are represented as interconnected subsystems that exchange forces and motions in real time. The hydrodynamic formulation follows the WEC-Sim framework, the aero-servo-hydrodynamic control is provided by MOST, and the station-keeping forces are computed using the embedded MoorDyn module. Following each time-domain simulation, the statistical evaluation of mooring responses is

conducted in accordance with BV NR-493 [8] for short-term extreme value estimation, while the minimum safety factors are adopted from BV NR-572 [9].

Case study wind-wave energy system

The wind-wave energy system considered in this study consists of a FOWT, three WECs, and a mooring system. The FOWT is based on the reference prototype developed under NREL Task 37 [10,11], which comprises the IEA 15-MW reference wind turbine supported by the UMaine VoltturnUS-S semi-submersible platform. The semi-submersible platform also serves as the primary supporting structure for the integrated WECs. Three identical heaving point-absorbing WECs, originally proposed by Su and Yang [12], are integrated within the three side columns of the semi-submersible. Each WEC buoy has a diameter of 8 m and a total height of 8 m, consisting of a 4 m cylindrical section and a 4 m hemispherical bottom. The system-level coupling architecture adopted in this study is illustrated in Figure 1.

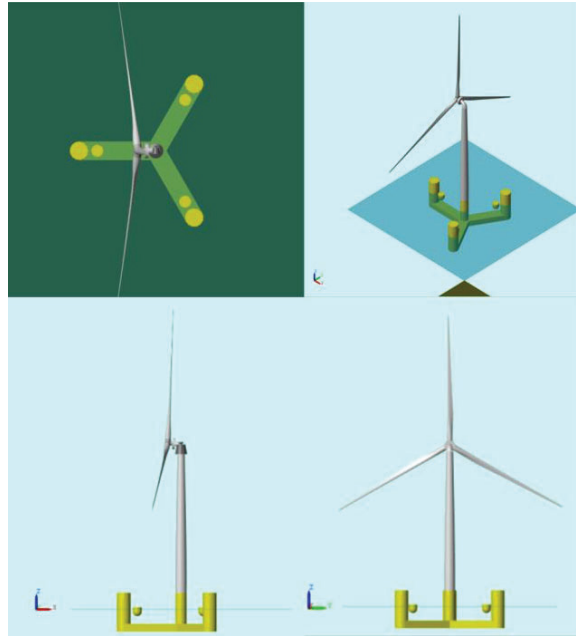


Figure 1 Schematic of the case study wind-wave system

Mooring systems

The objective of this study is to investigate semi-taut mooring systems employing a segmented chain-synthetic fiber rope-chain hybrid configuration. To examine the influence of rope axial stiffness, two types of synthetic fiber ropes are considered: nylon and high-modulus polyethylene (HMPE). Chain segments are retained at the terminations to enhance abrasion resistance. The key design variables examined in this study are the anchor radius and pretension level. The adopted mooring system specifications are summarized in Table 1. Each case is classified according to rope type, anchor radius, and pretension. For instance, N370P10 denotes a

nylon rope with an anchor radius of 370 m and a pretension of 10% of the minimum breaking load (MBL), whereas H490P30 represents an HMPE rope with a 490 m anchor radius and a pretension of 30% MBL. In total, twelve configurations are established to systematically evaluate the effects of rope stiffness and pretension on mooring performance at a water depth of 200 m.

Table 1 Key specifications of the mooring system models

Properties	Values	Units
Mooring system type	hybrid taut	[-]
Mooring chain category	studless chain - nylon/HMPE - studless chain	[-]
Mooring chain grade	R3-grade (studless)	[-]
Mooring pattern	3×1	[-]
Water depth	200	[m]
Anchor radius spacing	370/490	[m]
Fairlead depth	14	[m]
Fairlead radius spacing	58	[m]
Pretension (% MBL)	10/30/50	[N]
Studless chain length	10/10	[m]
Mooring chain diameter	180	[mm]

Environmental condition

A representative environmental condition is selected based on IEA Task 37 [11], specifically design load case (DLC) 1.6, which falls under the power production design situation defined in IEC 61400-1 [13] and is treated as an ultimate limit state (ULS) load case. This DLC corresponds to turbine operation at rated wind speed under the normal turbulence model. The hub-height wind speed corresponding to the maximum structural thrust is selected for the case study. Accordingly, the environmental condition is defined by a hub-height wind speed of 12 m/s, a significant wave height of 8.5 m, a peak wave period of 13.1 s, and a surface ocean current speed of 0.5 m/s. Irregular waves are modeled using the JONSWAP spectrum with a peak enhancement factor of 2.75. Both wind and current profiles follow power-law distributions, with exponents of 0.11 for wind and 1/7 for ocean currents.

Results

Effect of hydrodynamic multibody interaction

The influence of fully coupled hydrodynamic interactions on system responses is first investigated. The simulation results indicate that the platform responses exhibit only minor differences when hydrodynamic multibody interactions are included. In contrast, as illustrated by the representative results in Figure 2, the WEC

responses show noticeable deviations across most degrees of freedom when multibody hydrodynamic effects are neglected. These findings indicate that the WEC units experience stronger wave radiation and inertial coupling effects due to their smaller scale and proximity to the floating platform. Accounting for hydrodynamic multibody interactions is therefore essential for accurately predicting WEC hydrodynamic loads and dynamic responses.

