

Study on edge plasma transport
in island divertor configuration in Heliotron J

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Abstract

This study aims to elucidate edge plasma transport in the island divertor configuration. The edge plasma is influenced by the core plasma, impurities from the solid wall and 3D transport induced by magnetic islands in the island divertor configuration. The fluctuation characteristics within the magnetic island were investigated using a Langmuir probe. Additionally, the phenomenon of spontaneous changes in the island divertor configuration was examined. An imaging bolometer was applied to measure the radiation distribution.

The summary of each chapter is as follows.

Chapter 1 provides an overview of the energy challenges and the significance of fusion power generation. The edge plasma is need to be controlled to maintain a high temperature plasma in the core region of a magnetically confined fusion plasma. The divertor plays a critical role in preventing impurities, sputtered from the solid wall upon contact with the plasma, from penetrating the core plasma. The island divertor employed in low magnetic shear stellarator/heliotron devices. The concept of the island divertor involves utilizing magnetic islands formed at rational surfaces in the plasma periphery, in contact with the solid wall, to function as a divertor.

Chapter 2 discusses the tools used for measuring edge plasma, specifically the Langmuir probe, imaging bolometer, and AXUV. The measurement principles of the Langmuir probe are described in detail. Additionally, data analysis methods, including fast Fourier transform (FFT) and statistical analysis, are also discussed.

Chapter 3 provides an overview of the Heliotron J device. It begins by describing the general characteristics of the device and the properties of its magnetic configuration. The Heliotron J device employs a helical-axis heliotron configuration, aiming to achieve a balance between good particle confinement and MHD stability. The device's magnetic configuration is adjustable, allowing for the alteration of current ratios in each coil. The chapter also details the heating systems and diagnostic tools used in this study on the Heliotron J device.

Chapter 4 describes the development of an imaging bolometer to measure the plasma radiation distribution. During the NBI startup experiment, the temperature in the region corresponding to the plasma core increased, while the temperature in the region where no radiation was expected remained unchanged. Comparison with radiation simulations using the EMC3-EIRENE code showed that, although there were some minor differences, the overall trends in the upper and lower regions were consistent. The increase in thin-film temperature was found to correlate with the AXUV measurement. These results suggest that IRVB measurements are feasible on Heliotron J.

The distribution of the temperature increase changes at different configurations of the magnetic field structure. In order to investigate the relationship with the magnetic island structure, it is necessary to compare the results with the radiation distribution simulation by EMC3-EIRENE. Radiation distribution measurements that are not affected by noise due to ECH and magnetic fields will be performed in the future. Higher sensitivity of IRVB and measurements in ECH plasmas are also needed.

Chapter 5 discusses the non-uniformity of fluctuations within the magnetic island. Experiments were conducted under configurations with and without the island to clarify the impact of the magnetic island. Measurements were performed using a movable multi-point Langmuir probe.

The presence of the magnetic island was first confirmed by observing the localized attenuation and delay in the propagation of thermal pulses at the position of the magnetic island in a vacuum. The electron density in the magnetic island region is consistently high and nearly constant in the steady-state plasma distribution. Additionally, the electron temperature decreases near the wall, while it is constant inside the magnetic island.

The magnetic island influences the mechanisms of turbulence, altering the normalized fluctuation intensity, statistical characteristics, fluctuation diffusion, and fluctuation-driven transport. The normalized density fluctuation intensity increases from the inner to the outer region of the magnetic island, while the normalized potential fluctuation intensity is enhanced in parts of the island. Intermittent transport, as indicated by skewness and kurtosis values, is suppressed within the island,

where PDFs are close to Gaussian. However, outside the island region, intermittent transport is enhanced, and the PDF deviates from Gaussian. The density fluctuation is more pronounced at the outer boundary, with the direction of fluctuation spreading reversed at the boundary of the magnetic island. The turbulence driving term remains constant within the island but increases significantly at the outer boundary. In contrast, the turbulent spreading term is negative at both boundaries, peaking at the center of the island. The poloidal electric field fluctuation peaks inside the magnetic island, and the fluctuation-driven particle flux shows peaks in both the center and the outer boundary of the island. These findings suggest that various fluctuation mechanisms coexist and generate spatially modulated transport even within the structure of an edge magnetic island.

In Chapter 6, the changes in the edge magnetic field structure and spontaneous oscillation due to plasma current are discussed. The transition from the divertor to limiter configuration has been observed in Heliotron J when the co-direction plasma current increases the rotational transform at the configuration of the rotational transform profile close to the $4/8$ rational surface. Observations using AXUV and divertor probes revealed changes in the plasma profile, indicating an expansion of the confinement region, as well as the shift of the divertor footprint, associated with the transition from the divertor configuration to the limiter configuration. These changes in the edge magnetic structure qualitatively agree with calculations using a field line tracing code based on the assumption of the on-axis current. Furthermore, plasma currents at which the limiter configuration transition was observed in some magnetic configurations with different rotational transforms were consistent with the qualitative trends predicted by the calculations, supporting the idea that the plasma current modifies the edge magnetic structure.

At the time of the magnetic structure transition, spontaneous oscillations with a toroidal mode number $n = 1$ were observed at around 2 kHz. These oscillations were detected in various diagnostics, including electron density, plasma current, and magnetic fluctuations. Although the comparison with the calculations, assuming the on-axis current, was qualitative, divertor probe measurements suggested that the plasma could oscillate between the divertor and limiter configurations. Additionally, AXUV measurements indicated that the plasma profile in the edge region

was oscillating. The transition to the limiter configuration would alter the transport in the edge region, causing the edge plasma to oscillate as a transient response.

Chapter 7 concludes the thesis.

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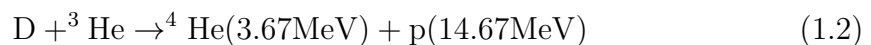
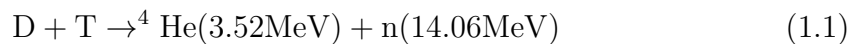
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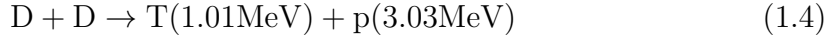
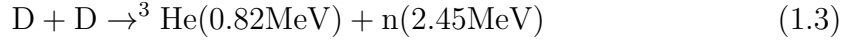
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Chapter 1 Introduction

1.1 Fusion energy

In modern society, we consume vast amounts of energy. Moreover, with population growth and the modernization of developing countries, it is expected that energy demand will increase even further in the future. Since the Industrial Revolution, humanity has relied heavily on fossil fuels as an energy source, but in recent years, issues such as environmental pollution caused by greenhouse gases from combustion and the depletion of resources have emerged. Until now, nuclear power generation through nuclear fission has been used as an alternative energy source to fossil fuels, but it comes with inherent problems, such as the handling of high-level radioactive waste from spent fuel, as well as the risk of the spread of radioactive materials due to accidents, disasters, or terrorism. In particular, in Japan, the Tōhoku earthquake and the resulting tsunami that occurred in March 2011 led to disasters at the Fukushima Daiichi Nuclear Power Plant, including a core meltdown and the spread of radioactive materials. As a result, concerns about nuclear power plants have grown, making it difficult to continue relying on nuclear power as a primary energy source. On the other hand, renewable energy sources such as solar power and wind power are being increasingly adopted. However, since their output is influenced by weather conditions and the amount of energy generated per unit area is low, it is challenging for them to serve as base-load power sources. Nuclear fusion power is being highly anticipated as a solution to these issues. In nuclear fusion reactions, atomic nuclei with small mass numbers collide and fuse, and the energy corresponding to the mass defect m that occurs during this process is obtained according to $E = mc^2$. The reactions that are currently considered feasible for use in fusion reactors are as follows:





As can be understood from Equations (1.1-1.4), nuclear fusion reactions do not emit greenhouse gases, such as carbon dioxide, during the reaction process. Additionally, fusion reactors, by their very nature, do not run the risk of runaway reactions, and the radioactive waste produced is not at the high levels of concern associated with nuclear fission power plants. Moreover, unlike solar and wind power, nuclear fusion is not affected by weather conditions, making it a viable candidate for use as base-load power. Currently, the use of the reaction in Equation 1.1 is anticipated for achieving nuclear fusion power. Tritium (T), which serves as the fuel for this reaction, is almost non-existent on Earth. However, it can be synthesized from lithium, which is abundant in seawater, through the following reaction. Therefore, concerns about fuel depletion are minimal.



Therefore, the realization of nuclear fusion power holds the potential to solve today's energy problems. Research aimed at making nuclear fusion power a reality is being conducted around the world.

1.2 Magnetic confinement plasma

In order to achieve nuclear fusion, as indicated by the Lawson criterion [1], it is necessary to confine the nuclei of deuterium and tritium in a high-temperature and high-density state for a sufficiently long time. Two methods have been proposed to achieve this state: inertial confinement and magnetic confinement. The inertial confinement method involves enclosing deuterium and tritium in a spherical container (pellet) a few millimeters in diameter and irradiating the pellet with a powerful laser. The high-temperature, high-density plasma generated by this process triggers nuclear fusion explosively before dissipating.

The magnetic confinement method uses the property of charged particles, which move along magnetic fields due to the Lorentz force, to prevent the plasma from dissipating and maintain the high-temperature, high-density plasma. To confine particles, a method was conceived in which magnetic field lines are shaped into a torus to eliminate the ends of the magnetic field lines and confine the plasma. However, in a simple torus structure, the magnetic field gradient between the inner and outer parts of the torus causes charge separation between electrons and ions. This separation of electrons and ions generates an electric field within the plasma, which leads to outward transport of the plasma via $E \times B$ drift, making it impossible to confine the plasma. As a solution, a poloidal magnetic field is added to the toroidal magnetic field, twisting the magnetic field lines into a helical shape. To generate this poloidal magnetic field, the method of passing current through the plasma is known as the tokamak system, while the method of generating it through twisted external coils is called the helical/stellarator system.

Tokamak devices have a fundamentally axisymmetric structure, and they are ahead of helical devices in terms of plasma temperature, density, and other performance measures. In JT-60U, the necessary temperature, density, and confinement properties were achieved to attain an energy multiplication factor of $Q = 1$ in deuterium plasma discharges [2]. The ITER, currently under construction in France with the goal of beginning operation in 2034 [3], also employs the tokamak method. However, the challenges include the difficulty of steady-state operation due to the need to induce plasma current, and the necessity to avoid a disruption, a phenomenon where the plasma current suddenly ceases and energy is released in a short period.

Helical/stellarator devices, on the other hand, generate the magnetic field necessary for plasma confinement by passing current through twisted coils [4–6]. Although this results in a more complex structure for both the plasma and the coils/vacuum vessel, the system offers the advantages of no need to induce plasma current, thereby avoiding disruptions, and making steady-state operation easier to achieve. At Kyoto University, research has been conducted using a magnetic field configuration called the Heliotron, a type of helical axis configuration.

1.3 Edge plasma

In magnetic confinement fusion, the core plasma consists of magnetic flux surfaces that are confined without intersecting the solid wall within the separatrix as shown in Fig. 1.1. Outside this boundary lies the scrape-off layer (SOL), where magnetic field lines intersect with the solid wall. In the SOL, particularly near the divertor plate, the plasma is sometimes referred to as divertor plasma. Particles and heat from the core plasma are transported across the separatrix into the SOL via cross-field transport. Within the SOL, particles and heat flow predominantly along magnetic field lines and contact the divertor plate [7].

In this study, the edge plasma encompasses the region from the vicinity of the separatrix to the SOL and divertor plasma.

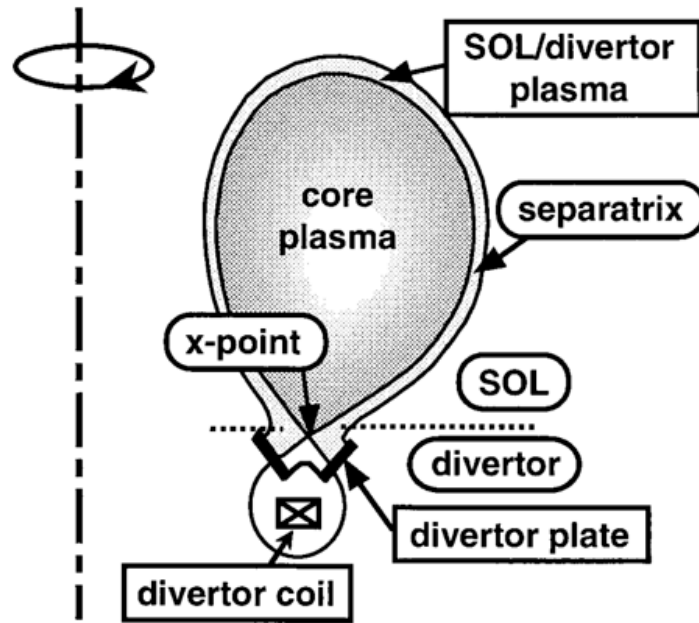


Figure 1.1: Cross section view of Tokamak plasma with divertor configuration [7]

The edge plasma, which serves as the boundary condition for the core plasma, plays a critical role in confinement performance and regulates the entry of impurities from the plasma-facing walls into the core region. It also influences, and is influenced by, factors such as the exhaust of helium ash, heat removal, and hy-

drogen recycling at plasma-facing walls, which are essential for fuel cycle processes. Particularly in maintaining stable, long-duration fusion burn, a deep understanding and effective control of edge plasma characteristics—such as high plasma heat flux, plasma-surface interactions, and particle transport—are crucial.

1.3.1 Plasma transport in SOL

Diffusive transport

In the scrape-off layer (SOL), magnetic field lines intersect with the solid walls, leading to changes in physical quantities along the magnetic field direction as a result of plasma-wall interactions. When the SOL thickness is considerably smaller than the minor radius of the plasma, the SOL can be approximated as a two-dimensional slab, with the radial direction as x and the direction along magnetic field lines as z , assuming plasma uniformity in the direction perpendicular to these. In Figure 1.2, the thickness corresponds to x .

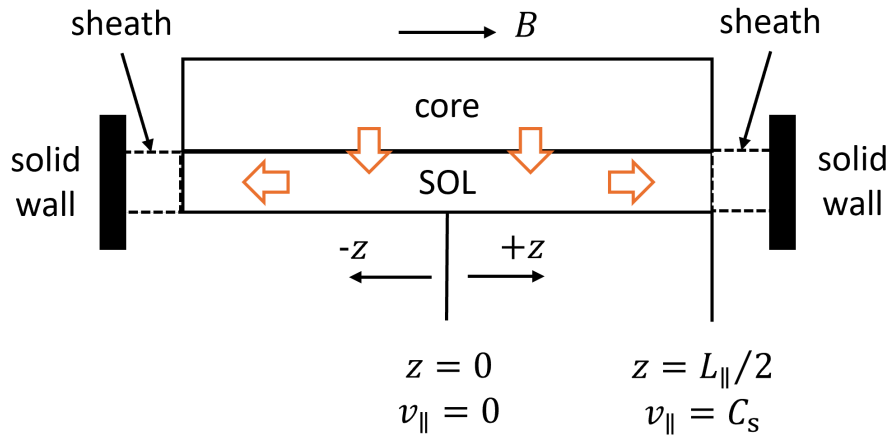


Figure 1.2: Model of SOL terminated in sheath

The schematic profile of plasma parameters along magnetic field lines is illustrated in Figure 1.3. This figure represents the scenario where strong hydrogen recycling occurs near a limiter or divertor target plate, with neutralized hydrogen atoms and molecules being ionized, redirected towards the target, and undergoing repeated neutralization processes [8]. Here, C_s denotes the ion sound speed.

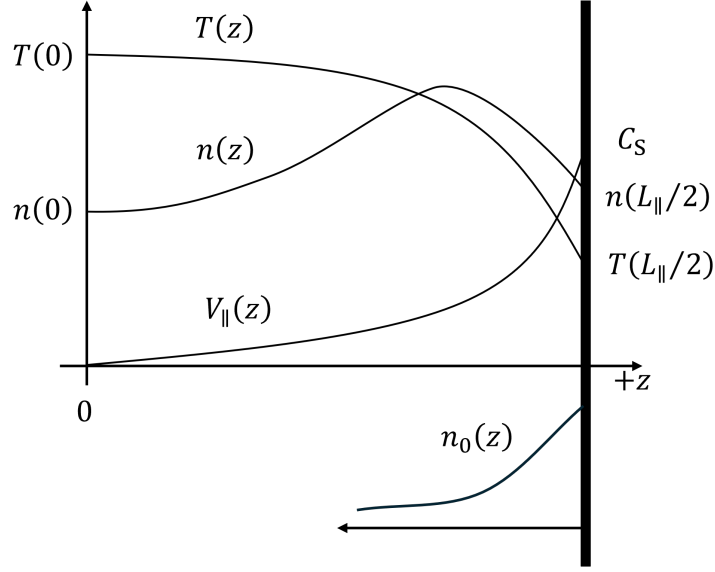


Figure 1.3: Profile of plasma density, temperature, and flow velocity along magnetic field lines near the target plate [8].

The density profile perpendicular to magnetic field lines is determined by the balance between the cross-field particle flux (Equation 1.7) and the particle flux toward the divertor plate (Equation 1.8), represented by the continuity equation (Equation 1.9). Here, $D_{\perp}$ denotes the cross-field diffusion coefficient.

$$\Gamma_{\perp} = -D_{\perp} \frac{dn}{dr} \quad (1.7)$$

$$\Gamma_{\parallel} = nC_s \quad (1.8)$$

$$-\frac{d}{dr} \left[D_{\perp} \frac{dn}{dr} \right] = \frac{nC_s}{L/2} \quad (1.9)$$

Assuming $D_{\perp}$ and C_s are radially uniform, Equation 1.9 yields:

$$n(r) = n(0) \exp \left(-\frac{r}{\lambda} \right) \quad (1.10)$$

where

$$\lambda = \left(\frac{D_{\perp} L/2}{C_s} \right)^{1/2}. \quad (1.11)$$

According to Equation 1.10, the radial density profile in the SOL plasma decays exponentially with a characteristic length λ . However, observations have revealed

that the plasma density gradient near the last closed flux surface (LCFS) differs from that in regions farther away, indicating that the exponential form of Equation 1.10 cannot fully represent the density profile in the SOL. Figure 1.4 shows the radial density distribution observed in the SOL of the Alcator C-Mod tokamak [9]. Relatively high plasma density extends up to the vicinity of the first wall, suggesting the influence of non-diffusive transport on this density profile formation.

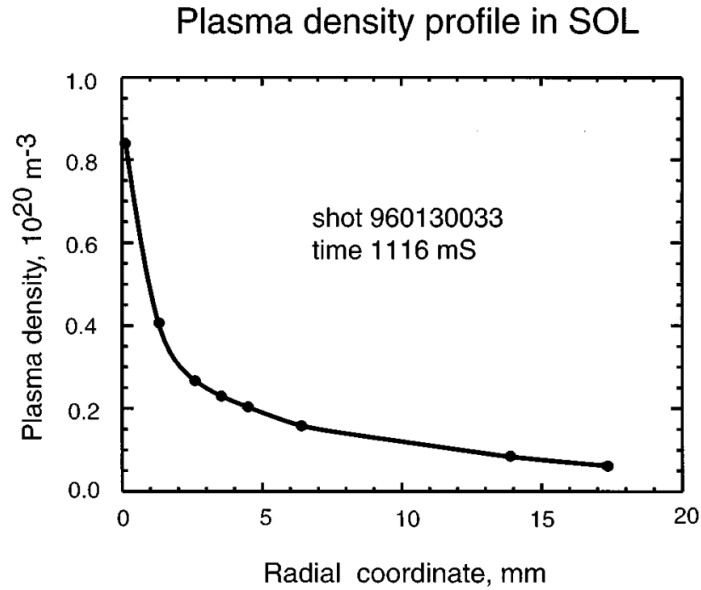


Figure 1.4: Radial density profile of SOL plasma in the Alcator C-Mod tokamak. The horizontal axis indicates the radial distance outward from the LCFS [9].

Non-diffusive transport

Blob Consider a plasma object, or blob, as shown in the Figure 1.5. When a radial force F acts on the blob, the $F \times B$ drift causes electrons and ions to drift in opposite directions, leading to polarization within the plasma blob. The polarization electric field, combined with the toroidal magnetic field, results in an $E \times B$ drift, causing the plasma blob to be transported toward the first wall [10].

Edge localized mode In H-mode discharges, when the pressure gradient near the LCFS becomes steep, an instability known as Edge Localized Mode (ELM)

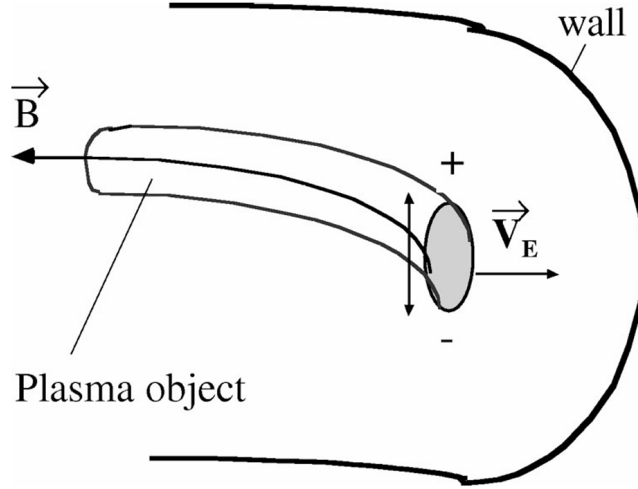


Figure 1.5: Plasma blob polarization and associated drift result in outward motion of plasma structure in the tokamak boundary [10].

occurs, periodically releasing heat and particles. As illustrated in Figure 1.6, the plasma released by ELMs exhibits a filamentary structure [11]. The significant energy outflow associated with ELMs can severely impact the durability of the divertor plates and overall plasma performance, making it essential to control and mitigate the energy release. Methods such as pellet injection, resonant magnetic perturbation application, and operating in regimes with smaller ELM amplitudes have been developed as effective strategies for ELM control.

Drift Particle and heat fluxes in the edge region are influenced by $E \times B$ drift as well as curvature and ∇B drifts. Figure 1.7 provides an overview of the impact of these drifts in the SOL of both tokamaks and stellarators, specifically Wendelstein 7-X. The drifts alter the heat flux distribution on divertor targets based on the toroidal magnetic field direction, affecting heat load patterns on the targets [12].

Impurity transport

Sputtering and evaporation from the first wall and divertor plates release impurity particles into the plasma. Once released, these impurity particles are ionized in the SOL plasma. The resulting ions then travel along magnetic field lines through the

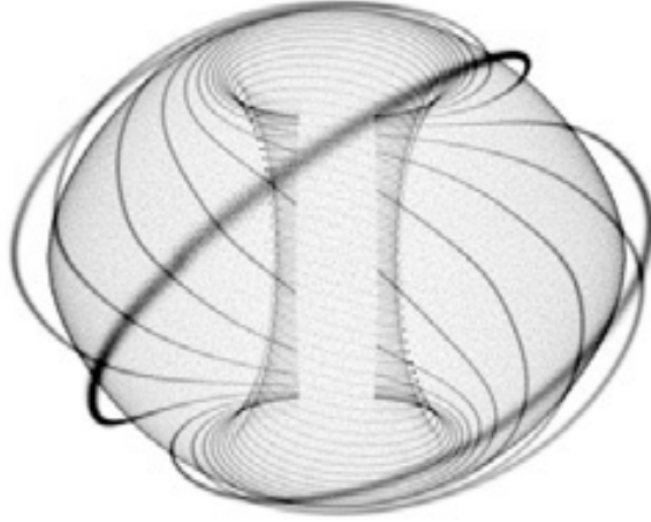


Figure 1.6: Spatial structure of an ELM in the MAST tokamak plasma geometry [11].

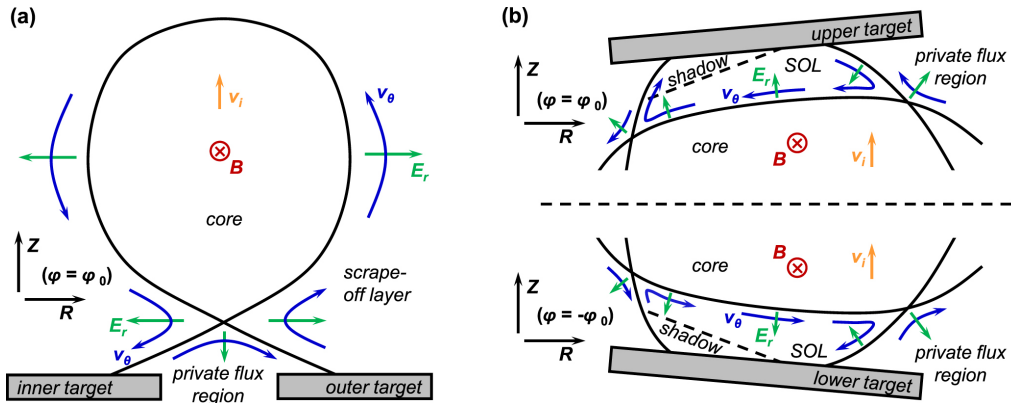


Figure 1.7: Schematic depiction of radial electric fields E_r and the resulting poloidal drift flows v_θ in (a) lower-single-null tokamak geometry and (b) the upper and lower island divertor geometry of W7-X in the low-iota configuration. The magnetic field B is assumed to point into the page in each case. Correspondingly, the direction of ion ∇B and curvature drift v_i is upward [12].

SOL toward the divertor region. If these ions are transported sufficiently across the magnetic field lines before reaching the divertor plates, they may cross the LCFS

into the core region, where they cool the core plasma.

In the SOL, impurity particles experience forces driving them either toward the divertor plates or toward the core region. Figure 1.8 illustrates the parallel forces acting on impurity ions, with each force described as follows [13].

- $FF \equiv m_z(v_i - v_z)/\tau_s$ is the friction force on the impurity ions moving with fluid parallel velocity v_z exerted by the background ions moving with fluid parallel velocity v_i . τ_s is the stopping time.
- $FE \equiv ZeE$ is the straightforward, and fundamental electrostatic force exerted by the parallel electric field E in the SOL.
- $FeG \equiv \alpha_e(d(kT_e)/ds)$ is the electron temperature gradient force, where α_e is the coefficient of order Z^2 .
- $FiG \equiv \beta_i(d(kT_i)/ds)$ is the ion temperature gradient force, where β_i is the coefficient, also of order Z^2 .

Measuring the radiation from impurities is fundamental to understanding and controlling phenomena such as radiative collapse and divertor detachment. Since radiation primarily occurs outside the LCFS, extrapolation based on assumptions about magnetic flux surfaces is not feasible, making multidimensional measurements essential. The InfraRed imaging Video Bolometer (IRVB) is employed as a diagnostic tool capable of multidimensional radiation measurements. As shown in Figure 1.9, modeling calculations and IRVB measurements in neon puff experiments in LHD have demonstrated qualitative agreement [14].

1.3.2 Divertor

Role of divertor

In both tokamak and helical magnetic confinement fusion reactors, a critical component is the divertor. From the early stages of fusion research, the issue of plasma contacting the containment vessel, leading to sputtering-induced erosion of the vessel and contamination from impurities that degrade the plasma, has been a significant concern. One of the methods devised to prevent direct contact between

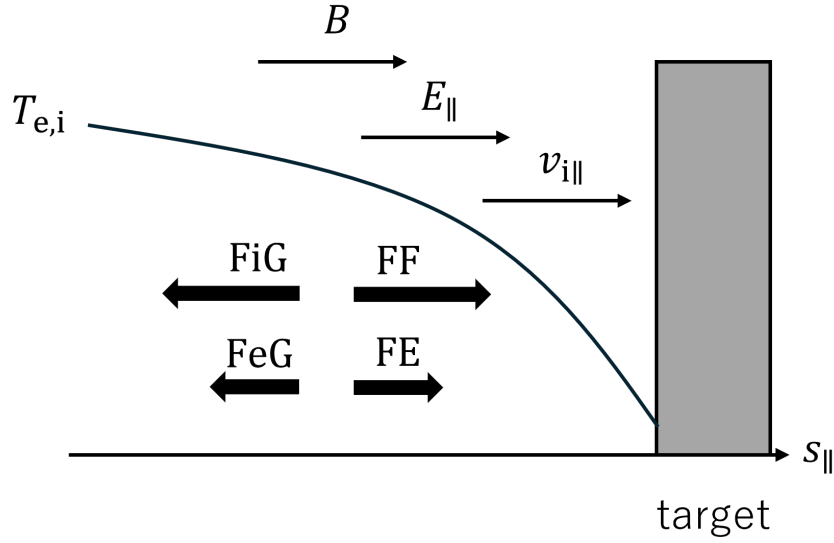


Figure 1.8: The principle parallel forces acting on impurity ions in the SOL. The friction, FF, and electrostatic, FE, forces are usually toward the target while the electron- and ion- temperature gradient forces, FeG, FiG, are usually away. Typically $|FF| > |FE|$, $|FiG| > |FeG|$ [13].

the plasma and the vacuum vessel wall is the limiter. The limiter configuration, as shown in Figure 1.10(a) [15], consists of structures that protrude inward into the vacuum vessel, limiting the plasma's position within the vessel and creating a separatrix that divides the confinement region from the Scrape-Off Layer (SOL). This method prevents the vacuum vessel wall from being directly exposed to the high-temperature plasma. However, while the limiter shields other parts of the vessel from plasma, the limiter itself remains in direct contact with the plasma. This allows impurities generated from the limiter to easily enter the core plasma. Additionally, the limiter is subjected to a significant thermal load. To address these issues, a method was developed where the separatrix is formed not by solid structures but by magnetic fields. This method is what is now referred to as the divertor.

In divertor configurations (Figure 1.10(b) [15]), this is realized by magnetic field topologies that direct the open field lines into remote areas which are sufficiently distant from the confined plasma and are equipped with high-heat-flux targets that

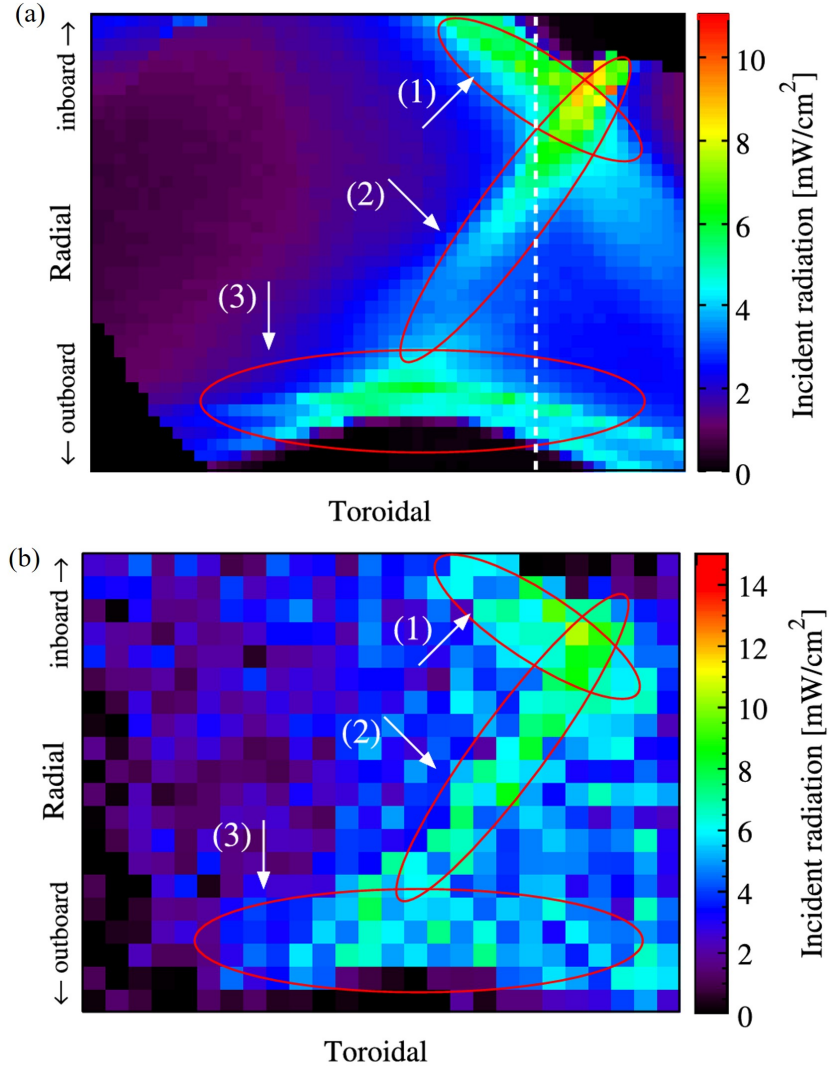


Figure 1.9: (a) The synthetic image of the modeling calculation result with the neon puff. (b) Two-dimensional radiation image measured by the 6.5-U bolometer with the neon puff. (1) and (2) are X point traces. (3) is a plasma edge region [14].

can withstand the high heat and particle loads. The confined plasma does not touch the walls and the magnetic topology of the divertor configuration guides the edge plasma towards the target plates.

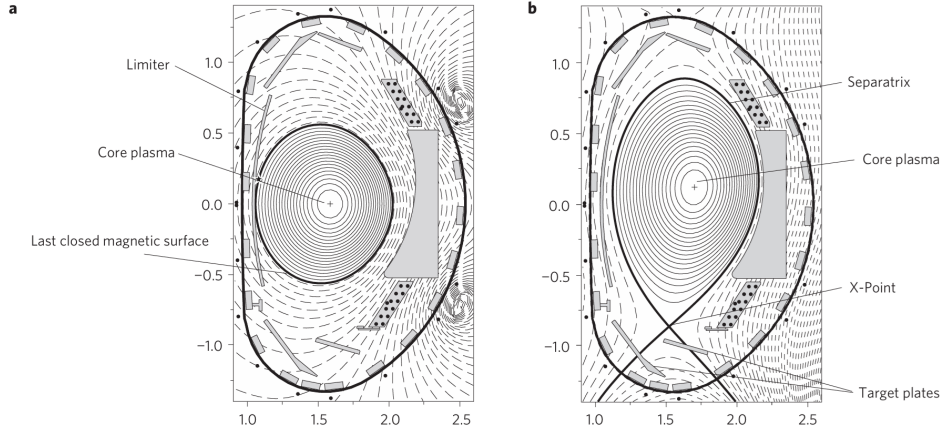


Figure 1.10: (a) Limiter and (b) divertor configurations in Tokamak devices [15]

Divertor type

Several types of divertors have been devised. In tokamak devices, the poloidal divertor (Figure 1.10(b)) is commonly adopted. In a poloidal divertor, divertor coils are installed, and a current is passed in the same direction as the plasma current, forming a separatrix in the shape of a figure-eight to confine the plasma. By placing divertor plates intersecting this separatrix, the plasma can be intercepted without solid materials directly contacting the confinement region.

In helical devices with large magnetic shear, such as the Large Helical Device (LHD), a helical divertor, as shown in Figure 1.11, is employed [16]. The stochastic magnetic field geometry is generated by the helical coil system due to the overlapping of magnetic island chains. Two X-points are created by the helical coils of LHD as shown in figure 1.11(b), and these X-points rotate poloidally when they move toroidally. Beyond these X-points, four divertor legs induced by the stretch of the flux tubes are connected to the divertor target plates.

In contrast, in low magnetic shear helical devices like the Wendelstein 7-AS (W7-AS) and Wendelstein 7-X (W7-X), an island divertor is used. The details of the island divertor will be discussed in section 1.3.3.