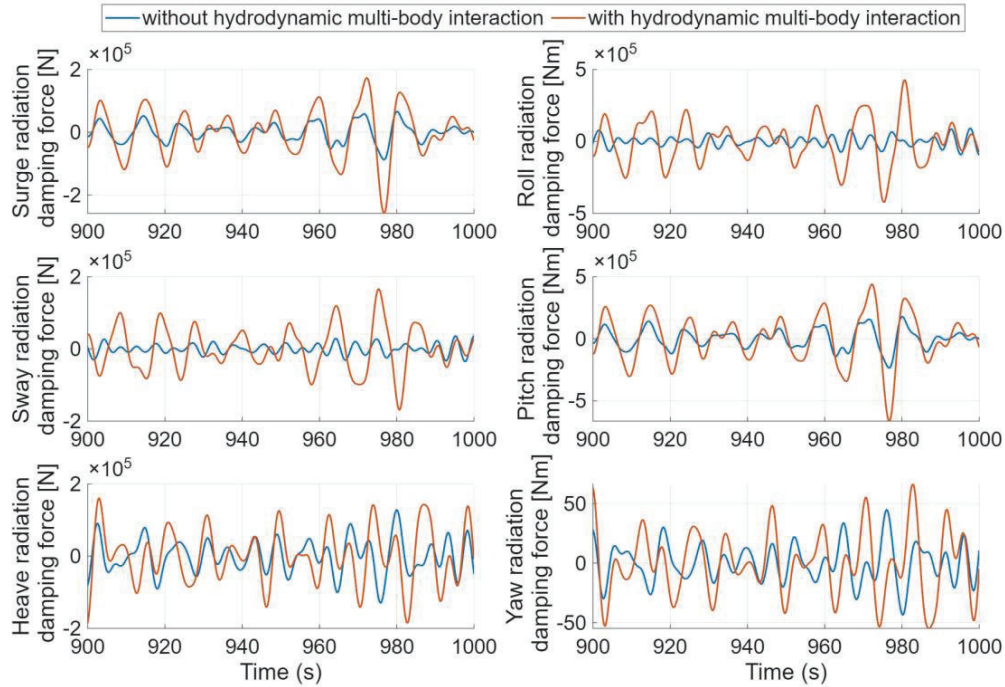


Figure 2 Radiation damping forces of the WEC with and without hydrodynamic multibody interaction

Mooring line tension and platform offset

Table 2 summarizes the design tensions and corresponding utilization ratios for all twelve mooring configurations. The results show that only N370P10 and N490P10 satisfy the allowable tension criteria, whereas all other configurations—particularly those employing HMPE ropes—exceed the permissible limits. For the nylon configurations N370P30, N370P50, N490P30, and N490P50, the tension utilization exceeds 100%. In the case of HMPE ropes, the tension utilization ranges from approximately 200% to 550%, indicating that the substantially higher axial stiffness of HMPE leads to excessive dynamic tension responses and failure to meet allowable design limits.

Table 2 Design tension and tension utilization by configuration and material

T_D [kN], T_D/T_a [%]		Material	
Configuration	Chain ($T_a = 10693.3$)	Nylon ($T_a = 3857.8$)	
N370P10	3581.5	33.49	91.57
N370P30	5195.9	48.59	133.34

N370P50	6938.2	64.88	6885.6	178.49
N490P10	3346.2	31.29	3300.1	85.54
N490P30	4989.3	46.66	4939.1	128.03
N490P50	6791.8	63.51	6740.0	174.71
Configuration	Chain ($T_a = 10693.3$)		HMPE ($T_a = 11147.7$)	
H370P10	29959.4	280.17	29917.4	268.37
H370P30	47551.6	444.69	47500.9	426.10
H370P50	65887.8	616.16	65829.2	590.52
H490P10	26462.5	247.47	26423.5	237.03
H490P30	34404.5	321.74	34365.4	308.27
H490P50	45461.6	425.14	45419.5	407.43

The analysis of design horizontal offset, presented in Table 3, reveals a strong dependence on mooring line axial stiffness. The HMPE configurations, characterized by high stiffness, provide significantly greater static and dynamic horizontal restoring forces. As a result, platform excursions are effectively constrained, with design horizontal offsets ranging from 8.09 m to 10.53 m. The corresponding offset utilization ratios remain below 35%, confirming compliance with the prescribed offset criteria with a substantial safety margin. In contrast, the compliant nature of nylon ropes results in considerably larger platform offsets under identical environmental loading. Although increasing pretension reduces the offset to some extent (from approximately 57.78 m to 36.90 m), all nylon configurations exceed the allowable offset limits. The offset utilization ratios range from 123% to 192.6%, demonstrating that the low-modulus characteristics of nylon ropes fundamentally compromise station-keeping performance.

Table 3 Platform offset responses for various case-study mooring configurations

Configuration	O_D [m]	O_D/O_{EX} [%]
N370P10	49.11	163.71
N370P30	40.44	134.79
N370P50	35.39	117.96
N490P10	55.06	183.52
N490P30	46.30	154.32
N490P50	41.16	137.21
H370P10	8.32	27.73
H370P30	9.32	31.07
H370P50	10.71	35.70
H490P10	8.62	28.73
H490P30	8.54	28.47
H490P50	9.42	31.40

To resolve the conflicting tension and offset requirements identified above, a redundant six-line (3×2) hybrid mooring system is proposed and evaluated under the same DLC 1.6 conditions. The four non-redundant

configurations exhibiting the most favorable performance (N370P10, N490P10, H370P10, and H490P10) are reformulated into redundant layouts, denoted as RN370P10, RN490P10, RH370P10, and RH490P10, respectively. Among all configurations investigated, RN370P10 demonstrates the most balanced overall performance. For this configuration, the tension utilization ratio is reduced to approximately 50%, while the maximum horizontal offset is constrained to 26.91 m, corresponding to an offset utilization of 89.7%.