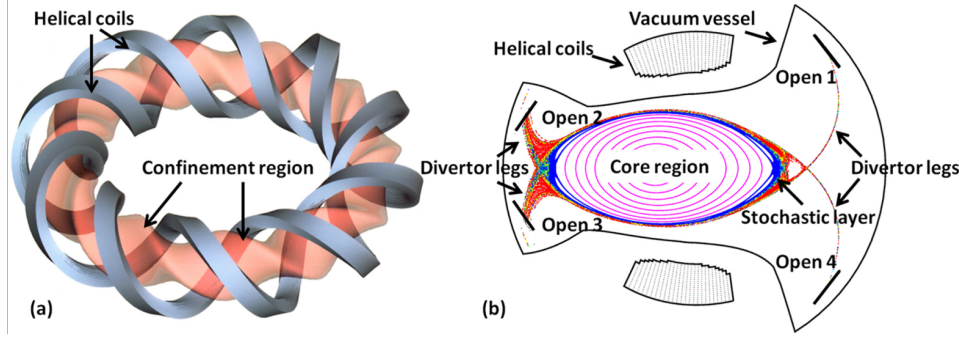


Figure 1.11: Schematic views of the LHD magnetic configuration in the confinement region and the helical coils (a) and poloidal cross section of LHD at the toroidal angle of $\phi = 18^\circ$ (b). [16]

1.3.3 Island divertor concept

Magnetic island

First, the concept of magnetic islands is discussed. In magnetic confinement plasmas, achieving favorable confinement performance requires the formation of nested magnetic flux surfaces. However, magnetic islands, which are magnetic field structures, can be induced by perturbations in the magnetic field arising from the plasma itself or from external sources. To provide a clearer understanding of the magnetic field line trajectories within magnetic islands, the case of a vacuum magnetic field is considered.

The magnetic field lines in a magnetic confinement device follow a helical trajectory along the torus. The rotational transform ι is defined by the angle $\Delta\theta$ through which the magnetic field line advances in the poloidal direction during one full toroidal rotation, as expressed by the following equation:

$$\iota = \frac{\Delta\phi}{2\pi} = \frac{1}{2\pi} \oint \frac{B_\theta R}{B_\phi r} d\phi \quad (1.12)$$

where R, r, θ and ϕ represent the major radius, minor radius, poloidal angle, and toroidal angle, respectively. Normally, due to the presence of magnetic shear ($\iota' = \partial\iota/\partial r$), the rotational transform varies along the minor radius. In Figure 1.12(a), the blue dashed line, black solid line, and red thick line represent the trajectories of magnetic field lines at different minor radius positions, corresponding to

magnetic surfaces on the outer side of the minor radius. Now, suppose a perturbation magnetic field $\tilde{B}_r$ is applied due to some external factor. This perturbation field can be expressed by a Fourier series as $\tilde{B}_r = \sum_{m,n} \tilde{B}_{rm,n} \exp i(m\theta - n\phi)$, where m and n are the poloidal and toroidal mode numbers of the perturbation, respectively. The sources of the perturbation magnetic field could include coil misalignment, external perturbation coils, or plasma instabilities. However, the strength of the perturbation magnetic field is much smaller than the confinement magnetic fields B_θ and B_ϕ , so it does not significantly alter the magnetic field line trajectories. Nonetheless, as shown by the thick arrows in Figure 1.12(b), when the twist of the magnetic field line (solid line) matches the mode numbers of the perturbation field, the magnetic field line constantly experiences the perturbation in the same direction, leading to an amplified displacement of the magnetic field line. Under these conditions, a magnetic island forms on the magnetic surface satisfying $\iota = n/m$. At point A in Figure 1.12(b), the magnetic field line is displaced outward in the radial direction by an outward perturbation magnetic field. Due to magnetic shear, the trajectory of the field line bends in the direction indicated by the red thick line. Near point B, the magnetic field line is influenced by an inward perturbation field and tends to return to the original magnetic surface (black solid line). As a result, the displacement in the radial direction becomes finite. For the magnetic field line represented by the blue dashed line, the displacement is in the opposite direction compared to the red thick line. Consequently, a magnetic island forms, as illustrated in the projection plane. It can be observed that the magnetic field lines within the magnetic island trace helical trajectories around the center (O-point) of the island. Additionally, the magnetic island spirals around the torus such that $m\theta - n\phi$ remains constant. The width w of the magnetic island is determined by the balance between the perturbation magnetic field $\tilde{B}_{rm,n}$, the magnetic shear, and other factors, and is given by the following equation:

$$w = 4\sqrt{\frac{r_s \tilde{B}_{rm,n}}{m\iota' B_\theta}} = 4\sqrt{\frac{r_s \tilde{B}_{rm,n}}{n\iota' B_\theta}} \quad (1.13)$$

where r_s is the minor radius position of the O-point [17].

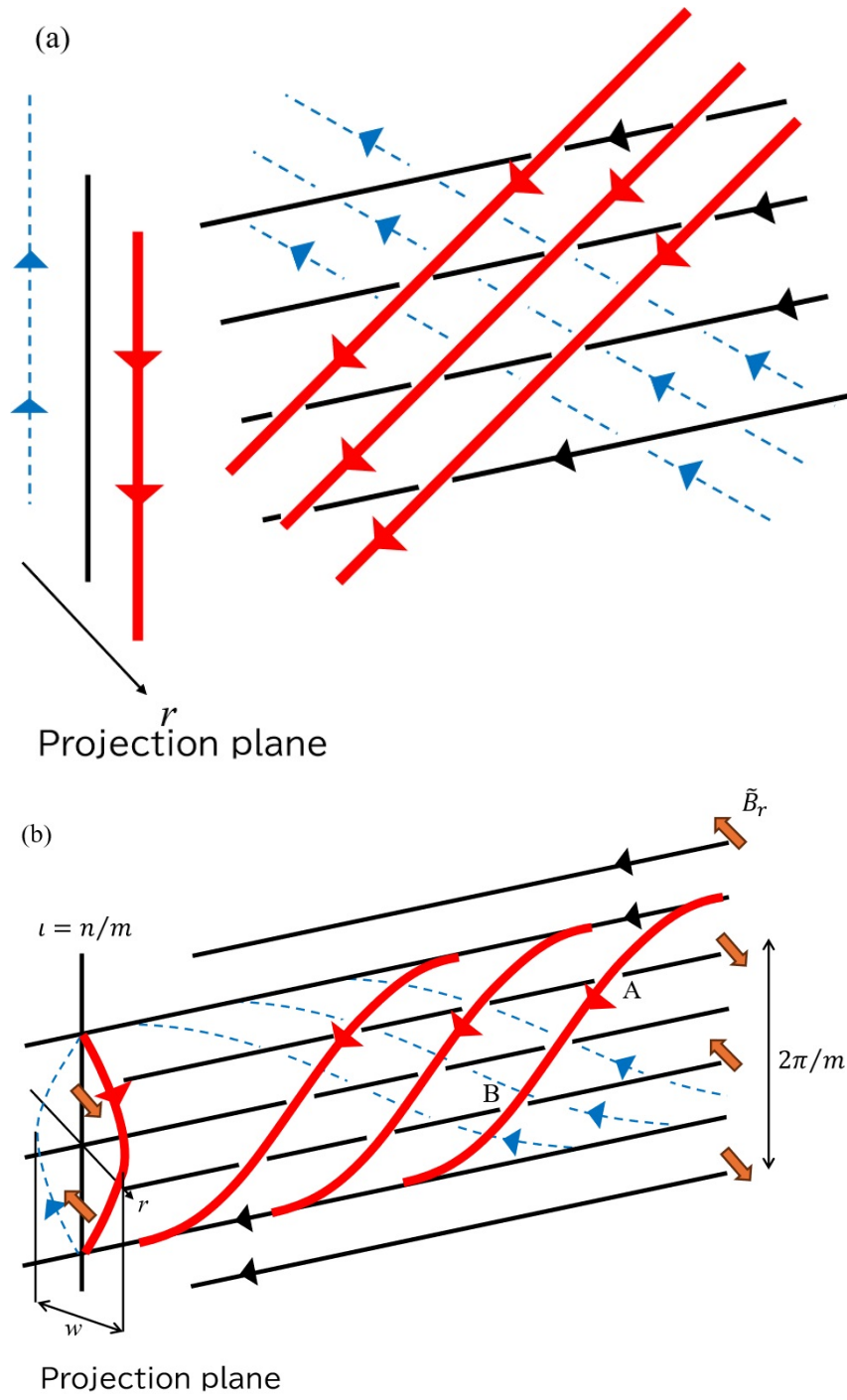


Figure 1.12: Formation of magnetic island

Example of island divertor

Here, two examples of magnetic island divertors are introduced. Figure 1.13 illustrates the case of W7-AS [18]. In this device, a magnetic island with $m/n = 9/5$ exists in the peripheral region. Heat and particles from the plasma that flow across the last closed flux surface (LCFS) into the peripheral magnetic island are transported along the magnetic field lines and directed toward the divertor plates that are positioned adjacent to the magnetic island. Baffle plates prevent gas molecules from leaking out of the divertor chamber, effectively increasing the gas pressure within the chamber. Through the use of a magnetic island divertor, good confinement performance was achieved in the W7-AS device, and a transition to H-mode was observed [19–22]. In the case of the W7-X device, long-duration discharges have been realized by combining the magnetic island divertor with a water-cooling system [23].

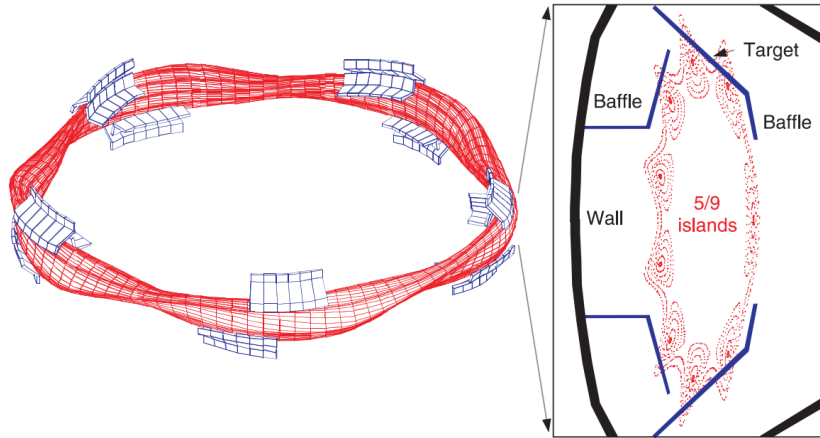


Figure 1.13: Island divertor in Wendelstein 7-AS [18]

Figure 1.14 presents an example of the Local Island Divertor (LID) employed in the Large Helical Device (LHD). In the LHD, a magnetic island with $m/n = 1/1$ is created using additional external coils, and a divertor head is inserted into a portion of the magnetic island to incorporate a pumping function. The implementation of the LID has enabled the achievement of excellent energy confinement [24].

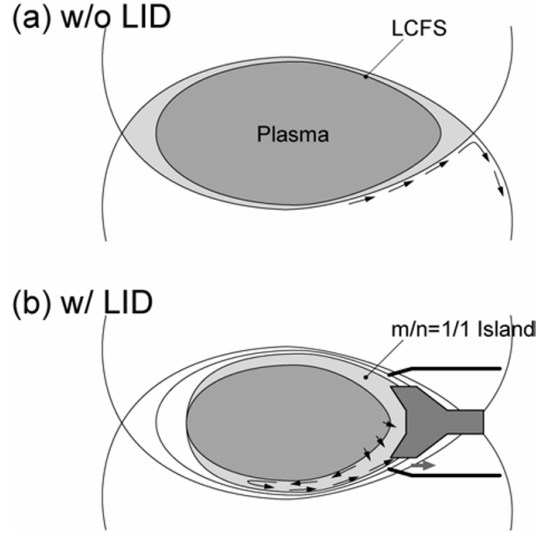


Figure 1.14: Local island divertor in Large Helical Device [24]

1.3.4 Plasma transport in magnetic island

Plasma rotation

In LHD, steady poloidal rotation inside a magnetic island was measured while increasing the width of the magnetic island. Near the O-point of the magnetic island, the plasma rotation becomes zero. In the vicinity of the separatrix of the magnetic island, shear is formed to align with the poloidal rotation of the plasma surrounding the magnetic island. As the width of the magnetic island increases, the zero-rotation region near the O-point expands. Furthermore, when the shear of the poloidal rotation near the X-point increases, poloidal rotation appears near the O-point of the magnetic island. As illustrated in Figure 1.15, when both the width of the magnetic island and the shear at the X-point are large, significant torque is exerted around the magnetic island, which drives the poloidal rotation within the magnetic island [25].

Heat and particle transport

In LHD, an experiment was conducted in which a magnetic island formed by an externally applied perturbation field was targeted by the injection of a TESPEL

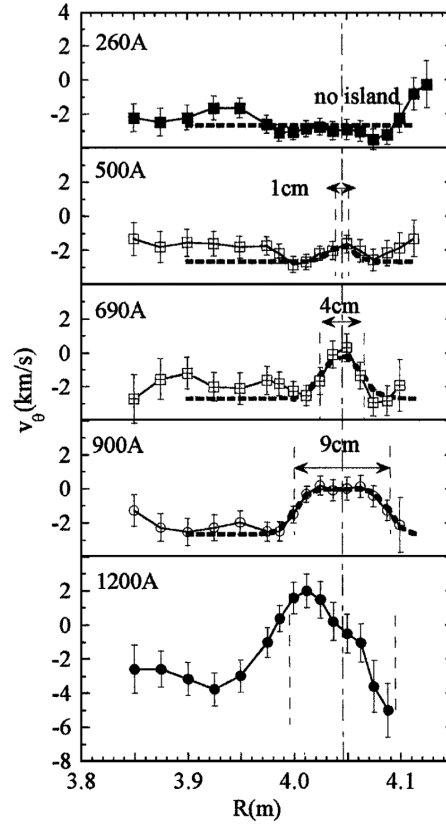


Figure 1.15: Radial profiles of poloidal rotation velocity, for various currents of $n/m = 1/1$ external perturbation coils [25]

(Tracer Encapsulated Solid PELlet) into the X-point of the magnetic island. The ablation of the TESPEL caused cooling of the periphery of the magnetic island, inducing a cold pulse directed toward the O-point. As shown in Figure 1.16, the propagation speed of this cold pulse was slow, and its amplitude decayed rapidly. From the propagation characteristics of the pulse, it was determined that the electron thermal conductivity across the magnetic field lines inside the magnetic island is approximately one-tenth that of the surrounding plasma [26].

Turbulence transport

Since the plasma turbulence is known as one of the major transport players, measurement of turbulence would help to reveal the transport inhomogeneity around a

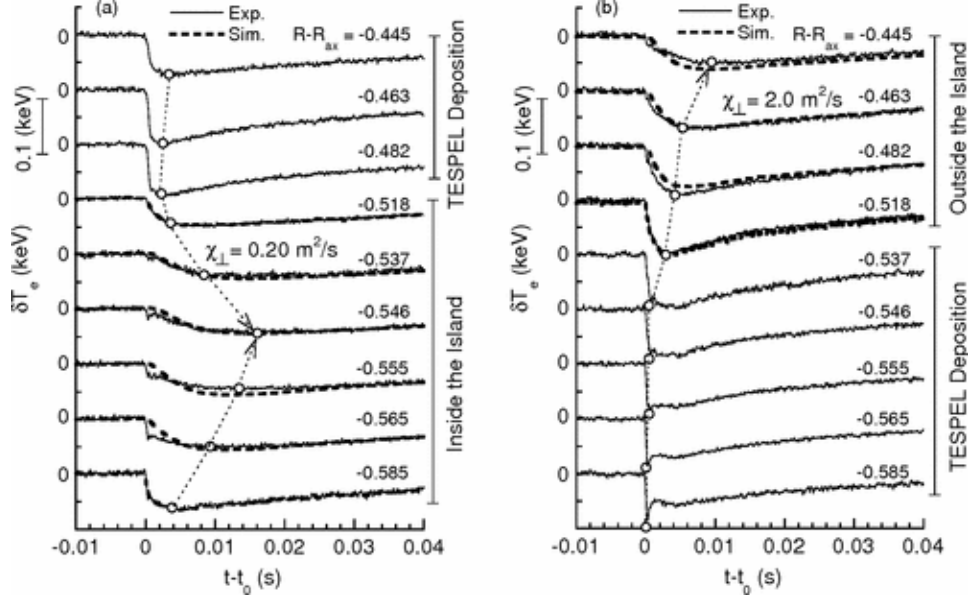


Figure 1.16: The time evolutions of the measured (solid line) and the simulated (broken line) temperature perturbation at different radii [26]

magnetic island.

The lower turbulent fluctuation inside a magnetic island where the pressure profile fattens has been observed consistently in different plasmas. In J-TEXT ($R = 1.05$ m and $a = 0.255$ m) which is a descendant of TEXT, a static $m/n = 4/1$ magnetic island is generated and controlled by applying the RMP field in the edge of Ohmic plasma for study of plasma turbulence around the island. A fast reciprocating multi-tip Langmuir probe array is used to measure various profiles and floating potential fluctuation across the island [27]. Although the size of the island was relatively small (full width ~ 1 cm), it could be identified by the flat temperature profile. The root-mean-square (RMS) amplitude of floating potential fluctuations ($k_{\theta} \sim 1 \text{ cm}^{-1}$) in the frequency band of 30-400 kHz is calculated over the edge region for cases with and without the island. The fluctuation amplitude drops about 30% inside the magnetic island and increases near the island boundary. As shown in Figure 1.17, it was also found that the fluctuation-driven particle transport estimated by the product of ion saturation current and poloidal electric field fluctuations decreases inside the island.