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国際化推進共同研究概要

〔採択番号〕 25RE-6

タイトル: Steps to Digital Twins and Real-time Monitoring for floating offshore wind turbines

研究代表者: Hu Zhiqiang

所内世話人: HU Changhong

研究 概 要:

浮体式洋上風車のデジタル・ツインとリアルタイム・モニタリング技術の実現を目指して国際化推進共同研究プロジェクトを立ち上げ、今年度は2年目で、風力補助推進船へのSADA手法適用に関する研究を実施した。特に、風速と風向のリアルタイム入力により、船舶エンジンのエネルギー効率を向上する最適化検討について有望な成果が得られた。その研究成果はスウェーデン・ヨーテボリにあるチャルマース工科大学で開催されたICSOS 2025会議に発表された。さらに、この共同研究に関連のある風車ブレード制御に関する研究について、中国深セン市の華南理工大学で開催されたAPCOW 2025会議に論文を投稿して発表した。

Steps to Digital Twins and Real-time Monitoring for floating offshore wind turbines

Zhiqiang Hu

Marine, Offshore and Subsea Technology, School of Engineering, Newcastle University, UK

This collaborative research project between RIAM at Kyushu University and the Marine, Offshore, and Subsea Technology Group at School of Engineering, Newcastle University was launched in 2024. And this project continued in year 2025. Its goal is to develop technology for real-time monitoring of floating offshore wind turbines. The research outcomes are expected to lead to a promising solution for Operation & Maintenance cost reduction in offshore wind industry.

The research originated from a novel concept *SADA*, initially proposed by Prof Zhiqiang Hu's research team at Newcastle University in 2020. In 2025, *SADA* was further developed to be used in wind-assisted propulsion vessel field, to validate its feasibility in other marine technology fields. Additionally, this project extends the *SADA* method to a further application stage by integrating a mooring model into the *DARwind* code, the core component of the *SADA* methodology. Furthermore, the use of AI technology has also been started to enhance the accuracy of offshore floating wind turbine O&M real time monitoring.

In 2025, the research team completed research on employing *SADA* method into a wind-assisted propulsion vessel. The vessel engine energy consumption efficiency can be optimized with the real-time input of wind speed and wind velocity. Based on the research outcomes of the *SADA* application in wind-assisted propulsion vessel, a paper was submitted to the *ICSOS 2025* conference held at Chalmers University of Technology at Gothenburg, Sweden.

Additionally, another research paper financially supported by the RIAM fund was submitted to *APCOW 2025* conference co-organized by RIAM at South China University of Science and Technology, Shenzhen, China.

Starting from 2024 and continued in 2025, Zhiqiang Hu and his research team at Newcastle University have been focusing on developing a digital twin system for the monitoring and maintenance of floating offshore wind turbines (FOWTs). This research aims to address the challenges of reducing operation and maintenance costs while advancing digital twin technology for the offshore wind industry. The collaborative research outcomes achieved in 2025 are summarized below.

- 1) The research of *SADA* application in wind-assisted propulsion vessel comes out a paper published in the Proceedings of ICSOS2025. Miss Zhu Huang, a PhD supervised by Prof Zhiqiang Hu, attended the conference and gave presentation based on the research

outcomes. The title of the paper is ‘Application of an AI-based *SADA* method in the prediction of propulsion performance and energy-saving optimization for wind-assisted propulsion vessels.’ Additionally, after the conference, this paper was invited to be further revised and submitted to journal of *Ships and Offshore Structures*. Currently, this paper is under revision and expects to receive final acceptance. The research was financially supported by the RIAM research project and co-authored with Prof. Changhong Hu of Kyushu University.

- 2) The 2nd Asia-Pacific Conference on Offshore Wind Technology (APCOW 2025) was hosted by South China University of Science and Technology in December 2025. Mr. Yuqing Hao, a PhD student supervised by Zhiqiang Hu at Newcastle University, presented on the topic " Design of a Pitch Angle Oscillation Control System for Wind Turbine Blade Dynamic Stall Simulation in Wind Tunnel." Mr Yuqing Hao gave a presentation in the Conference and has discussed with other scholars. Additionally, Zhiqiang Hu also attended the conference and chaired a session.

国際化推進共同研究概要

〔採択番号〕 25RE-7

タ イ ト ル : Assessment of Shared-Mooring and Anchor Configurations for Floating Offshore Wind Turbine Array

研究代表者 : Yu, Yi-Hsiang

所内世話人 : 劉 盈溢

研究概要 : 本研究は、中水深域における浮体式洋上風力発電の「共有係留」および「共有アンカー」システムが荷重分布に与える影響を調査した。FAST.Farm を用い、IEA 15MW 風車 (UMaine VoltturnUS-S) を対象に、共有アンカー5 基および共有係留 3 基のアレイ構成を各種設計荷重下で検証・コスト評価した。

解析の結果、共有アンカーはベクトルの打ち消し効果により合成荷重を低減しつつ、運動性能や安全性を単一風車と同等に維持できることが判明した。一方、チェーンとポリエステル併用の共有係留は、柔軟性ゆえに偏位や張力が増加するものの、動的ケーブルの安全基準内であった。経済面では、従来の全チェーン方式に対し資本支出を大幅に削減できる。本知見は、中水深域における共有システムの最適化と経済的優位性を裏付けるものである。

国際化推進共同研究報告書

25RE-7

タイトル: Assessment of Shared-Mooring and Anchor Configurations for Floating Offshore Wind Turbine Array

研究代表者: Yu, Yi-Hsiang

所内世話人: 劉 盈溢

Introduction

Globally, the offshore wind industry has experienced exponential growth in recent years, driven by the urgent imperative to transition towards renewable energy and achieve carbon neutrality. Following this global trend, and benefiting from the superior wind resources of the Taiwan Strait [1], Taiwan has actively expanded its offshore wind capacity to meet its energy transition goals [2]. By August 2025, significant milestones had already been achieved, with seven wind farms completed, comprising over 400 fixed-bottom turbines and exceeding 3.9 GW of grid-connected capacity [3]. As the industry continues to mature, the next phase of development is expected to extend into deeper marine environments, specifically targeting depths greater than 70 meters [4]. This transition positions Floating Offshore Wind Turbines (FOWTs) as a highly competitive alternative with significant expansion potential. This technology offers the distinct advantage of accessing stronger and more consistent wind resources farther offshore, while significantly reducing construction noise and visual impacts on coastal communities.

Despite these advantages, FOWTs face multifaceted challenges, including complex array layout designs, wake effects, and the intricate dynamics of mooring and anchoring systems. Furthermore, their economic feasibility is strongly influenced by environmental conditions—such as wind, waves, currents, and water depth—which directly dictate installation and maintenance costs. To address the high capital expenditure (CAPEX) associated with FOWTs, recent research has shifted from single-turbine analysis to integrated array optimization. This approach emphasizes the optimized design of turbine placement, the impact of wake effects, and the configuration of mooring systems and electrical cables. Specifically, shared mooring and shared anchor configurations have emerged as effective strategies to reduce the number of anchors and the total length of mooring lines, thereby lowering system costs without compromising stability. In this context, Pillai et al. [5] simulated an array of three IEA 15 MW floating wind turbines using a shared-anchor configuration. Their results demonstrated that anchor sharing can reduce peak loads by up to 67% compared to single-turbine scenarios. Despite this reduction, the study emphasized that shared anchors significantly alter load directionality, meaning that traditional drag embedment anchors, which are typically designed for unidirectional loads, are not suitable

for such configurations. Lozon et al. [6] used FAST.Farm to demonstrate the technical feasibility of shared mooring systems for large-scale floating wind farms. Their results indicated that such configurations reduce anchor counts and line lengths while effectively mitigating low-frequency surge motions; nonetheless, shared lines introduce complex coupling frequencies absent in isolated systems. Chemineau et al. [7] investigated the trade-offs of shared mooring lines and shared anchors. They noted that meeting the required turbine spacing (approximately 7D) might offset the savings from reduced anchors, increasing mooring line costs. Nevertheless, the study indicated that both configurations demonstrate significant economic viability when installation, maintenance, and optimized layouts are considered.

However, most existing studies on shared mooring systems focus predominantly on deep-water regions, often suggesting optimal cost-effectiveness at depths exceeding 400 meters [8]. In contrast, potential development sites in the Taiwan Strait typically range from 50 to 100 meters. This specific intermediate-depth range exhibits distinct mechanical characteristics and hydrodynamic responses that remain underexplored, particularly regarding how shared mooring configurations interact with the region's specific metocean conditions.

To address these challenges, this study aims to investigate the mechanical behavior of shared mooring and anchoring systems, specifically focusing on load variation and distribution by comparing these array configurations with a conventional single-turbine system. Furthermore, a preliminary cost estimate is conducted to examine potential economic benefits and evaluate the overall feasibility of these configurations within the environmental context of the Taiwan Strait. This report provides only an overview of the study; more details can be found in the study to be presented at OMAE2026 [9].

The remainder of this paper is organized as follows. First, the numerical simulation tools and a description of the case study design, including wind farm layouts, mooring configurations, and environmental conditions. Finally, the simulation results are presented, covering both dynamic responses and economic analysis.

Methodology and Numerical Simulation Setup

Simulation Tool: FAST.Farm

To capture the complex dynamic interactions within a floating wind farm, this study utilizes FAST.Farm [10], a comprehensive multi-physics engineering tool developed by the National Renewable Energy Laboratory (NREL). FAST.Farm extends the capabilities of the OpenFAST framework to the farm level, employing the Dynamic Wake Meandering model to predict wake deficits, advection, and meandering. This capability is essential for evaluating power performance and structural loading variations across the array caused by turbine-wake interactions.

Computationally, FAST.Farm functions as a central driver that manages global environmental conditions—such as ambient wind and wave fields—while spawning multiple OpenFAST instances to model individual turbines in parallel. This architecture preserves the aero-hydro-servo-elastic dynamics of each turbine while accounting for farm-wide wake interactions. Furthermore, the framework is integrated with MoorDyn to model inter-turbine connections, enabling the simulation of shared mooring lines and shared anchors to capture the coupled dynamic responses of the array.

Turbine Layout

In this study, the IEA 15 MW reference wind turbine mounted on the UMaine VoltturnUS-S semi-submersible platform [11] is employed. To establish a benchmark for evaluating load variations and dynamic differences in shared-array concepts, a conventional single-turbine system is simulated in OpenFAST. This baseline model consists of an isolated IEA 15 MW wind turbine moored by three independent catenary lines, arranged symmetrically with 120° spacing. The mooring system is configured with an anchor radius of 650 m from the platform center [12]. This configuration serves as the reference for quantifying vector cancellation effects and motion characteristics in the shared-array systems described subsequently. In this study, the global coordinate system is defined with the positive x-axis aligned with the wind and wave propagation direction (0°), as illustrated by the directional arrow in Figure 3.