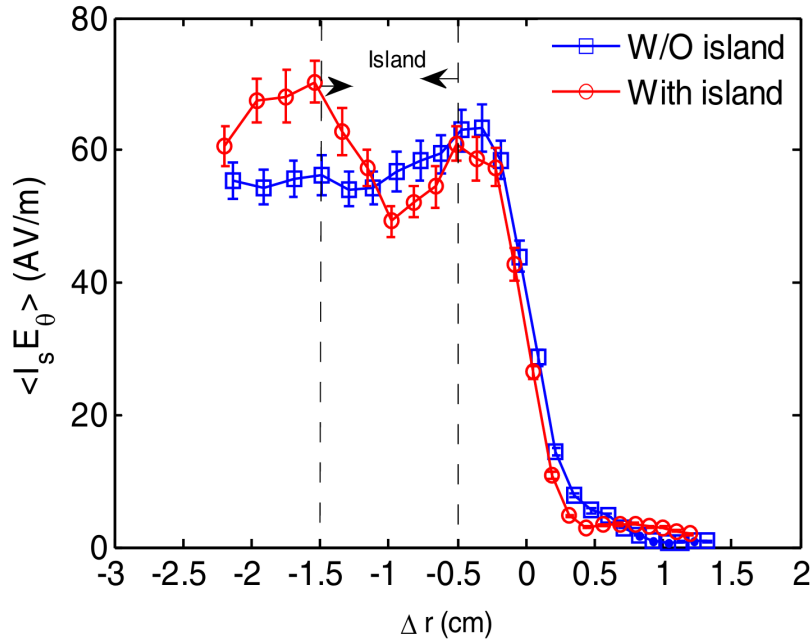


Figure 1.17: Radial profiles of $\langle \delta I_s \delta E_\theta \rangle$ with and without islands in J-TEXT [27].

1.4 Motivations and objectives

Advanced stellarator-heliotron devices, characterized by low magnetic shear, utilize island divertors for controlling heat and particle transport in the peripheral plasma region. Therefore, understanding transport within the island divertor is important. However, as discussed in Section 1.3.4, the transport mechanisms within magnetic islands are complex. In addition, factors such as impurity contamination from solid walls are anticipated, raising concerns about the significant influence of impurities. Consequently, experimentally elucidating plasma transport in island divertors holds great significance.

Heliotron J, a helical device known for its flexible magnetic field control, is capable of realizing various divertor configurations, including leg divertors, island divertors, and limiters, within a single device. This flexibility facilitates direct comparisons between different divertor structures, making Heliotron J particularly suitable for investigating transport in the island divertor.

In this study, we examined the fluctuation characteristics and fluctuation-driven

transport inside magnetic islands in Heliotron J. Additionally, we investigated a phenomenon where the configuration spontaneously transitions from island divertor to limiter, accompanied by significant oscillations in plasma parameters.

1.5 Organization of thesis

This thesis consists of seven chapters.

Chapter 1 describes the background of this study, including fusion plasma research and studies on edge plasmas and divertors in fusion reactors. In particular, studies on magnetic islands and island divertors are described. Chapter 2 describes the measurement tools and analysis methods for the edge plasma used in this study. Chapter 3 describes the characteristics of the magnetic configuration of the Heliotron J system. The heating and measurement systems applied to the Heliotron J system are also described. Chapter 4 describes the application of the imaging bolometer and the radiation distributions in several configurations. Chapter 5 describes the non-uniformity of the fluctuation characteristics inside the edge magnetic island. The fluctuation characteristics were evaluated in terms of fluctuation intensity, statistical properties, turbulence driven/spreading, and fluctuation driven particle flux profiles. Chapter 6 describes changes in the edge magnetic field structure and spontaneous plasma oscillations. Chapter 7 is a summary of this thesis.

Chapter 2 Edge plasma measurement and analysis methods

2.1 Introduction

In this chapter, the edge plasma measurement and analysis methods are described.

2.2 Measurement tools

2.2.1 Langmuir probe

The probe measurement method involves directly inserting electrodes into the plasma, extracting current from the plasma, and analyzing it to determine plasma parameters [17]. The parameters obtained include electron temperature, electron density, spatial potential, and their fluctuations. The electrostatic probe method provides excellent spatial resolution since measurements are taken at the probe's location. Additionally, by using the triple probe method, which will be described later, it also offers high temporal resolution. Moreover, the structure is simple and inexpensive. However, since current is directly drawn from the plasma, it inevitably disturbs the plasma.

In the following sections, the basic single probe method will first be described, followed by an explanation of the triple probe method used in this study.

Single probe method

The circuit configuration of the single probe method is shown in Figure 2.1 A metal electrode is used as the probe, and a variable voltage source, V_p , is connected to it. By varying V_p over a wide range and measuring the corresponding current I_p , the current-voltage characteristics shown in Figure 2.2 can be obtained. These current-voltage characteristics are classified into three regions, with the plasma's

floating potential V_f — where the current is zero — and the plasma space potential V_s as boundaries.

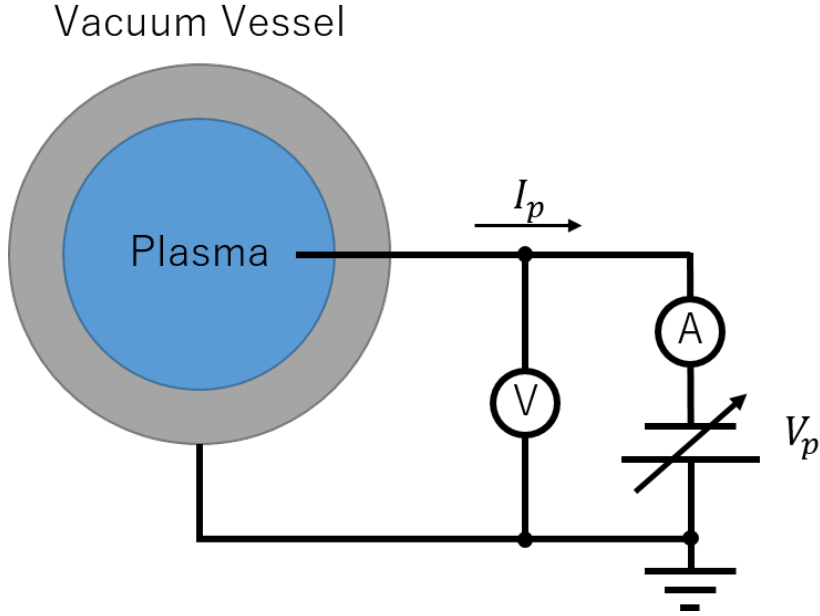


Figure 2.1: circuit configuration of the single probe method

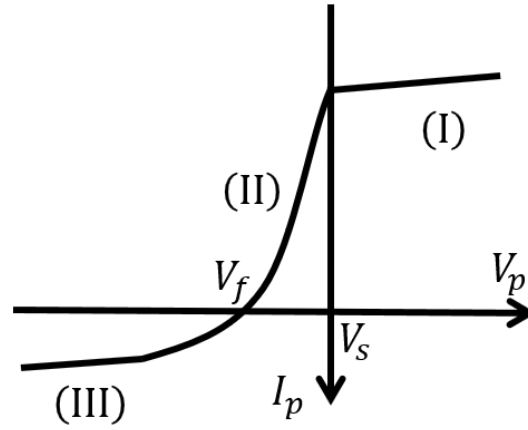


Figure 2.2: the current-voltage characteristics

When the probe is at V_s , it is at the same potential as the surrounding plasma, and the thermal diffusion current caused by the thermal motion of plasma particles

flows into the probe. This can be expressed as follows for both electrons and ions, respectively.

$$I_{e0} = \frac{1}{4} n_e \langle v_e \rangle S = \frac{1}{4} n_e \left(\frac{8kT_e}{\pi m_e} \right)^{1/2} S \quad (2.1)$$

$$I_{i0} = \frac{1}{4} n_i \langle v_i \rangle S = \frac{1}{4} n_i \left(\frac{8kT_i}{\pi m_i} \right)^{1/2} S \quad (2.2)$$

Here, n_e and n_i represent the electron and ion densities, $\langle v_e \rangle, \langle v_i \rangle$ are the average thermal velocities of electrons and ions, S is the probe surface area, k is the Boltzmann constant, T_e and T_i are the electron and ion temperatures, and m_e and m_i are the electron and ion masses. Both I_{e0} and I_{i0} flow into the probe simultaneously. When the electron and ion densities and temperatures are approximately equal, the ratio $I_{e0}/I_{i0} \propto (m_i/m_e)^{1/2} \sim 42.8$, meaning that $I_{e0} \gg I_{i0}$. Therefore, a negative current of $-I_p(V_s) = -I_{e0} + I_{i0}$ flows into the probe. When the probe potential becomes more positive than V_s , ions are repelled from the probe surface while electrons are attracted, forming an electron sheath at the probe surface. As the voltage increases, the electron current increases, as shown in region (I) of Figure 2.2.

If a negative voltage is applied to the probe, making the probe potential more negative than V_s , electrons are repelled from the probe surface, causing the electron current to decrease, while ions are attracted and form an ion sheath, increasing the ion current. However, since the electron current is still larger than the ion current, the apparent current is dominated by the electron current. As shown in region (II) of Figure 2.2, the negative current rapidly decreases with increasing negative voltage, becoming zero at V_f , where the electron and ion currents are equal.

If the probe potential becomes more negative than V_f , the electron current decreases further, while the ion current increases, leading to a positive current flowing into the probe, as shown in region (III) of Figure 2.2.

In regions (II) and (III) of Figure 2.2, where the potential is more negative than V_s , the electron current can be expressed as a function of $V = V_p - V_s$ as follows.

$$I_e(V) = I_{e0} \exp\left(-\frac{eV}{kT_e}\right) \quad (2.3)$$

Taking the natural logarithm of both sides of equation 2.3 and differentiating with respect to V , the electron temperature can be determined by the following equation:

$$T_e = -\frac{e}{k} \left(\frac{d \ln I_e(V)}{dV} \right)^{-1} \quad (2.4)$$

In other words, by plotting $I_e(V)$ on a logarithmic scale and calculating the slope of the resulting line, the electron temperature T_e can be derived.

Next, we describe the calculation of the electron density n_e . There are two methods to determine the electron density: one using the electron current and the other using the ion current. In the case of the electron current, the electron density can be calculated by substituting the measured thermal diffusion electron current I_{e0} from equation(2.1) and the electron temperature T_e determined from equation (2.4) into the formula. For the ion current, it can be calculated based on the condition of ion sheath formation. When an ion sheath is formed, the ion current I_i flowing into the probe, considering the ion charge number z , is given by the following equation:

$$I_i = \exp \left(-\frac{1}{2} \right) n_e z e S \left(\frac{k(T_e + T_i)}{m_i} \right)^{1/2} \quad (2.5)$$

Therefore, the electron density can be expressed by rearranging equation (2.5) as follows:

$$n_e = \frac{\exp(1/2)I_i}{ze^{3/2}S} \sqrt{\frac{m_i}{T_e + T_i}} \quad (2.6)$$

Here, the temperature is expressed in units of [eV]. Since the electrostatic probe method cannot directly calculate the ion temperature, it is sometimes assumed that $T_i = 0$ or $T_i = T_e$.

Additionally, the space potential V_s can be determined by drawing tangents to regions (I) and (II) and finding their intersection.

In this way, the single probe method allows for the determination of electron temperature, electron density, and space potential by sweeping the voltage on a single electrode. However, since the current-voltage characteristic must be obtained, the time resolution depends on the sweep time of the applied voltage, which is typically not very high. This makes it unsuitable for cases where plasma parameters change rapidly. To achieve high time resolution measurements, the triple probe method is effective.

Triple probe method

The triple probe method involves using three probes simultaneously, with a constant voltage applied between them. By measuring the current flowing to one of the probes and the potential difference between the other probes, it is possible to measure the electron temperature, electron density, space potential, and their fluctuations simultaneously.

As shown in Figure 2.3, one of the three electrodes, all having equal surface area S , is left floating (T_3) to measure the floating potential, while a DC voltage is applied between the remaining two electrodes (T_1, T_2). Since almost no current flows through T_3 ($I_3 = 0$), and T_1 and T_2 can be considered a closed circuit, the direction of the currents is opposite, and their magnitudes are equal ($I_1 + I_2 = 0$). Moreover, since the potential difference between T_1 and T_2 is known, measuring V_1 allows us to determine V_2 .

The current-voltage values obtained with this circuit, assuming the plasma is uniform at the positions of the three probe terminals, will match the current-voltage characteristics obtained by sweeping the voltage in the single probe method. Figure 2.4 shows an ideal example of the current-voltage values obtained with the triple probe, along with the current-voltage characteristics from the single probe measurements. Here, the space potential is set as the reference potential ($V_s = 0$).

Here, when the electron energy distribution follows the Boltzmann distribution, the currents flowing through T_1, T_2 and T_3 in Figure 2.3 are expressed as follows:

$$I_1 = I_e(V_1) + I_i(V_1) = -I_{e0} \exp(eV_1/T_e) + I_i \quad (2.7)$$

$$I_2 = I_e(V_2) + I_i(V_2) = -I_{e0} \exp(eV_2/T_e) + I_i \quad (2.8)$$

$$I_3 = I_e(V_3) + I_i(V_3) = -I_{e0} \exp(eV_3/T_e) + I_i \quad (2.9)$$

Here, T_e is the electron temperature, and $I_e(V), I_i(V)$ represent the electron and ion currents flowing into the electrode at potential V . The units for each parameter are temperature [eV], potential [V], and current [A]. Assuming that the ion current is approximately constant with respect to the probe potential, we set $I_i(V_1) = I_i(V_2) = I_i(V_3) = I_i$. From $I_3 = 0, I_1 + I_2 = 0$, solving equations (2.7)-(2.9):

$$\frac{I_3 - I_1}{I_2 - I_1} = \frac{1}{2} = \frac{1 - \exp(e(V_3 - V_1)/T_e)}{1 - \exp(e(V_2 - V_1)/T_e)} \quad (2.10)$$

If a sufficiently large potential difference is applied between T_1 and T_2 , such that $e(V_1 - V_2) \gg T_e$, we can approximate $\exp\{-e(V_1 - V_2)/T_e\} = 0$, and the electron temperature is given by:

$$T_e = e(V_1 - V_3)/\ln 2 \quad (2.11)$$

The electron density can be calculated using equation (2.6) for T_e and I_i , as derived from equation 2.11.

When the electrode potential is at the floating potential V_f , the electron current is given by equations (2.1) and (2.3) as:

$$I_e(V_f) = \frac{1}{4}en_e \left(\frac{8T_e}{\pi m_e} \right)^{1/2} S \exp \left(-\frac{eV_f}{T_e} \right) \quad (2.12)$$

Since the electron current and ion current are equal at this point, setting equation (2.12) equal to equation (2.5) yields:

$$V_f = \left[\frac{1}{2e} - \frac{1}{2e} \ln \left\{ 2\pi z^2 \frac{m_e}{m_i} \left(1 + \frac{T_i}{T_e} \right) \right\} \right] T_e \quad (2.13)$$

Considering that the space potential V_s is set as the reference potential $V_s = 0$, the floating potential V_f can be expressed as:

$$V_s = V_f + \left[\frac{1}{2e} - \frac{1}{2e} \ln \left\{ 2\pi z^2 \frac{m_e}{m_i} \left(1 + \frac{T_i}{T_e} \right) \right\} \right] T_e. \quad (2.14)$$

2.2.2 InfraRed video bolometer

An InfraRed Video Bolometer (IRVB) captures radiation from plasma through a pinhole, which is received by a thin film and converted into heat [28]. (Figure 2.5) This heat is emitted as infrared radiation, which is observed by an infrared camera to measure the heat distribution on the thin film. By solving the heat diffusion equation shown in Equation (2.15) based on this heat distribution, the radiation distribution of the plasma can be determined. Here, Ω_{rad} and Ω_{bb} represent the radiation energy of the plasma and the radiation energy of the thin film, respectively,

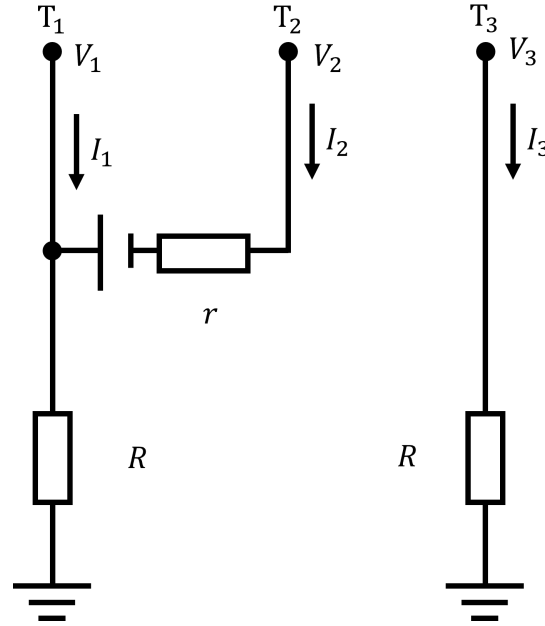


Figure 2.3: circuit configuration of the triple probe method

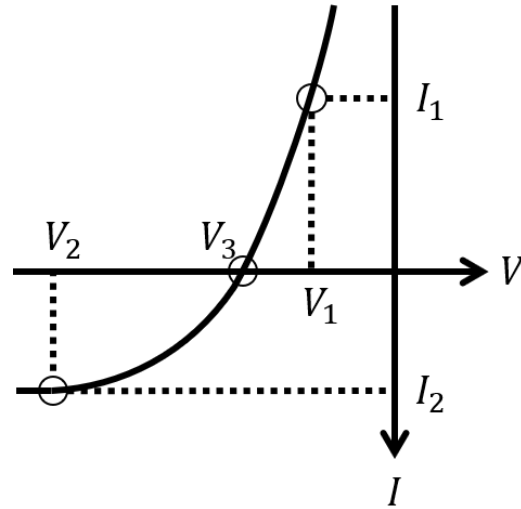


Figure 2.4: the current-voltage characteristics of the triple probe

as shown in Equations (2.16) and (2.17).

$$-\Omega_{\text{rad}} + \Omega_{\text{bb}} + \frac{1}{\kappa} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \quad (2.15)$$

$$\Omega_{\text{rad}} = \frac{P_{\text{rad}}}{k t_f l^2} \quad (2.16)$$

$$\Omega_{\text{bb}} = \frac{29 \sigma_{\text{S-B}} (T^4 - T_0^4)}{k t_f} \quad (2.17)$$

In these equations, κ is the thermal diffusivity, k is the thermal conductivity, t_f is the thickness of the thin film, l^2 is the pixel area of the thin film, ε is the emissivity, σ_{S-B} is the Stefan-Boltzmann constant, and T_0 is the background temperature.