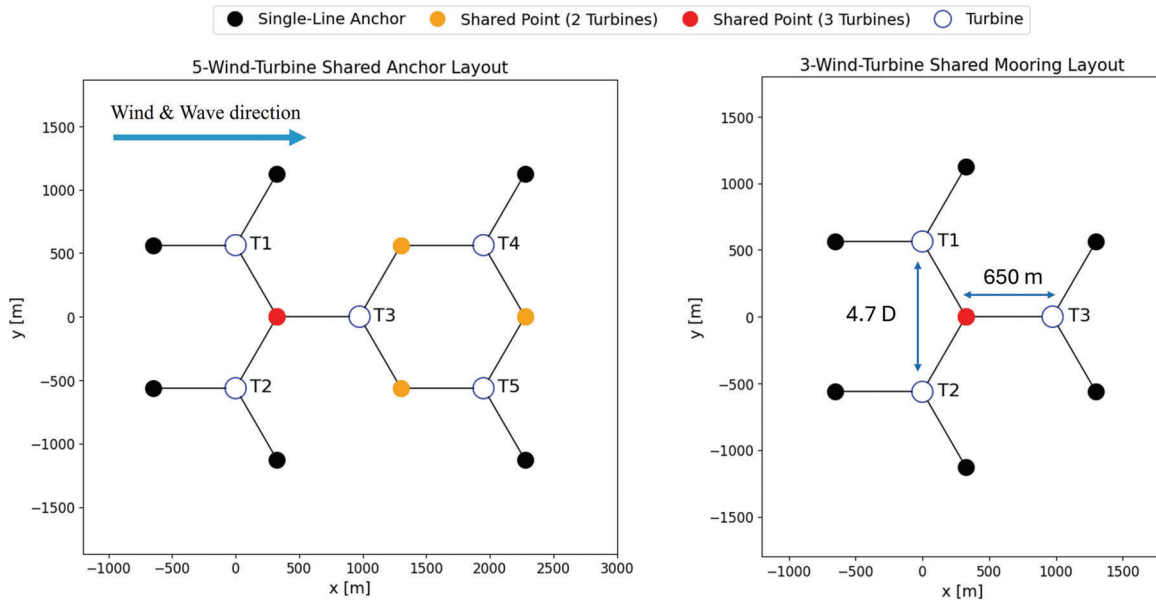


Fig. 3. Schematic layouts of the simulated wind farms.

To investigate the load distribution characteristics of shared anchors and analyze the force variations resulting from different mooring line connectivity, a floating wind farm model comprising five IEA 15 MW wind turbines is developed. The specific layout configuration is illustrated in Figure 3 (Left). As depicted in the figure, red markers represent shared points supporting three turbines, while yellow markers denote shared points supporting two turbines. The turbines are arranged with an inter-turbine spacing of 1,125.8 m, corresponding to approximately $4.7D$, where D denotes the rotor diameter of 240 m.

In the shared mooring scenario, the array is composed of three turbines arranged with the same inter-turbine spacing as the shared anchor configuration, adopting a taut-leg mooring configuration which is inspired by the research of Chemineau et al. [7]. As illustrated in Figure 3 (Right), one mooring line from each turbine extends toward a central convergence point (red marker). Unlike the shared anchor case, these lines do not connect directly to the seabed. Instead, they meet at a connection node, which is anchored to the sea floor by a single vertical mooring line. In the numerical model, this node is treated as a massless connection point without

hydrodynamic volume. While a physical deployment would require a submerged buoy, this simplification removes additional hydrodynamic drag and damping, rendering the resulting motion predictions conservative regarding the dynamic response.

Mooring Properties

Based on the IEA Wind Task 49 specifications [13], this study compares two distinct mooring configurations using Chain R4 (0.185 m diameter) for structural integrity. The single-turbine and five-turbine arrays utilize a catenary configuration, while the three-turbine shared system employs a taut-leg hybrid design, combining Chain R4 at high-wear interfaces with polyester rope mid-sections for axial stiffness. This shared mooring setup is partitioned into three functional categories: outer lines (peripheral anchors), shared lines (central junction node), and vertical lines (shared anchor tether), with all lines pretensioned by reducing their unstretched length relative to their physical span.

Environmental Conditions and Load Cases

This study utilizes metocean data from the Hsinchu buoy (2009–2024) [14] and the Inverse First-Order Reliability Method (IFORM) [15] to define environmental conditions for a 100 m water depth in the Taiwan Strait. Three critical Design Load Cases (DLCs) are established with aligned wind and wave directions to simulate conservative, high-stress scenarios: Case 1 (Extreme Wind) uses the Extreme Turbulence Model ($V_{\text{mean}} = 38.61$ m/s) to test anchor holding capacity under typhoon-level drag; Case 2 (Extreme Wave) evaluates hydrodynamic excitation and dynamic mooring tension during peak sea states ($H_s = 6.145$ m); and Case 3 (Rated Operation) focuses on the Ultimate Limit State (ULS) at rated wind speed (10.85 m/s), where maximum aerodynamic thrust induces the most significant platform surge and offset.

Anchor Load Analysis

Case 1: Extreme Wind Survival Condition

This section evaluates mean anchor forces under Case 1 survival conditions ($V_{\text{mean}} = 38.61$ m/s; $H_s = 4.06$ m; $T_p = 10.46$ s, Parked). Despite typhoon-level winds, loads remain relatively low because the feathered blades minimize aerodynamic thrust, leaving the system dominated by tower drag and wave forces. The analysis reveals a significant performance gap between shared anchor configurations:

- **Load Reduction in 3-Line Systems:** The 3-line shared anchor exhibits a substantial reduction in resultant force (≈ 800 kN) compared to the single-turbine baseline (≈ 2700 kN). This is due to the 0° environmental alignment and parked rotor symmetry, which allow for near-perfect cancellation of transverse (F_y) forces, leaving only the surge (F_x) component.
- **Varied 2-Line Performance:** Shared anchors connecting one upstream and one downstream line show only marginal reduction, as geometric asymmetry prevents effective force cancellation.
- **Shared Mooring (SM) Efficiency:** The SM configuration demonstrates the most effective load transfer. While outer anchors handle high tension due to taut-leg stiffness, the central shared anchor records the lowest load (≈ 450 kN). The junction buoy effectively neutralizes horizontal components through symmetry, transmitting primarily vertical reaction forces to the seabed.

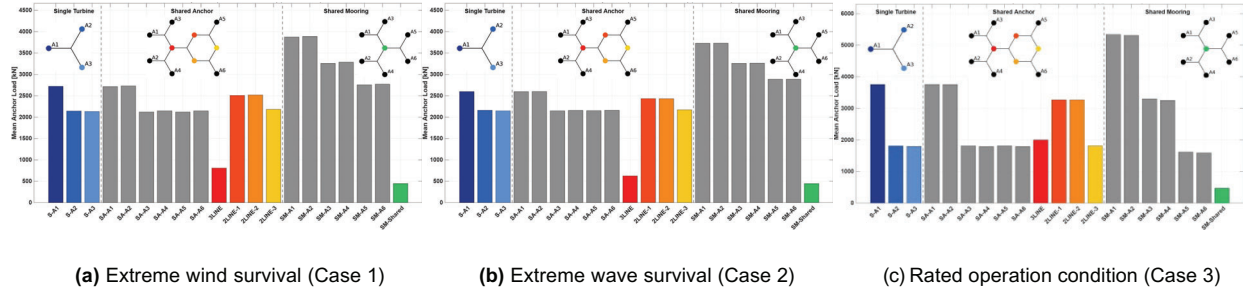


Fig. 4. Comparison of mean anchor loads under extreme survival conditions.

Case 2: Extreme Wave Survival Condition

Under the extreme wave condition ($V_{\text{mean}} = 33.165$ m/s; $H_s = 6.145$ m; $T_p = 13.305$ s), mean anchor loads are slightly lower than those in Case 1, as the reduced mean wind speed results in lower steady aerodynamic drag—the primary driver of mean tension. The 3-Line shared anchor (3LINE) continues to demonstrate superior robustness, reducing the mean load to approximately 650 kN. This confirms that the vector cancellation mechanism effectively neutralizes forces even under intensified hydrodynamic excitation. Conversely, the 2-Line shared anchors (2LINE-1, 2LINE-2) remain limited by asymmetric loading, showing performance levels comparable to the single-turbine baseline ($S-A1 \approx 2600$ kN).

Case 3: Rated Operation Condition

During rated operation ($V_{\text{mean}} = 10.85$ m/s; $H_s = 4.56$ m; $T_p = 10.04$ s), the system experiences its highest loads due to peak aerodynamic thrust. This creates a sharp disparity between upstream anchors ($S-A1 \approx 3800$ kN) and slack downstream anchors in the single-turbine baseline. In the shared configurations, the 3-Line shared anchor remains effective but shows slightly less efficient cancellation compared to Case 1 due to the high-thrust directional imbalance. 2-Line anchors (2LINE-1, 2LINE-2) struggle with this asymmetry, bearing loads similar to the upstream baseline. Most notably, the shared mooring (SM) configuration shifts the extreme horizontal thrust (over 5300 kN) to the peripheral anchors via the taut-leg system, allowing the central shared anchor to remain minimally loaded (≈ 500 kN) as the junction node isolates the seabed from horizontal shear.

Mooring Line Tension and Safety Assessment

To evaluate structural integrity, this study defines the characteristic extreme tension as $T_{\text{char}} = \mu + 2.326\sigma$, representing the 99% upper confidence bound to ensure statistical robustness. Analysis across all scenarios identifies Case 3 (Rated Operation) as the critical design driver, as peak aerodynamic thrust at the rated wind speed generates higher tensions than those in feathered survival conditions (Cases 1 and 2). The all-chain systems (Single and Shared Anchor) exhibit similar characteristic tensions (≈ 4700 kN) and high safety factors (over 5.8), while the Shared Mooring system experiences the highest loading (6008 kN). Although the shared mooring's safety factor is lower (2.05) due to the polyester segment's strength limit, it remains safely above the 1.67 requirement, proving that the hybrid design is structurally optimized for material efficiency without compromising safety.

Platform Motion Analysis

This section evaluates station-keeping capabilities by comparing total displacement and platform pitch against safety limits: a 30 m offset for cable integrity and a 5° pitch limit for operational efficiency. The analysis confirms that all shared topologies are feasible; while the Shared Mooring system exhibits the largest horizontal excursion (20.09 m), it remains well within the 30 m threshold. Although the mean pitch for the shared mooring configuration (5.41°) slightly exceeds the 5.0° target due to surge-pitch coupling, the resulting aerodynamic loss, calculated at approximately 0.45%, is negligible.

Table 6. Comparison of allowable design limits versus characteristic platform motions ($\mu + 2.326\sigma$).

Condition	Parameter	Design Target	Simulated Characteristic		Status
			Single / SA	Shared Mooring	
Case 1: Extreme Wind (Survival)	Char. Offset	< 30.0 m	4.35	8.44	Passed
	Char. Pitch	< 15.0°	< 2.0°	< 2.0°	Passed
Case 2: Extreme Wave (Survival)	Char. Offset	< 30.0 m	3.53	6.50	Passed
	Char. Pitch	< 15.0°	< 1.0°	< 2.0°	Passed
Case 3: Rated Operation (ULS)	Char. Offset	< 30.0 m	5.39	18.78	Passed
	Mean Pitch	< 5.0°	4.28°	5.41°	Acceptable*

*Acceptable deviation: Theoretical power loss due to inclination is negligible (< 0.5%).

Total Cost Analysis

This economic assessment focuses on material capital expenditure (CAPEX) for mooring lines and anchors, providing a first-order comparison of topology efficiency. The Single Turbine baseline is the most expensive (2,307–4,041 k€), with the R4 chain accounting for 81% of the total cost. The Shared Anchor configuration offers a modest 7.4% saving by sharing piles, but costs remain high as mooring line requirements scale linearly with turbine count. In contrast, the Shared Mooring system achieves a dramatic 55–67.5% cost reduction (1,040–1,312 k€ per turbine). This superior efficiency is driven by the hybrid chain–polyester–chain design, which replaces the expensive, heavy chain with lower-cost synthetic rope while simultaneously leveraging shared anchor points.

Table 6. Total cost comparison: mooring lines and anchors.