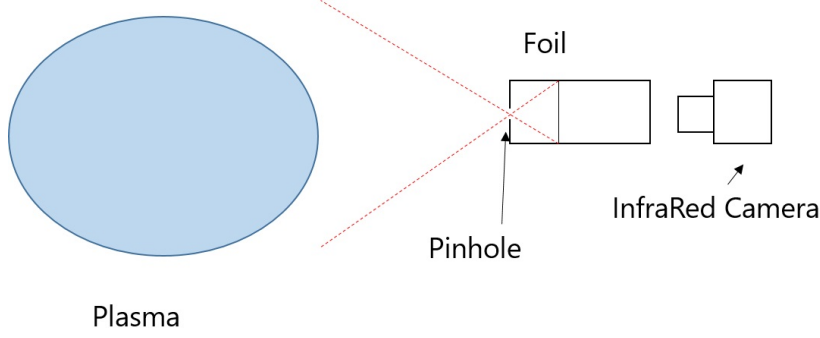


Figure 2.5: Schematic view of InfraRed Video Bolometer

2.2.3 Absolute eXtreme UltraViolet detector

AXUV stands for Absolute eXtreme Ultra Violet. It measures radiative losses by converting photons emitted from plasma into current values using photodiodes. The measurement energy range is from 1 to 10^4 eV, [29] allowing for the detection of radiation from visible light to the soft X-ray region.

2.3 Analysis methods

2.3.1 Fast Fourier transform

The fluctuation signals measured were analyzed using the Fast Fourier transform (FFT) [30] method. Given N data points $x(j)(j = 0, 1, 2, \dots, N - 1)$, the finite Fast Fourier transform is expressed as $X(k)$ as follows:

$$X(k) = \sum_{j=0}^{N-1} x(j) \exp \left(-i2\pi \frac{jk}{N} \right) \frac{T}{N} \quad (k = 0, 1, 2, \dots, N/2) \quad (2.18)$$

Here, the time resolution Δt , frequency resolution Δf , time t , frequency f , and Nyquist frequency f_N are given by the following relations:

$$\Delta t = T/N \quad (2.19)$$

$$\Delta f = 1/T \quad (2.20)$$

$$t = j\Delta t = j(T/N) \quad (2.21)$$

$$f = j\Delta f = k/T = k/(N\Delta t) \quad (2.22)$$

$$f_N = N/(2T) = 1/(2\Delta t) \quad (2.23)$$

The power spectrum $P(f)$ is defined as:

$$P(f) = \frac{1}{T} \langle X(f)X^*(f) \rangle = \frac{1}{T} \langle |X(f)|^2 \rangle \quad (2.24)$$

Here, $\langle \dots \rangle$ represents the ensemble average, and $*$ denotes the complex conjugate. The cross-spectrum $P_{XY}(f)$ is expressed as:

$$P_{XY}(f) = \frac{1}{T} \langle X^*(f)Y(f) \rangle \quad (2.25)$$

From this, the coherence and phase difference are calculated as:

$$\text{Coh}_{XY}(f) = \frac{|P_{XY}(f)|}{\sqrt{P_{XX}(f)P_{YY}(f)}} = \frac{|\langle X^*(f)Y(f) \rangle|}{\sqrt{|X(f)|^2|Y(f)|^2}} \quad (2.26)$$

$$\text{Pha}_{XY} = \frac{\text{Im}(P_{XY})}{\text{Re}(P_{XY})}. \quad (2.27)$$

2.3.2 Statistical analysis

The intermittency can be characterized by using the probability density function (PDF) and by computing the higher central moments of the fluctuating quantities, i.e

$$F_p(X) = N^{-1} \sum (X_j - \bar{X})^p / \sigma_X^p \quad (2.28)$$

where N is the number of data points in the time series of the variable X , the summation is over all data points. $\bar{X} = N^{-1} \sum X_j$ is the mean and $\sigma_X = \sqrt{N^{-1} \sum (X_j - \bar{X})^2}$ is the standard deviation of X . The skewness $S = F_3$ measures the positive-negative asymmetry of the PDF, and the kurtosis $K = F_4 - 3$ measures “flatness” of the PDF, i.e., whether the distribution is more peaked or flatter than a normal distribution. Figure 2.6 shows the shape of the PDF and the sign of skewness and

kurtosis. When $S > 0$, there is a positive tail, and when $S < 0$, there is a negative tail. When $K > 0$, the distribution is concentrated at the mean value, and when $K < 0$, the distribution is flat. Gaussian turbulence has $S = 0 = K$, whereas S and K are positive in the SOL when blobs are present [31].

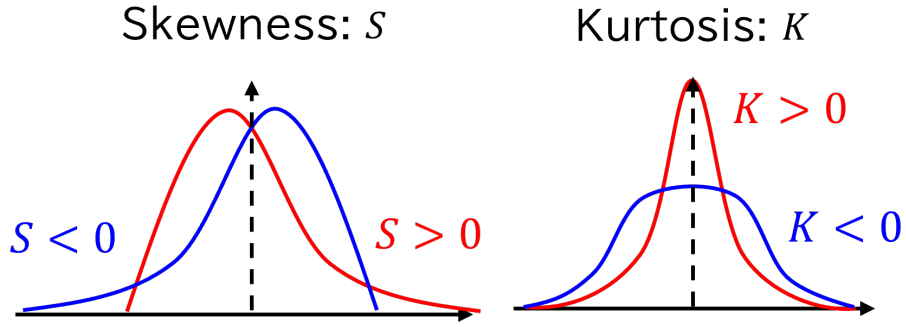


Figure 2.6: Shape of the PDF and the sign of skewness and kurtosis.

Chapter 3 The Heliotron J device

3.1 Introduction

The magnetic confinement plasma study of helical devices including stellarator/heliotron has reached the point to expand the plasma parameter and to challenge a long-time plasma discharge to achieve a nuclear fusion reactor.

In this chapter, the concept of a helical-axis heliotron Heliotron J is described. The heating systems and diagnostic are also introduced.

3.2 Characteristics of magnetic configurations in Heliotron J

3.2.1 Magnetic configuration design concept of Heliotron J

The Heliotron E experiment played a pioneering role globally in exploring unique aspects of fusion plasma, including current-free plasma generation and sustainment, heating, wall conditioning, and pellet injection experiments, differentiating itself from the tokamak approach [32]. The magnetic configuration of Heliotron E relied on the magnetic well to ensure MHD stability, particularly with a planar magnetic axis helical configuration. Achieving a magnetic well across the entire plasma region, not just the core, is theoretically challenging. To balance MHD stability with efficient particle confinement, Heliotron J relaxes the planar magnetic axis constraint and adopts a helical-axis heliotron configuration. This configuration allows for improved MHD stability and particle transport characteristics by taking advantage of three-dimensional magnetic field structures [33–35].

In advanced helical devices, including the helical-axis heliotron configuration, it is theoretically impossible to produce a truly symmetric configuration in Boozer coordinates [36, 37]. However, configurations with approximate symmetry modes, known as quasi-symmetric configurations, have been developed to improve both

MHD stability and particle transport. Three primary types of quasi-symmetry configurations are as follows:

- Quasi-helical symmetry $B(r, L\theta - M\zeta)$
- Quasi-axisymmetry $B(r, \theta)$
- Quasi-poloidal symmetry $B(r, \zeta)$

Here, r , θ , ζ represent the plasma minor radius, poloidal angle, and toroidal angle in Boozer coordinates, respectively [37]. Optimizing quasi-poloidal symmetry has led to the development of quasi-isodynamic configurations, which leverage three-dimensional characteristics to create a more effective magnetic field arrangement [38]. The quasi-isodynamic concept aims to localize most trapped particles in a region where the magnetic field intensity varies minimally, effectively keeping the magnetic axis nearly linear, which improves particle confinement in three-dimensional magnetic structures.

3.2.2 Helical-axis heliotron configuration

In Heliotron J, the helical-axis heliotron configuration is introduced with the aim of achieving both good particle confinement and MHD stability. The fundamental concept behind good particle confinement is to bring the magnetic surfaces and particle orbits as close together as possible. In the helical-axis heliotron magnetic field, a region where the magnetic field lines that form the magnetic surfaces are nearly straight is created in part of the torus, known as the "straight section." A locally quasi-isodynamic magnetic structure is formed in this straight section. Figure 3.1 shows the vacuum magnetic surfaces and constant magnetic field strength contours for each poloidal cross-section in the standard magnetic configuration of Heliotron J. Figure 3.1(right) represents the cross-section of the straight section. In this region, the radius of curvature of the magnetic field is large, and the radial magnetic field gradient is small, which reduces ∇B drift and curvature drift, allowing the particle orbits to approach the magnetic surfaces. Furthermore, by making the magnetic field strength in the corner sections higher than in the straight sections, mirror-like magnetic fields are formed in each toroidal section, trapping particles

with large pitch angles in the straight sections. Thus, the helical-axis heliotron magnetic configuration utilizes not only the toroidal component (toroidicity) and helical component (helicity) that have traditionally been used, but also the bumpy component (bumpiness) representing toroidal ripple. By combining these components, good particle confinement is achieved.

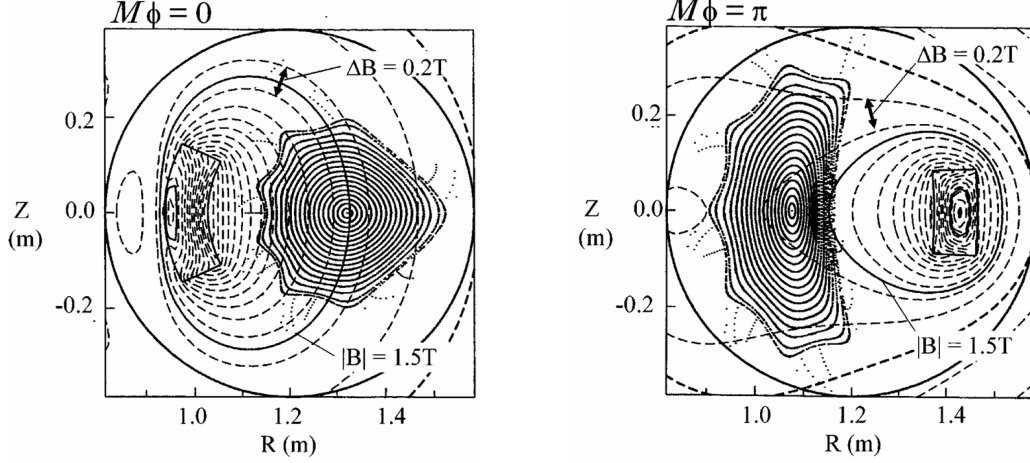


Figure 3.1: Magnetic surfaces and constant magnetic field strength contours [33].

Bumpiness is a characteristic magnetic field parameter in the helical heliotron configuration [36, 39–42]. The spatial variation structure of the magnetic field strength B can be expressed as a sum of spectral components using Boozer coordinates, as follows:

$$B(r, \theta, \zeta) = \sum_{m,n} B_{m,n}(r) \cos(m\theta - n\zeta) \quad (3.1)$$

Here, θ represents the poloidal angle, ζ the toroidal angle and r the minor radius. Figure 3.2 illustrates the major magnetic field components in the standard magnetic configuration of Heliotron J [33]. Here, the $(m, n) = (0, 0)$ component is shown with a value reduced by 0.8, while the other components are normalized by the uniform magnetic field component $B_{00}(a)$ at the outermost magnetic surface. Among these components, the toroidicity $\epsilon_t = B_{10}/B_{00}$, helicity $\epsilon_h = B_{14}/B_{00}$, and bumpiness $\epsilon_b = B_{04}/B_{00}$ are identified as the key components.

Moreover, while Heliotron E suppressed MHD instability through a high magnetic shear with an increasing rotational transform toward the edge region, Heliotron

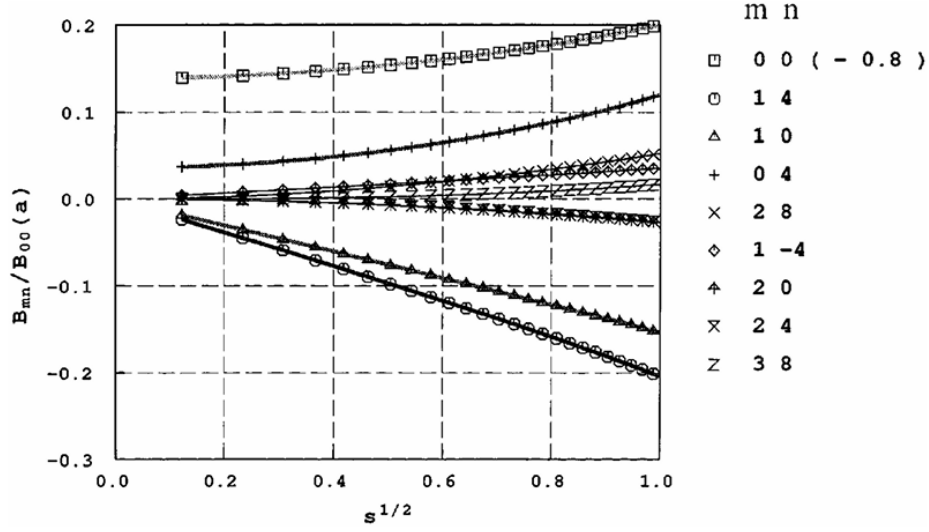


Figure 3.2: Major magnetic field components in the standard magnetic configuration [33]

J adopts a configuration with low magnetic shear, maintaining a nearly uniform rotational transform. Instead, a magnetic well is formed throughout the entire plasma region, contributing to MHD stability. Figure 3.3 shows the rotational transform and magnetic well profiles in the standard configuration of Heliotron J. In the standard configuration, the rotational transform at the magnetic axis is 0.56, and the magnetic well depth at the outermost magnetic surface is 1.5%. This combination of a uniform rotational transform and shallow magnetic well enables Heliotron J to achieve both MHD stability and low magnetic shear.

3.2.3 Device configuration

Heliotron J has flexibility to extensively modify a vacuum magnetic field configuration using external coils. The Schematic view of coil system of Heliotron J is shown in Figure 3.4. Heliotron J boasts a major radius (R) of 1.2 m, an average minor radius (a) ranging from 0.1 to 0.2 m, and a magnetic field strength on the magnetic axis of less than 1.5 T. It is equipped with a unique $L/M = 1/4$ continuous winding helical coil (HF), where L represents the pole number and M the pitch number, along with two types of toroidal coils (TA and TB) and three sets of

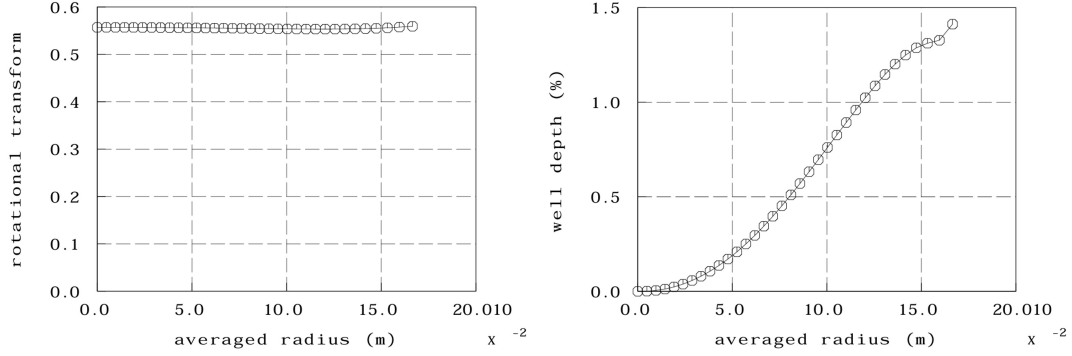


Figure 3.3: Rotational transform and magnetic well profiles in the standard configuration of Heliotron J.

vertical magnetic field coils(MV, AV and IV). These components together produce a low magnetic shear configuration [34, 35, 43]. The device's magnetic configuration is adjustable, allowing for the alteration of current ratios in each coil. In Figure 3.4, MV coil is not described. The maximum value of current for each coils are as follows; HF: 960 kAT (120 KA $\times$ 8 turns), TA: 600 kAT (120 KA $\times$ 5 turns), TB: 218 kAT (10.9 KA $\times$ 20 turns), MV: 840 kAT (120 KA $\times$ 7 turns), AV: 144 kAT (6 KA $\times$ 24 turns), IV: 480 kAT (6 KA $\times$ 80 turns).

3.2.4 Rotational transform

The rotational transform is closely related to confinement performance and, in stellarator-heliotron devices, is normalized in accordance with the ISS04 scaling law [44], as shown in equation 3.2. Heliotron J, compared to devices such as LHD and W7-X, possesses a rotational transform distribution with lower shear. As illustrated in the Figure 3.5, it is capable of controlling the rotational transform over a wide range. Table 3.1 shows the coil parameters for each magnetic configuration.

$$\tau_E^{\text{ISS04}} \propto a^{2.28} R^{0.64} P^{-0.61} n_e^{-0.54} B^{0.84} \iota_{2/3}^{0.41} \quad (3.2)$$

By controlling the rotational transform, the relative position of low-order rational surfaces can be adjusted. This allows the geometric shape of the magnetic structure

Table 3.1: Coil settings for each magnetic configuration in the rotational transform scan.