Configuration	Mooring Cost (k€)	Anchor Cost (k€)	Total Cost (k€)	Cost per WT (k€)	Savings (%)
Single Turbine (1 WT)	1,523–3,257	784	2,307–4,041	2,307–4,041	—
Shared Anchor (5 WTs)	8,142–16,284	2,427	10,569–18,711	2,114–3,742	7.4–8.4
Shared Mooring (3 WTs)	1,099–1,915	2,024	3,123–3,939	1,041–1,312	55–67.5

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国際化推進共同研究概要

〔採択番号〕 25RE-8

タ イ ト ル： High-Precision Two-Phase Interface Simulation Based on Low-Resolution Mesh and Convolutional Neural Networks

研究代表者： LIU Cheng

所内世話人： HU Changhong

研究 概 要：

低解像度格子とCNNに基づく高精度二相界面CFDシミュレーション方法の開発に関して国際化推進共同研究プロジェクトを立ち上げ、今年度は予定通り実施した。特に、自由表面が異なる細分化レベルの領域を通過する際に生じる粗目/細目格子境界の処理、自由表面における気泡の上昇および跳ね返り挙動に対する液体粘度と表面張力の影響などの課題について成果を上げた。関連の成果を纏めてJournal of Computational Physicsなどの国際トップ誌に共著論文を投稿した。

High-Precision Two-Phase Interface Simulation Based on Low-Resolution Mesh and Convolutional Neural Networks

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This collaborative research project between the Research Institute for Applied Mechanics (RIAM) at Kyushu University and the School of Ocean and Civil Engineering at Shanghai Jiao Tong University (SJTU) was launched in 2025. Its goal is to develop advanced numerical methods for high-fidelity simulation of complex two-phase interfaces, particularly focusing on adaptive mesh refinement techniques and machine learning approaches for interface capturing. The research outcomes are expected to lead to improved computational efficiency and accuracy in multiphase flow simulations for marine and offshore engineering applications.

The research originated from the long-standing collaboration between Prof. Cheng Liu's research team at SJTU and Prof. Changhong Hu's team at RIAM. Over the past three years, the two teams have co-authored more than ten SCI papers. With the rapid development of machine learning and artificial intelligence, both teams agreed that initiating new collaborative research on next-generation intelligent CFD solvers is highly necessary. In 2025, the research team achieved significant progress in developing robust numerical methods for two-phase flow simulations with adaptive mesh refinement. The collaborative research outcomes achieved in 2025 are summarized below.

- 1) The first achievement is the development of a robust numerical framework for simulating two-phase flows with gravity and surface tension on adaptive meshes, published in *Journal of Computational Physics*. This work addresses the critical challenge of handling coarse/fine grid interfaces when the free surface passes through regions of different refinement levels. The proposed method employs a pressure compensation approach and a Ghost Fluid Method-based surface tension model, ensuring accurate modeling of gravity and surface tension effects across adaptive mesh interfaces. Key innovations include a novel pressure compensation method to handle pressure gradient discontinuities at coarse/fine interfaces in the presence of gravity, eliminating spurious velocity components, and an improved treatment for surface tension jump conditions across inconsistently refined grids. The method was validated through comprehensive numerical tests including still water problems, static droplet tests, and moving droplet simulations, demonstrating comparable accuracy to uniform mesh simulations while significantly reducing computational costs.
- 2) The second outcome involves a comprehensive numerical investigation into the influence of liquid viscosity and surface tension on bubble rising and bouncing behavior at free surfaces, published in *Physical Review Fluids*. This study employed the axisymmetric two-

phase solver developed through the collaboration, incorporating a multiple marker front-capturing method to accurately capture two distinct gas-liquid interfaces without numerical coalescence, and a block-structured adaptive mesh refinement strategy to resolve millimetric bubbles. Key findings include that the terminal velocity of bubbles follows a logarithmic-linear decay relationship with the Morton number, bubble deformation decreases progressively with increasing viscosity until a critical threshold is reached, and the first bounce characteristics exhibit linear dependence on the Weber number while the second bounce shows a saturation effect for $We < 2.7$. The impact velocity primarily governs the first bounce amplitude, while the bubble shape becomes the dominant factor for subsequent bounces.

- 3) The third achievement is the development of an improved curvature estimation method based on the Height Function technique and Volume Preserving Mean Curvature motion, published in *International Journal for Numerical Methods in Fluids*. This method addresses the critical issue of non-smooth curvature distributions that generate spurious capillary waves in surface tension-driven flows. The proposed approach features a VPMC-based iterative procedure that eliminates high-frequency oscillations from curvature fields while preserving low-frequency characteristics and ensuring volume conservation, with tight coupling between curvature smoothing and VOF field adjustments. The method permits significantly larger time steps compared to conventional approaches, with demonstrated stability improvements of at least 3-5 times for equivalent accuracy, and achieves curvature estimation error reduction to approximately 1% compared to pre-smoothing values. The method was validated through 2D and 3D static droplet tests, free oscillation problems, and complex 3D applications including droplet impact onto deep liquid pools, confirming second-order spatial convergence and effective suppression of spurious currents.
- 4) The 13th International Workshop on Ship Hydrodynamics (IWSH) was held in August 2025 in Fukuoka. Yuxiao YANG, a graduate student from SJTU and co-researcher of this project, attended the conference and presented research on high-precision two-phase interface simulation methods based on adaptive mesh refinement. Additionally, Ruoqing Gao, who contributed significantly to this project as a co-researcher from SJTU, will commence postdoctoral research at RIAM, Kyushu University in April 2026, ensuring the continuity of the collaborative research.

国際化推進共同研究概要

〔採択番号〕 25RE-9

タ イ ト ル： Interpretable AI model to predict floating wind turbine wakes and power using CFD and field data

研究代表者： GAO Zhiteng

所内世話人： HU Changhong

研究 概 要：

浮体式洋上風車の後流と出力を高精度予測するためにCFDシミュレーション、現場実測、およびAIモデルの応用を融合したモデルの開発に国際化推進共同研究プロジェクトを立ち上げ、今年度は予定通り実施した。特に、長くて柔軟なタービンブレードと乱流風況場との複雑な相互作用、および超大型浮体式洋上風車の構造安全性と空力性能への影響に関する研究に有望な成果を上げた。関連の成果を国際誌Ocean Engineeringに共著論文として投稿した。

**Interpretable AI model to predict floating wind turbine wakes and power using
CFD and field data**

Zhiteng Gao

Institute of Energy Science, College of Engineering, Shantou University, China

This collaborative research project between RIAM at Kyushu University and the Institute of Energy Science, College of Engineering, Shantou University was launched in 2025. Its primary objective is to develop interpretable artificial intelligence models capable of accurately predicting the wake effects and power output of floating wind turbines through the integration of high-fidelity computational fluid dynamics (CFD) simulations and real-world field measurement data. By systematically combining data-driven learning strategies with rigorous physics-based modeling, the project seeks to significantly enhance prediction accuracy, improve model generalization under complex offshore conditions, optimize turbine design and operational control strategies, and ultimately reduce the Levelized Cost of Energy while improving long-term energy reliability and system resilience.

The research was initiated to address the unique wake interactions and dynamic responses of floating wind turbines (FWTs), which differ fundamentally from those of onshore and fixed-bottom offshore systems due to platform motion and complex marine atmospheric conditions. Since 2025, the collaboration has focused on developing interpretable physics-informed AI models that integrate CFD simulations with field measurements to improve wake evolution and power output predictions. Building on this foundation, advanced techniques such as physics-informed neural networks (PINNs) have been incorporated to ensure physical consistency and generalization capability while capturing multi-turbine interactions, platform dynamics, and atmospheric turbulence effects. These AI-enhanced frameworks further strengthen predictive robustness and provide technical support for the optimal design and efficient operation of floating wind turbines, contributing to cost reduction and improved energy performance.

In 2025, Zhiteng Gao and his co-researchers focused on investigating the complex interaction between long, flexible turbine blades and the ambient flow field, particularly its effects on the structural safety and aerodynamic performance of ultra-large offshore wind turbines. An advanced ALM–GEBT–FMD aerodynamic modeling framework was established to balance high-fidelity simulation accuracy with computational

efficiency, thereby enabling systematic parametric studies and engineering-scale applications. Using this coupled aeroelastic approach, a comprehensive aeroelastic and wake analysis was conducted on a 15 MW offshore wind turbine under both uniform inflow and wind shear conditions. The results show that wind shear and blade deformation amplify unsteady loads, underscoring the necessity of transient analysis for the safety assessment of large-scale offshore wind turbines.

Based on these research outcomes, Mr. Xiaohang Qian, a co-researcher of A.P. Zhiteng Gao, prepared the manuscript entitled “Aeroelastic and Wake Analysis of a 15 MW Offshore Wind Turbine under Different Inflow Conditions.” The paper has been submitted to journal *Ocean Engineering* and is currently under revision, with final acceptance anticipated. This research was financially supported by the RIAM research project and co-authored with Prof. Changhong Hu of Kyushu University.

国際化推進共同研究概要

〔採択番号〕 25RE-10

タイトル: Combining first principles molecular dynamics, free energy sampling and machine learning to understand the III-nitride semiconductors growth

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研究概要:

窒化ガリウム (GaN) などのIII族窒化物半導体は、広いバンドギャップを有する材料であり、光・電子デバイスや次世代パワーエレクトロニクスへの応用が期待されている。特にGaNは、高い絶縁破壊電圧と高温下での優れた構造安定性を有するため、パワーデバイスの実現に向けた有力候補である。しかしながら、エピタキシャル成長したGaN薄膜の結晶品質が十分でないため、電子デバイス材料としての実際の特性は理論値を下回っている。本研究では、第一原理分子動力学法を用い、GaNエピタキシャル成長中に生じる複雑な原子反応のメカニズムを解明した。具体的には、再構成表面下層の点欠陥の固体内拡散と、点欠陥直上のNH₂吸着分子の表面拡散の相関を解析し、点欠陥を含む表面系におけるGaN成長素過程を明らかにした。

Combining first principles molecular dynamics, free energy sampling and machine learning to
understand the III-nitride semiconductors growth

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The III-nitride semiconductors, and in particular gallium nitride (GaN), are wide bandgap materials of special interest for applications in optical and electronic devices and in next-generation power electronics. The case of GaN is rather peculiar because its properties make this compound a premier material in the field of power electronics, due to its high breakdown voltage and high structural stability at high temperatures. However, its actual performance in actual devices is below expectations. This is mainly due to the poor quality of epitaxially grown GaN thin films, resulting in defects that translate into performance degradation. To unravel the microscopic origin of this macroscopic undesired effect, we need methods and techniques able to get a precise insight into the mechanisms realized by complex atomic reactions occurring during the epitaxial growth. In the framework of our consolidated collaboration, we investigated adsorption and dissociation processes of gas-phase molecular precursors on GaN surfaces using first-principles molecular dynamics (FPMD) simulations enhanced by free energy sampling methods [1].

Despite the insightful information obtained to date, further studies are required because GaN often contains a high density of defects generated during epitaxial growth. In this study, to deepen our understanding of these issues, we used FPMD to investigate the evolution and diffusion of defects at both the experimental growth temperature (1300 K) and room temperature. We found that defect complexes of Ga and N near the growing surface are not static, point-like sites at high temperatures; instead, they exhibit high mobility of Ga vacancies around nearby N vacancies. Moreover, an NH_2 adduct—a precursor building block—remains stably adsorbed on the surface even in the presence of such defects, suggesting that GaN growth proceeds stably at 1300 K despite these imperfections. When the temperature falls below 1100 K, the diffusion of these complex defects is suppressed, suggesting that they are easily incorporated and remain within the crystal structure.

[1] M. Boero, K. M. Bui, K. Shiraishi, K. Ishisone, Y. Kangawa, A. Oshiyama, *Appl. Surf. Sci.* 599 (2022) 153935. <https://doi.org/10.1016/j.apsusc.2022.153935>