$\iota(0)/2\pi$	HV	TA	TB	AV	IV
0.442	74	79	87	-40	-65
0.463	74	79	87	-15	-27
0.481	82	74	82	-25	-25
0.499	85	72	80	-27	-30
0.512	84	74	81	25	65
0.527	85	73	80	25	55
0.550	87	74	82	26	28
0.557	88	73	80	45	75
0.558	92	70	76	20	49
0.567	89	73	80	49	75
0.582	92	71	78	34	39
0.591	93	71	77	35	35
0.598	94	70	77	38	39
0.613	97	69	77	47	55
0.621	97	72	72	32	10
0.633	98	71	71	51	51

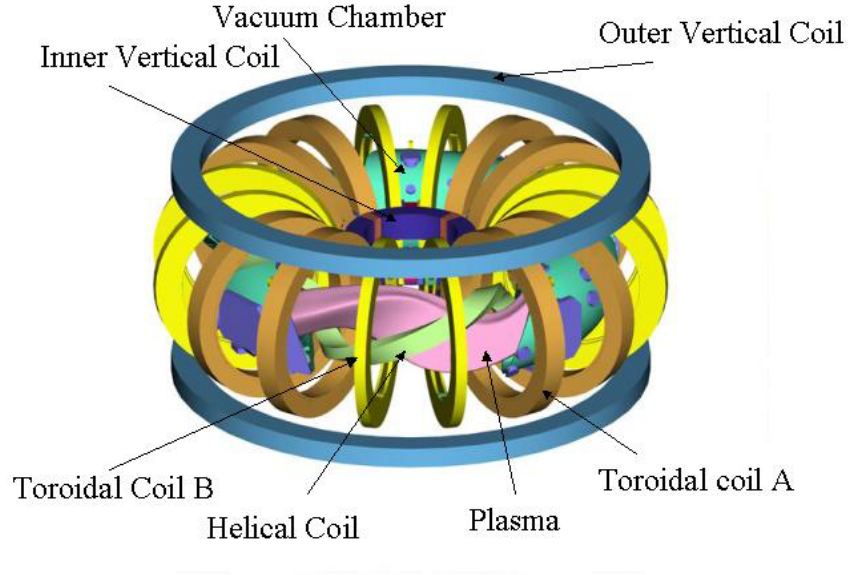


Figure 3.4: Coil system of Heliotron J

to be controlled. Figure 3.6 shows the Poincaré plot in the corner section for configurations near low-order rational surfaces, illustrating the formation of magnetic islands with different poloidal mode numbers in the peripheral region.

3.3 Heating systems

3.3.1 Electron cyclotron heating and current drive system

In this study, the plasma is initiated and sustained by electron cyclotron heating (ECH). ECH is a method to transfer power to plasma by millimeter range of waves [45, 46]. When an electromagnetic wave propagates through plasma, the electric field of wave accelerates the charged particles that heat plasma by collisions. In addition, the current is driven by creating asymmetry in the velocity distribution function with respect to the direction of the magnetic field lines.

Characteristics of ECH/ECCD is as follow: electromagnetic waves in plasmas are

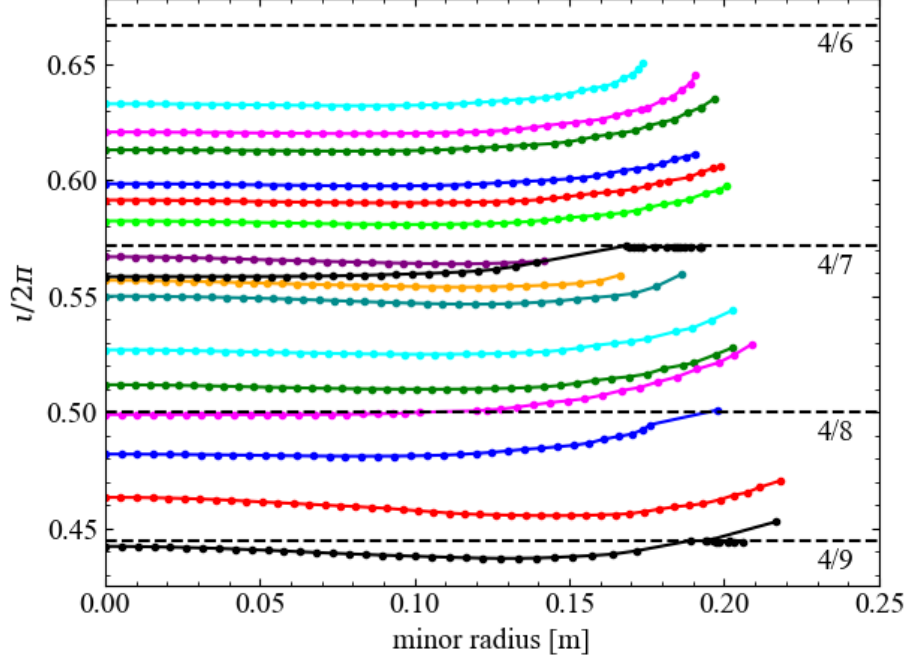


Figure 3.5: Rotational transform profile

subject to resonant absorption, thus we can carry out the localized plasma heating. In Heliotron J, plasma is generated and heated by second harmonic X-mode ECH, whose frequency is 70 GHz and maximum injection power is 0.4 MW. The parallel refractive index, which is important for ECCD, can be set in the range of -0.05 to 0.6, and both magnetic and non-magnetic axial incidence can be used [47–49].

3.3.2 Neutral beam injection system

Neutral Beam Injection (NBI) heating involves injecting a neutral particle beam, accelerated to high energy, into the plasma to heat it. By using a neutral particle beam, the injection can proceed without being affected by the magnetic field. In Heliotron J, two tangential NBI systems (BL1, BL2) are installed facing each other. The maximum injection power for each beam line is 0.8 MW, with a maximum pulse width of 0.2 seconds.

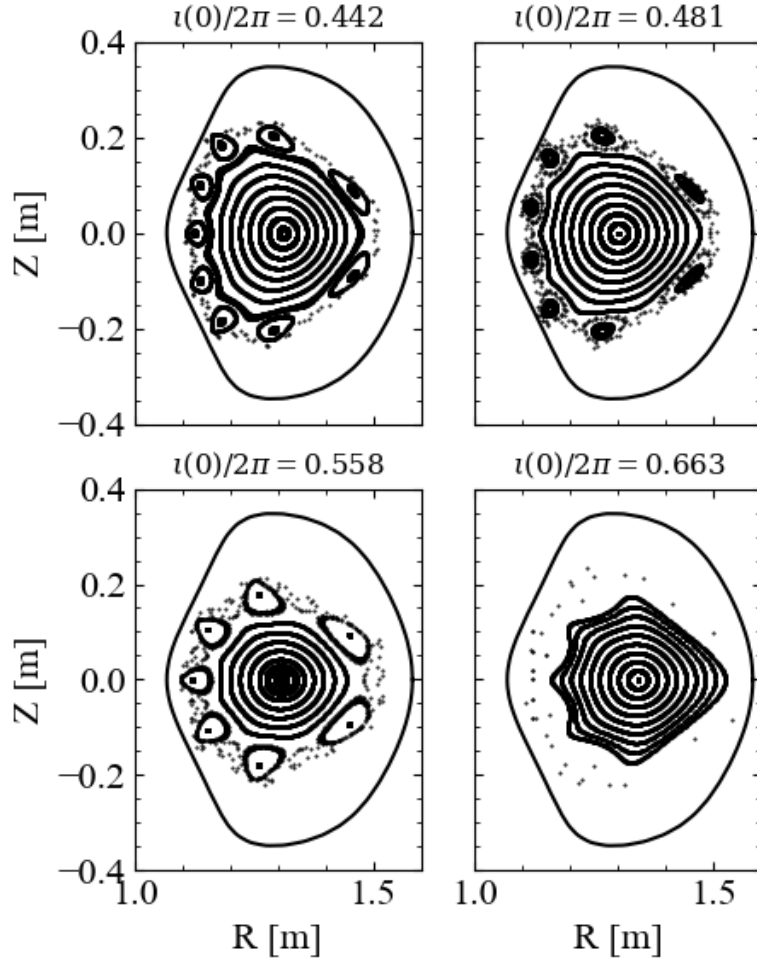


Figure 3.6: Poincaré plot of the low order rational surface from $4/9$ to $4/6$ in the corner section.

3.4 Diagnostics

Several diagnostics used in this study are described in this section. Figure 3.7 shows the position of the diagnostics in Heliotron J

Microwave interferometer

A microwave interferometer is a technique to measure the phase shift of microwave, which travels in the plasma, by comparing with the phase of the reference

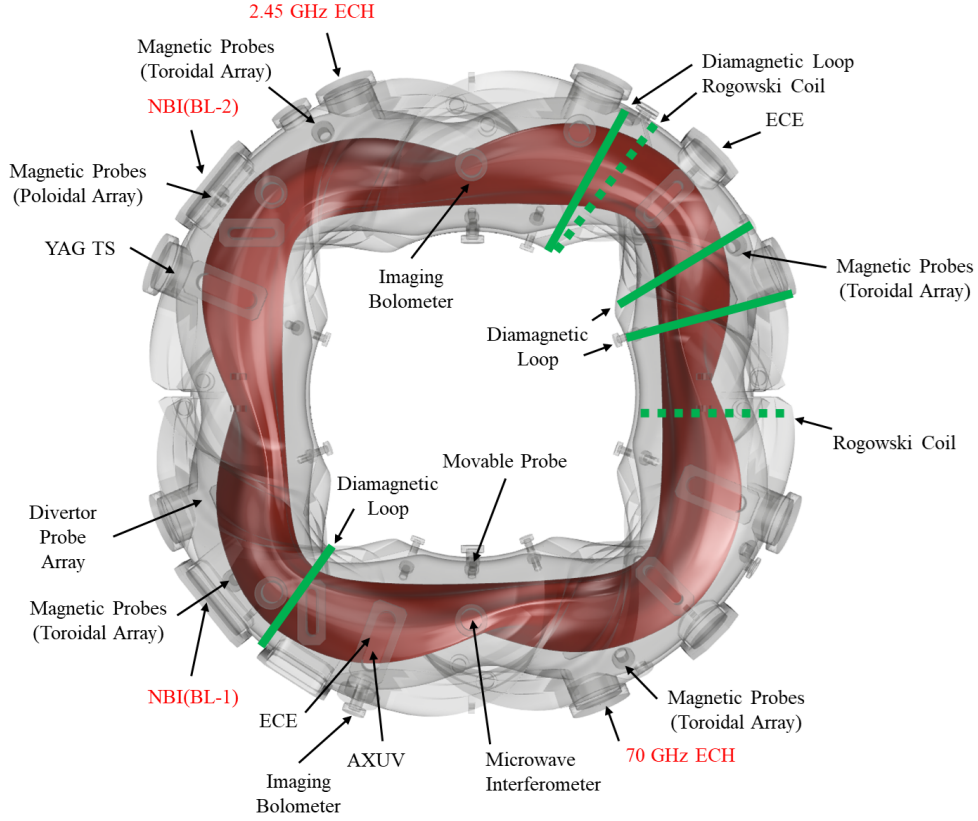


Figure 3.7: Schematic view of heating systems and diagnostics

wave. We can evaluate the electron density from the phase shift. However, the phase shift has a line integral effect on a traveling path, strictly speaking, as that it is a line-averaged electron density. In Heliotron J, we installed the microwave interferometer of O-mode injection, whose frequency is 130 GHz at #8.5 port. The cut-off electron density for this system is about $2.1 \times 10^{19} \text{m}^{-3}$.

Diamagnetic loop

A diamagnetic loop measures the change of magnetic flux in toroidal direction by poloidal loop around the plasma. The measurement of the diamagnetic effect is an important measurement of the plasma-stored energy (W_p), because the change of magnetic flux is proportional to the averaged pressure on the magnetic surface. Therefore we can evaluate the W_p via the diamagnetic loop.

Table 3.2: Position of toroidal magnetic probes

Name	R (m)	ϕ ($^\circ$)	θ ($^\circ$)
MP1	0.38155	33.3	320
MP2	0.38155	131.3	320
MP3	0.38155	213.3	320
MP4	0.38155	303.3	320

Rogowski coils

The Rogowski coil provides a direct measurement of the total current flowing through its center. In Heliotron J, a toroidal current is measured by Rogowski coils wound on the inner wall of the poloidal cross-section at two different toroidal angles.

Magnetic probes

To investigate the characteristics of macroscopic instabilities such as MHD instabilities, a toroidal and poloidal array of magnetic probes has been installed on the vacuum vessel wall. The installation locations of these magnetic probes are shown in Table 3.2 and Table 3.3. Using four magnetic probes, the toroidal mode number n can be estimated within the range of $|n| \leq 2$. The magnetic probes belonging to these toroidal arrays are selected in terms of size and coil turns to measure high-frequency magnetic fluctuations up to approximately 500 kHz (with an LCR resonance frequency of 1 MHz). Data are typically acquired with a sampling frequency of 1 MHz. On the other hand, the poloidal array consists of 14 magnetic probes, installed at intervals of 10° to 20° in the same poloidal cross-section, covering a total of 180° in the poloidal direction. Each probe measures magnetic field fluctuations in the poloidal direction. Although the LCR resonance frequency is lower, around 150 kHz, the poloidal mode number m can be estimated within the range of $|m| \leq 7$ based on the phase difference between the magnetic probes.

AXUV array

In order to investigate MHD equilibria, instabilities, and impurity behavior by measuring bremsstrahlung radiation from the plasma and impurity spectra in the

Table 3.3: Position of poloidal magnetic probes

Name	R (m)	ϕ ($^\circ$)	θ ($^\circ$)
PMP1	0.37	42.55	0.0
PMP2	0.37	42.55	350
PMP3	0.37	42.55	340
PMP4	0.37	42.55	330
PMP5	0.37	42.55	320
PMP6	0.37	42.55	310
PMP7	0.37	42.55	300
PMP8	0.3616	42.55	280
PMP9	0.3381	42.55	270
PMP10	0.2812	42.55	260
PMP11	0.2268	42.55	250
PMP12	0.1817	42.55	240
PMP13	0.1305	42.55	210
PMP14	0.1224	42.55	180

vacuum ultraviolet (VUV) to soft X-ray range, a radiation detector is installed at the top of the #7.5 port. The pinhole camera is used for this purpose. Figure 3.8 shows the sight lines of the AXUV measurement and the Poincaré plot in the standard configuration. A total of 16 channels are available, providing sight lines from the plasma core to the edge region.

Nd:YAG Thomson scattering measurement system

Thomson scattering of laser light is a popular method of measuring electron temperature and density profile in plasma. This method measures the scattering light due to electrons in the plasma. The electron density and temperature are obtained from the absolute intensity of scattering light and the Doppler broadening, respectively. The main performance parameters of the Thomson scattering measurement system are summarized in Table 3.4 [50, 51].

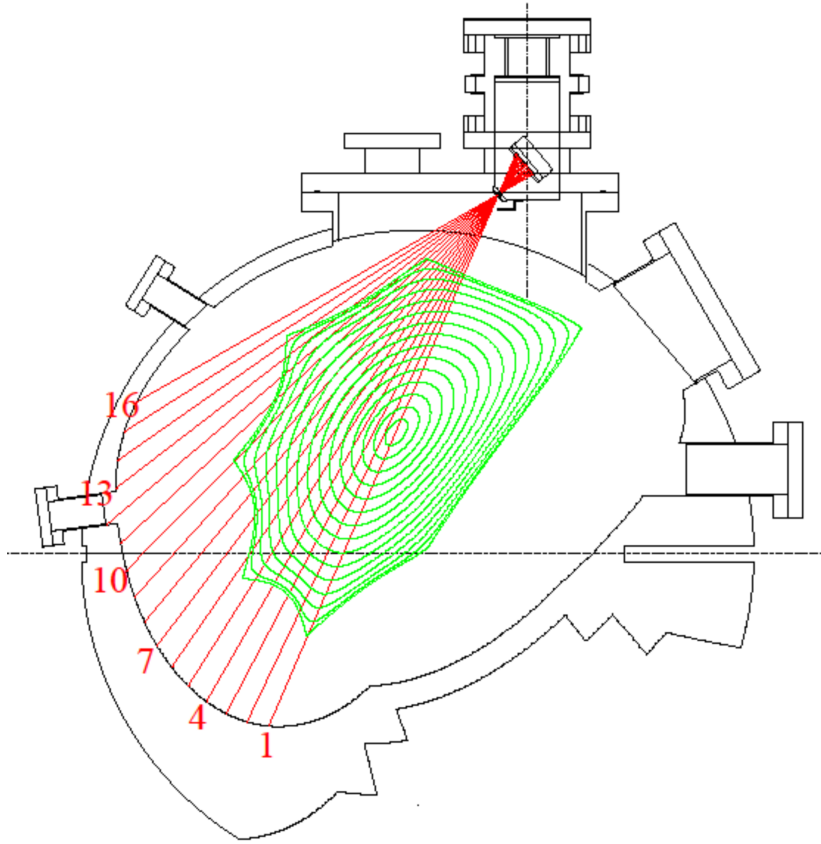


Figure 3.8: Sight line of AXUV with poincare plot of standard configuration

Electron Cyclotron Emission (ECE) measurement

The radiometer of the electron cyclotron emission (ECE) measurement system in the Heliotron J device covers the second harmonic X-mode ECE frequency range

Table 3.4: Main performance parameters of the Thomson scattering measurement system

Number of measurement spatial points	25
Spatial resolution	-1 cm
Measurable time interval	10 ms
Electron temperature measurement range	10 eV - 10 keV
Electron density measurement range	Above $5 \times 10^{18} \text{m}^{-3}$

of 58-74 GHz. In the standard configuration, it is capable of measuring from the plasma center on the low-field side to the outermost magnetic surface. The spatial resolution, determined by the magnetic field gradient and frequency resolution, is approximately 1 cm.

Movable multipin Langmuir probe

A movable multi-pin Langmuir probe is installed on the inner side of the #8.5 port. Figure 3.9 shows the front and side views of the probe. The probe pins are made of tungsten, and the support structure for the pins is constructed from boron nitride. The probe consists of five rows, each with five pins, for a total of 25 pins. The rows have a convex shape, with a height and width of 3 mm, and the center-to-center spacing between pins in each row is 2.5 mm.

The circuit configuration for the five channels in a single row of the probe is shown in Figure 3.10. The floating potential V_f is measured by T_1 and T_4 , while the ion saturation current I_{is} is measured by T_2 and T_3 . The signals for V_{f1} , V_{f2} , and V_p are measured using high-resistance R_f and R_p to ensure no current flow. On the other hand, I_{is} is measured using low-resistance circuits to avoid a drop in the bias voltage.

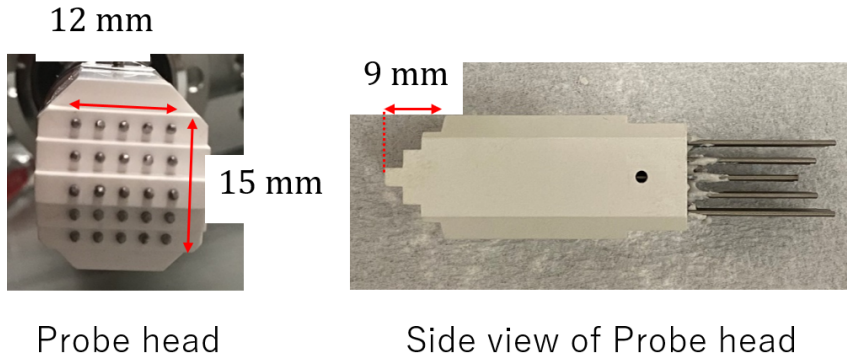


Figure 3.9: Front and side views of Langmuir probe

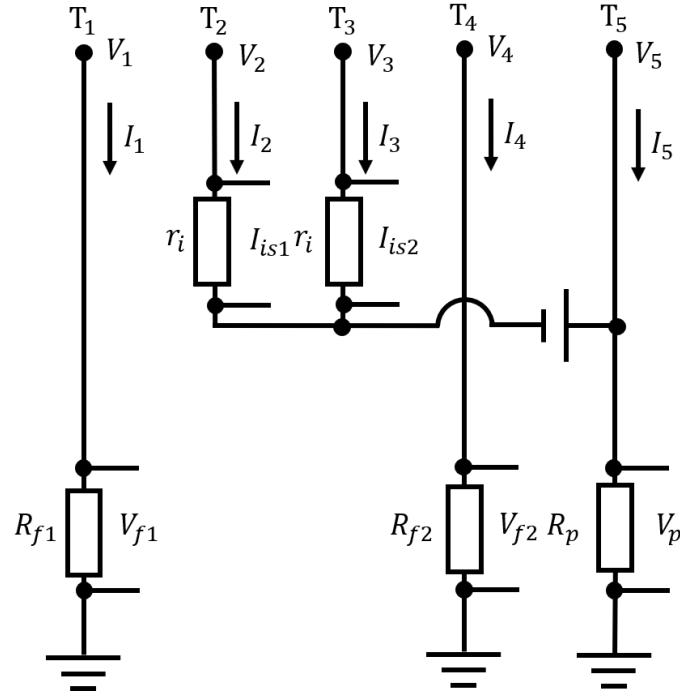


Figure 3.10: Circuit configuration for the five channels

Divertor probe array

In order to measure the particle flux and fluctuations in the divertor region, a divertor probe is installed on the lower side of the #5.5 port. Figure 3.11 shows an image of the divertor probe. The central column comprises 20 channels, with each electrode having a diameter of 0.8 cm and spaced 1 cm apart. Additionally, there are 8 channels on both the left and right sides, with a spacing of 1.25 cm between them. The body and electrodes are made of stainless steel.

The circuit configuration is shown in Figure 3.12. All resistors are $1\ \Omega$, and a DC voltage of -90 V is applied to measure the ion saturation current.



Figure 3.11: Appearance of the divertor probe

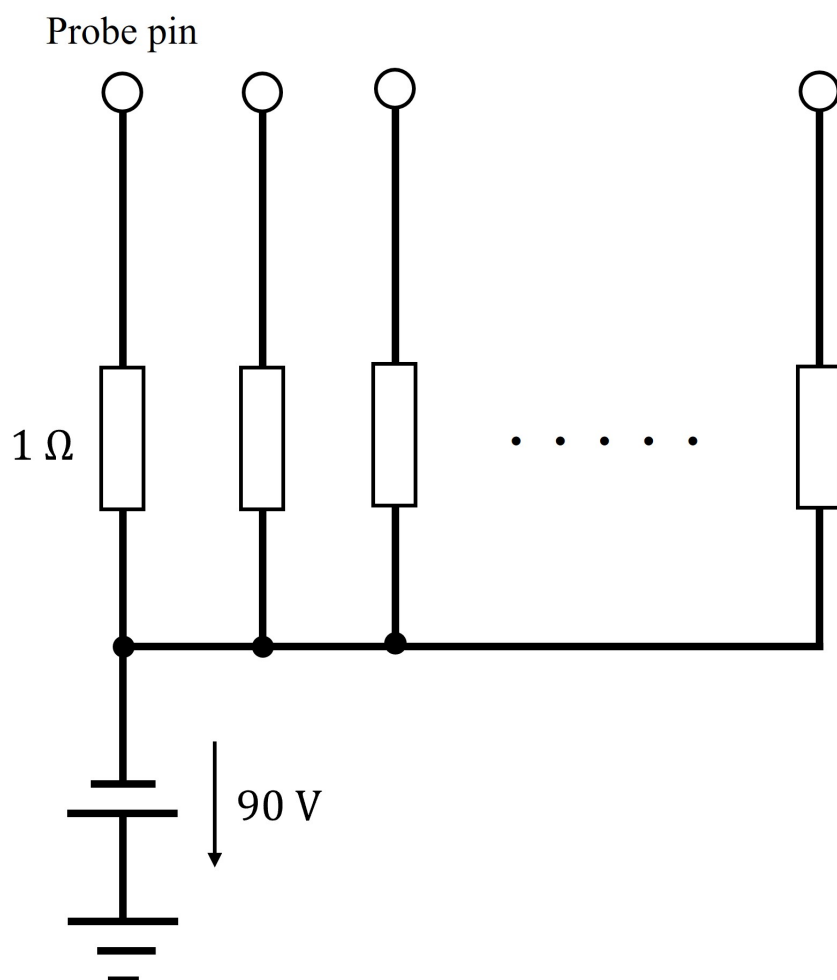


Figure 3.12: Circuit configuration of divertor probe

Chapter 4 Application of Infrared imaging video bolometer

4.1 Introduction

Measurement of the spatial distribution of plasma radiation is an important issue for understanding the physics of thermal and impurity transport and the detached divertor and radiative collapse in magnetically confined plasmas. Multi-dimensional measurement is required to obtain the plasma radiation distribution in three-dimensional plasmas, such as stellarator/heliotron plasmas. The infrared imaging video bolometer (IRVB) [28] has been recognized as a two-dimensional radiation diagnostic. The purpose of this study is to apply the IRVB to an advanced helical device, Heliotron J, and to demonstrate its capability for radiation distribution measurement in small and medium size devices.

4.2 Plasma radiation

The power balance equation for plasma is shown in equation (4.1)

$$\frac{dW}{dt} = P_{inj} - P_{rad} - \frac{W}{\tau_E} \quad (4.1)$$

Here, W represents the stored energy of the plasma, P_{inj} and P_{rad} denote the injected power and radiative loss power, respectively, and τ_E is the energy confinement time. If the injected energy equals the radiated energy, i.e., $P_{inj} = P_{rad}$, the stored energy of the plasma decays with a time constant of τ_E . In the steady state, where $dW/dt = 0$, the equation reduces to Equation 4.2.

$$\tau_E = \frac{W}{P_{inj} - P_{rad}} \quad (4.2)$$

Using this equation, confinement time and other related parameters in a steady state can be evaluated.

4.2.1 Radiation losses

A pure hydrogen plasma emits electromagnetic radiation. Microscopically this is due to the acceleration of the charged particles. Because of their lighter mass the electrons undergo larger acceleration than the ions. Consequently they radiate much more strongly and only the electrons need be considered. The electrons are accelerated in two ways. Firstly they are accelerated by collisions, the resulting radiation being called bremsstrahlung. Secondly they are subject to the acceleration of their cyclotron motion and the associated radiation is called cyclotron or synchrotron radiation. In the presence of impurities the bremsstrahlung is enhanced. There are also further losses due to the atomic processes of line radiation and recombination radiation.

Bremsstrahlung

The power radiated by an electron undergoing an acceleration a is

$$P = \frac{e^2}{6\pi\epsilon_0 c^3} a^2 \quad (4.3)$$

The acceleration of an electron during a collision with an ion is caused by the Coulomb force $Ze^2/4\pi\epsilon_0 r^2$, where r is their separation and Ze the charge on the ion, and so

$$a = \frac{Ze^2}{4\pi\epsilon_0 m_e r^2}. \quad (4.4)$$

Taking the duration of a collision to be $2r/v$, the energy lost per collision is $\delta E = P2r/v$ and equations 4.3 and 4.4 give

$$\delta E = \frac{Z^2 e^6}{6(2\pi\epsilon_0 cr)^3 m_e^2 v} \quad (4.5)$$

Thus, integrating over the impact parameter r , the bremsstrahlung radiation power per unit volume is given by

$$P_{\text{br}} = n_e n_z \int \delta E v 2\pi r dr = \frac{n_e n_z Z^2 e^6}{24\pi^2 \epsilon_0^3 c^3 m_e^2} \int \frac{1}{r^2} dr \quad (4.6)$$

The integral is $1/r$ but the divergence at small r is removed by quantum mechanical effects so that the lower limit of r is $h/m_e v$. Using this limit in $1/r$ and replacing

v by its average value from $\frac{1}{2}m_e v^2 = \frac{3}{2}T_e$, equation 4.6 gives the required form for P_{br} . Substituting the numerical factor obtained from a full calculation then gives the bremsstrahlung power due to ions of charge Z as

$$P_{\text{br}} = g \frac{e^6}{6(3/2)^{1/2} \pi^{3/2} \epsilon_0^3 c^3 h m_e^{3/2}} Z^2 n_e n_z T_e^{1/2} \quad (4.7)$$

where g is the Gaunt factor which gives a quantum mechanical correction. Under the conditions of interest $g \simeq 2\sqrt{3}/\pi$ and

$$P_{\text{br}} = 5.35 \times 10^{-37} Z^2 n_e n_z T_e^{1/2} [\text{Wm}^{-3}], \quad T_e \text{ in keV.} \quad (4.8)$$

[17]

Cyclotron radiation

The power radiated from a single non-relativistic electron is given by equation 4.3 with the acceleration of the cyclotron orbit, $a = \omega_{ce}^2 \rho_e$. Putting $\rho_e = (2T_e/m_e)^{1/2}/\omega_{ce}$ would then give a radiation power density

$$P_c = (e^4/3\pi\epsilon_0 m_e^3 c^3) B^2 n_e T_e. \quad (4.9)$$

[17]

4.2.2 Impurity radiation

The presence of impurities in the plasma produces energy losses through radiation. There are two types of process involved. The first is the enhancement of bremsstrahlung because of the higher value of the ionic charge for impurities. The second is the radiation which occurs through the atomic processes of line radiation and recombination.

In a steady state with negligible transport effects (coronal equilibrium), the power radiated from a given impurity species is proportional to the electron density n_e and to the impurity density n_I , and the radiated power density may be written

$$P_R = n_e n_I R, \quad (4.10)$$

where the radiation parameter R is a function of the electron temperature. Graphs of $R(T_e)$ are given in Figure 4.1 for a number of elements.

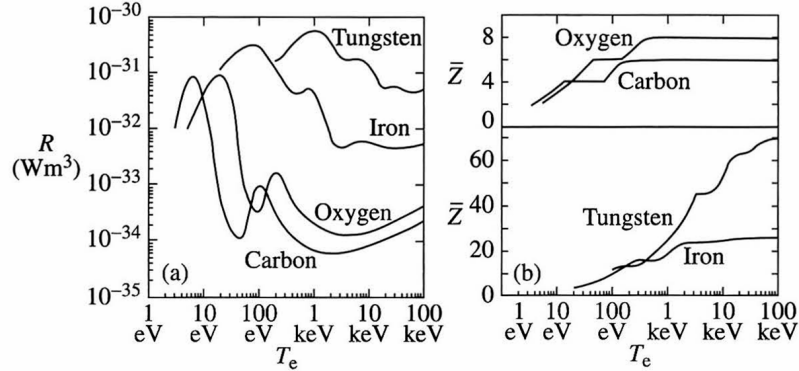


Figure 4.1: (a) The radiation parameter R and (b) the mean charge $\bar{Z}$ as functions of electron temperature for carbon, oxygen, iron and tungsten. [17]

The $R(T_e)$ curves have a principal maximum together with subsidiary maxima at higher temperatures. For light impurities the principal maximum occurs at a low temperature and above this temperature the radiation is substantially reduced. As the temperature is increased, electrons are successively removed from the impurity ions and when the ions are fully stripped only bremsstrahlung radiation remains. At a particular temperature a given impurity species will have a distribution of charge states Z . A mean value $\bar{Z}$, can be defined by

$$\bar{Z} = \sum n_z Z / n_I \text{ where } n_I = \sum n_z, \quad (4.11)$$

n_z being the density of ions in the charge state Z . Some graphs of $\bar{Z}(T_e)$ are given in Figure 4.1 [17].

4.2.3 EMC3-EIRENE

The simulation of plasma radiation was performed using the EMC3-EIRENE code [52, 53]. This code employs a Monte Carlo method on a 3D grid to solve the

Braginskii fluid equations, represented by equations (4.12) through (4.15).

$$\nabla_{\parallel} \cdot (n\mathbf{v}_{\parallel}) + \nabla_{\perp} \cdot (-D\nabla_{\perp}n) = S_p \quad (4.12)$$

$$\begin{aligned} \nabla_{\parallel} \cdot (m_i n \mathbf{v}_{\parallel} \mathbf{v}_{\parallel} - \eta_{\parallel} \nabla_{\parallel} \mathbf{v}_{\parallel}) + \nabla_{\perp} \cdot (-m_i n \mathbf{v}_{\parallel} D \nabla_{\perp} n - \eta_{\perp} \nabla_{\perp} \mathbf{v}_{\parallel}) \\ = \nabla_{\parallel} p + S_m \end{aligned} \quad (4.13)$$

$$\begin{aligned} \nabla_{\parallel} \cdot \left(-\kappa_e \nabla_{\parallel} T_e + \frac{5}{2} n T_e \mathbf{v}_{\parallel} \right) + \nabla_{\perp} \cdot \left(-\chi_e n \nabla_{\perp} T_e - \frac{5}{2} T_e D \nabla_{\perp} n \right) \\ = -k(T_e - T_i) + S_{ee} \end{aligned} \quad (4.14)$$

$$\begin{aligned} \nabla_{\parallel} \cdot \left(-\kappa_i \nabla_{\parallel} T_i + \frac{5}{2} n T_i \mathbf{v}_{\parallel} \right) + \nabla_{\perp} \cdot \left(-\chi_i n \nabla_{\perp} T_i - \frac{5}{2} T_i D \nabla_{\perp} n \right) \\ = k(T_e - T_i) + S_{ei} \end{aligned} \quad (4.15)$$

In these equations, $p = n(T_e - T_i)$ and $\eta_{\perp} = m_i n D$, where p denotes the pressure, n represents the density, m is the mass, and T stands for temperature. The subscripts i and e refer to ions and electrons, respectively. The subscripts $\perp$ and $\parallel$ indicate the directions perpendicular and parallel to the magnetic field lines. The parallel transport coefficients $\eta_{\parallel}$, κ_e and κ_i are considered classical, while the cross-field transport coefficients D , χ_e and χ_i are typically determined experimentally. The source terms S_p , S_m , S_{ee} and S_{ei} represent the particle, momentum, and energy sources arising from plasma-neutral interactions such as ionization, excitation, and charge exchange. EMC3-EIRENE can iteratively calculate the distribution of neutral particles in a steady-state plasma.

4.3 Experimental setup

4.3.1 IRVB system

A schematic of the IRVB system installed on Heliotron J is shown in Fig.4.2. The IRVB system is a type of pinhole camera, comprised of a pinhole (5 mm $\times$ 5 mm), a thin foil (35 mm $\times$ 35mm wide and 2.5 μ m thick, made from platinum and coated with carbon on both sides), and an infrared (IR) camera (DIAS infrared GmbH/PYROVIEW 640Lc, 50 fps, noise equivalent temperature difference: NETD < 0.08 K). The plasma radiation passing through the pinhole is imaged on the foil. The foil temperature increases in response to the radiation and the IR

camera measures the temperature distribution on the foil from the side opposite the plasma. The radiation distribution is reconstructed from the temperature distribution measured by the IR camera by solving the two dimensional thermal diffusion equation [28].

4.3.2 Viewing field

The IRVB observes the plasma from the outside of the torus, as shown in Fig.4.2. The viewing field angles cover the plasma from the plasma core to the edge. The region outside the last closed flux surface is also measured to evaluate the background noise of the IRVB signal. In total, 49 channels are used, with each channel having a $5\text{ mm} \times 5\text{ mm}$ square area. A spatial resolution of 3.5 cm is obtained at the major radius, $R = 1.2\text{ m}$, through the magnetic axis. A simulation result of the radiation distribution is shown in Fig.4.2(c), modeled by the three-dimensional transport code EMC3-EIRENE [54], which is projected on the surface at the same position as the IRVB foil.

4.3.3 Calibration of the infrared camera

Radiation from the plasma is projected onto a thin film through a pinhole, forming a two-dimensional temperature distribution on the film. When this temperature distribution is measured using an infrared camera, it produces a two-dimensional 16-bit digital dataset. To convert these digital data into temperature values, it is necessary to establish the relationship between the digital count values and temperature and then determine the calibration coefficients. A blackbody furnace is used as the temperature standard.

Method

The setup and concept of the calibration experiment are shown in Figure 4.3 and 4.4, respectively. In place of the thin film in the imaging bolometer, a blackbody furnace (Figure 4.5) was positioned to simulate the measurement conditions for plasma radiation. The blackbody furnace used in the experiment was the M345 model from LumaSense Technologies. This blackbody furnace can control both

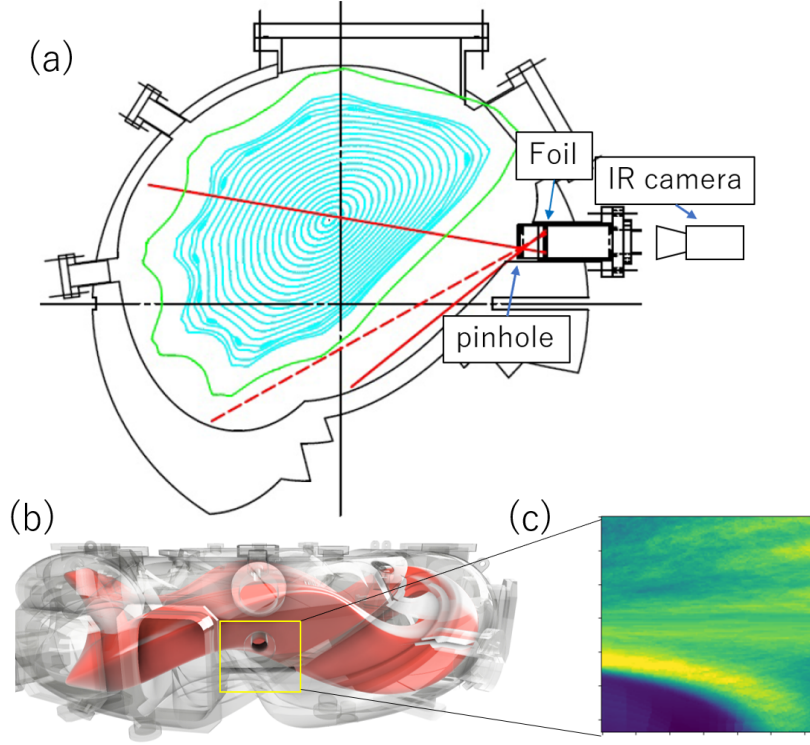


Figure 4.2: (a) Poloidal cross-section of flux surfaces (blue), the region where the plasma is known to exist (green), and the viewing angle of IRVB (red). No radiation is expected at the area below the red dashed line. (b) Side view of a Heliotron J CAD figure and (c) radiation distribution simulated with EMC3-EIRENE.

heating and cooling, with the front surface, visible in the figure, adjustable to temperatures with a precision of $0.01\text{ }^{\circ}\text{C}$. The blackbody surface was used as a substitute for the thin film and was observed using the infrared camera.

The temperature of the thin film in response to plasma radiation typically rises within the range of $20\text{ }^{\circ}\text{C}$ to $30\text{ }^{\circ}\text{C}$. Therefore, the blackbody furnace's temperature was varied from $20\text{ }^{\circ}\text{C}$ to $40\text{ }^{\circ}\text{C}$ in $1\text{ }^{\circ}\text{C}$ increments, and each setting was recorded by the camera for several seconds. The signal from the blackbody region in the camera image was spatially and temporally averaged, and the results were obtained in this manner. During the averaging process, the standard deviation was calculated to account for fluctuations in the digital count values due to noise.



Figure 4.3: Setup of the calibration experiment

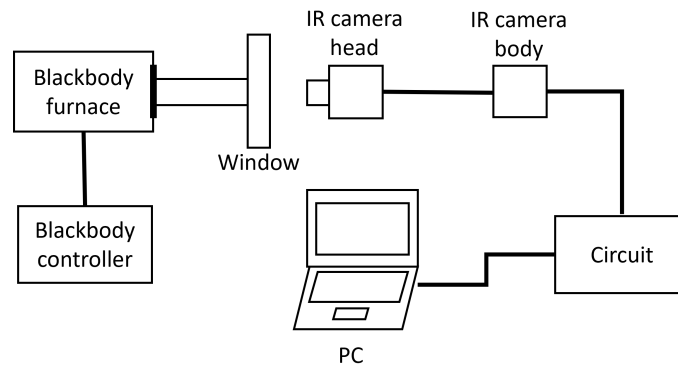


Figure 4.4: Concept of the calibration experiment

Results

The results of the measurements are shown in Figure 4.6, with the horizontal axis representing the blackbody furnace temperature and the vertical axis indicating the infrared camera's count values. The standard deviation for each measurement was small, on the order of a few tens of counts. The line in the figure represents a linear fit to the data for temperatures above 29 °C. The linear relationship between the count values and temperature is evident, especially for the temperature ranges of 20 °C and above 29 °C. The deviation from the linear fit observed in the range

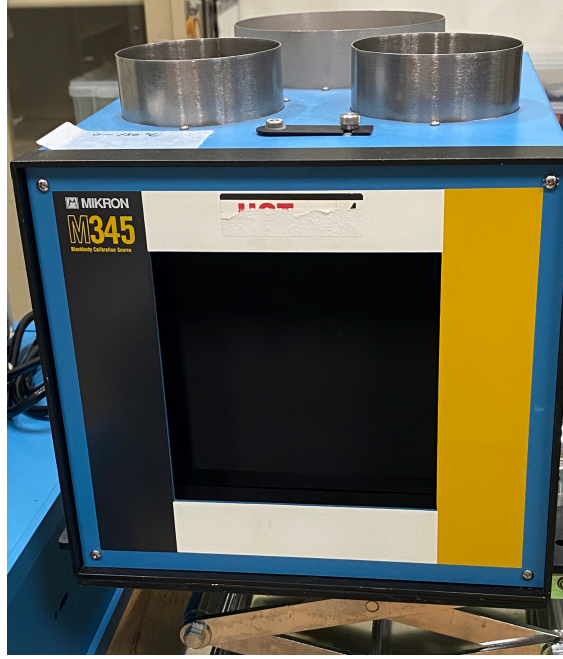


Figure 4.5: Blackbody furnace

from 21 °C to 28 °C is likely due to interference from ambient light, as this range is close to room temperature. Nevertheless, the relationship between temperature and digital count values can be considered linear, and this linear fit will be used for calibration within the temperature range of 20 °C to 40 °C.

4.3.4 Magnetic configurations in the rotational transform scan experiments

The Heliotron J device can adjust the shape of the magnetic configuration by controlling the rotational transform, which affects plasma transport characteristics. To measure the radiation distribution reflecting changes in transport, experiments were conducted across multiple magnetic configurations with different rotational transforms. This series of experiments includes configurations with magnetic islands present in the edge region, where radiation is expected.

The experimental configurations are shown in Figure 4.7. The configuration with $\iota(0)/2\pi = 0.48$ is an island divertor configuration with a toroidal mode number (n)

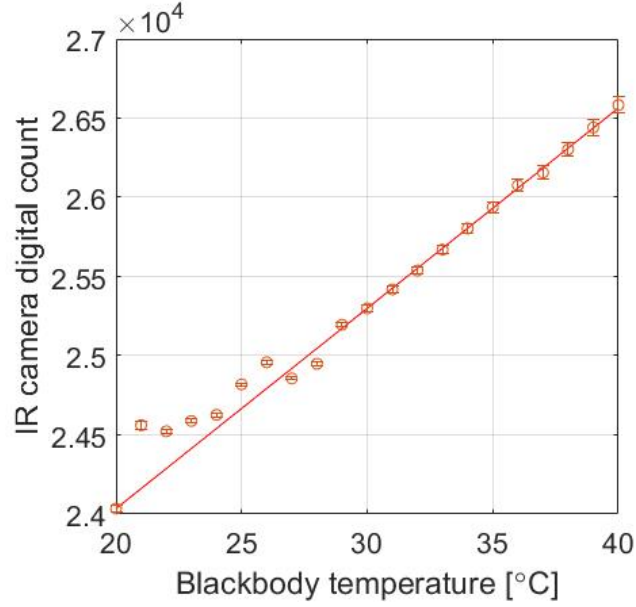


Figure 4.6: Results of the calibration

Table 4.1: List of magnetic configurations in rotational transformation scan

$\iota(0)/2\pi$	HV	TA	TB	AV	IV
0.48	82	74	82	-25	-25
0.52	83	73	80	0	-15
0.55	89	74	81	0	-30
0.56	93	71	78	0	-25
0.58	95	71	78	0	-40

of 4 and a poloidal mode number (m) of 8. Configurations with $\iota(0)/2\pi = 0.52$ and 0.58 represent limiter configurations. The configuration with $\iota(0)/2\pi = 0.55$ is the standard configuration, while $\iota(0)/2\pi = 0.56$ is a limiter configuration with an $n/m = 4/7$ magnetic island in the core region. The coil settings for each magnetic configuration are listed in Table 4.1.

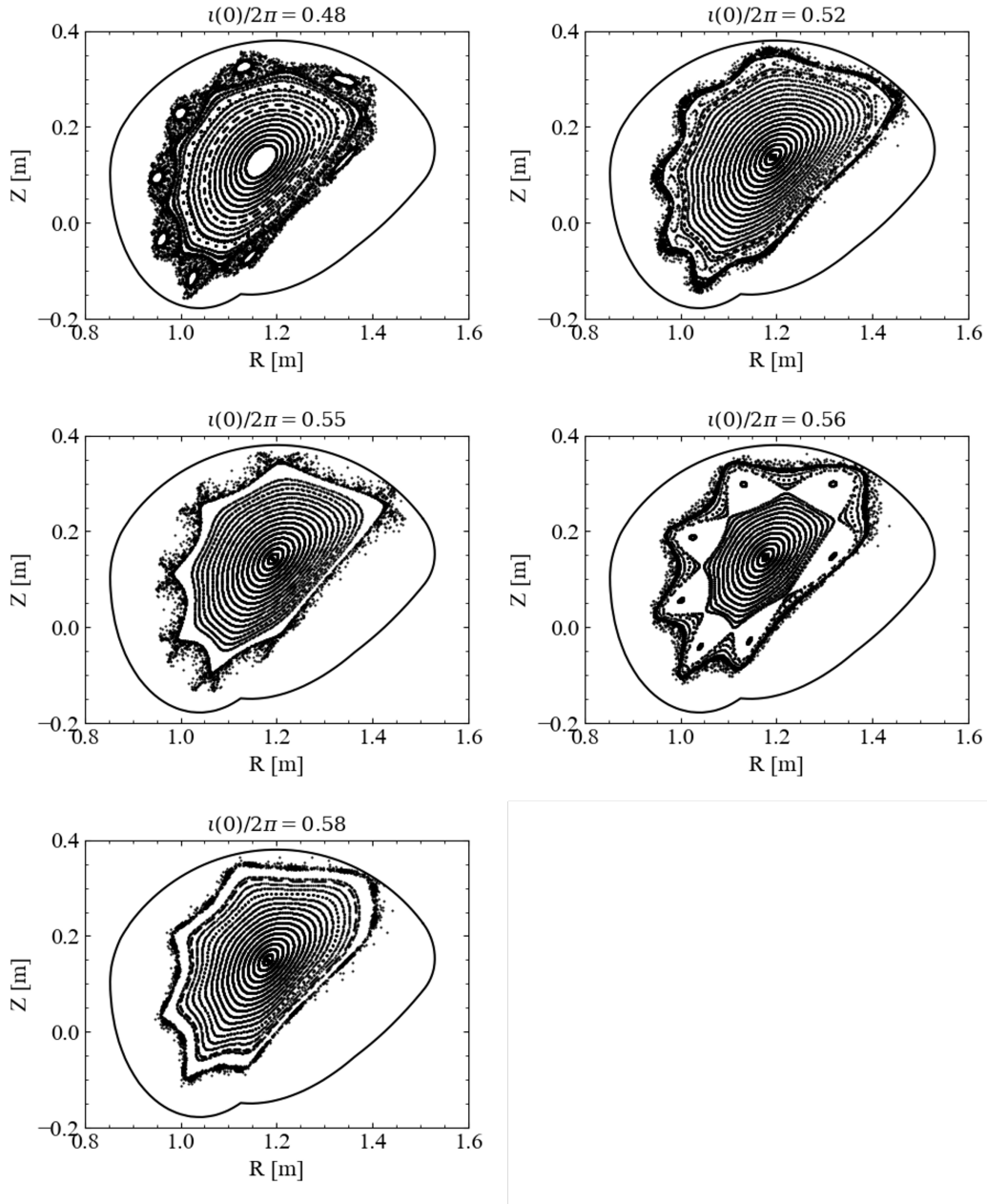


Figure 4.7: Poincaré plots of magnetic configurations with different rotational transforms.

4.4 Experimental results

4.4.1 Noise reduction from magnetic fields

The infrared camera used for measurements was selected for its capability to operate in a static strong magnetic field environment. However, in dynamic strong magnetic fields, significant noise was observed in the camera signals. In Heliotron J, the process of generating the magnetic field begins approximately one second before plasma discharge, with current supplied to each coil. During this period, noise appears in the camera signal, persisting even after the magnetic field reaches a steady state.

The noise was significantly reduced by twisting the two cables connecting the camera head to the camera body, suggesting that the noise source is likely a large loop formed between these cables, inducing loop currents. An example of noise induced by the magnetic field is illustrated in Figure 4.8. The horizontal axis represents the time (in seconds) from the onset of noise, corresponding to the start of the magnetic field ramp-up, while the vertical axis shows the average temperature change of the thin film. The blue line in the graph represents data for plasma shot #75158, while the orange line indicates data collected when the plasma was absent, with no 2.45 GHz microwave, ECH, or NBI heating applied.

The noise caused by the magnetic field, as indicated by the orange line, typically fluctuates around ± 1 °C and exhibits high reproducibility. Therefore, by taking the difference between data collected with and without plasma, it is possible to effectively remove the magnetic field-induced noise.

After processing to remove magnetic field noise, as shown in Figure 4.9, the temperature of the thin film rises starting around 1.0 seconds due to plasma radiation and then gradually decreases. However, it is important to note that this noise reduction method only provides relative temperature changes, not absolute temperature values. Consequently, it becomes impossible to directly convert the temperature distribution into a radiation distribution. Nonetheless, it is still feasible to estimate an approximate radiation distribution from the temperature data, allowing for meaningful analysis and discussion using the measured temperature distribution.

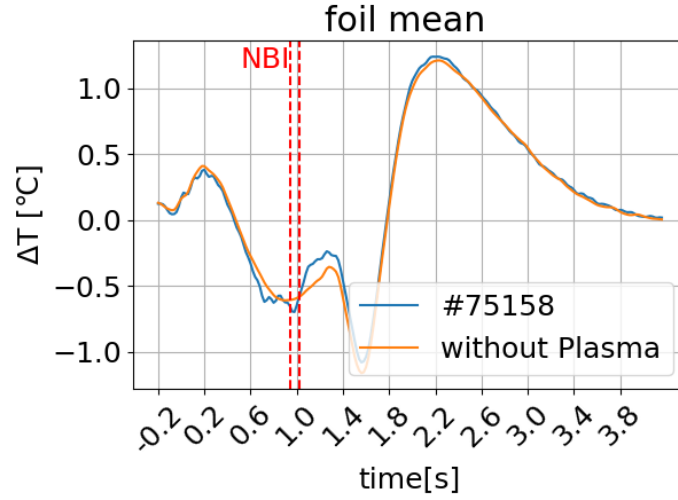


Figure 4.8: An example of noise induced by the magnetic field

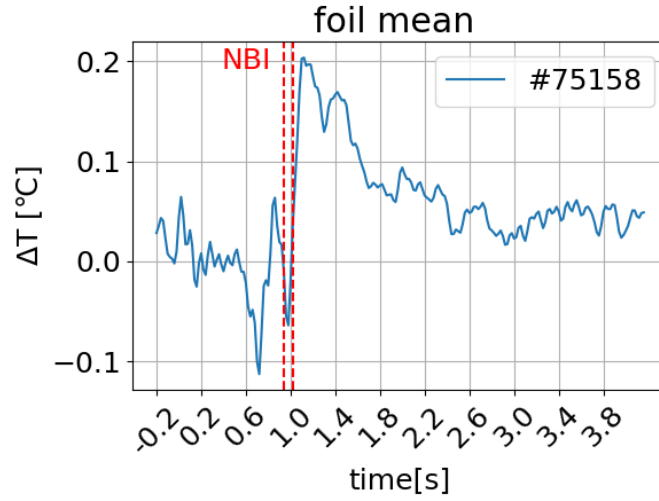


Figure 4.9: After processing to remove magnetic field noise

4.4.2 Influence of 2.45 GHz microwave

Figure 4.10 presents the measurement data for experiment #76435, in which 2.45 GHz microwaves were injected, but plasma was not generated. A temperature increase of approximately 1.5 °C is observed in the lower right portion of the figure.

This increase is likely due to the microwave energy not being absorbed by the plasma. Instead, the energy repeatedly reflected within the vacuum vessel and eventually heated the thin film through the pinhole.

However, given that the wavelength of the 2.45 GHz microwave is 12.2 cm, it is unlikely that it could pass through a 5 mm square pinhole and subsequently heat the thin film located 4.1 cm away from the pinhole. Therefore, it is possible that high-energy particles, which failed to initiate plasma formation, passed through the pinhole and collided with the thin film, causing a localized increase in its temperature.

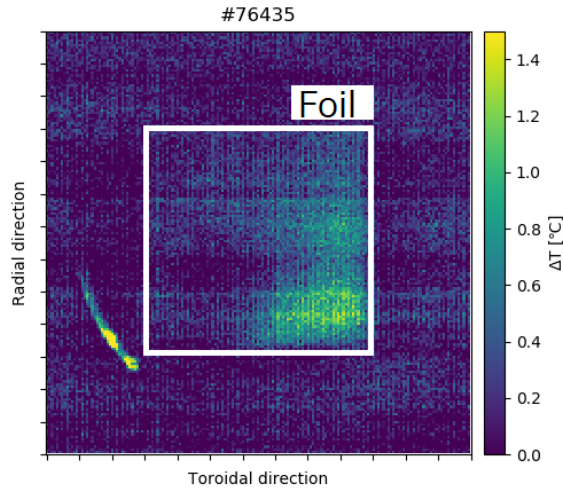


Figure 4.10: Influence of 2.45 GHz microwave

4.4.3 Impact of ECH

When ECH is used for plasma heating, the temperature of the entire thin film significantly increases compared to the conditions without ECH. In radiation measurements using AXUV, an increase in signal intensity by several times is considered unusual. This suggests that the 70 GHz microwave from the ECH likely enters through the pinhole and directly heats the thin film. Given that the wavelength of the 70 GHz microwave is 4.3 mm, it can easily pass through the 5 mm square pinhole.

Figure 4.11 shows the temporal change in the average temperature of the thin film for shot #75577, where plasma was heated solely with ECH, without using Neutral Beam Injection (NBI) heating. A sharp increase in temperature is observed at the moment when the ECH is injected. Additionally, Figure 4.12 illustrates the condition of the thin film after the temperature rise induced by the ECH. When compared with Figure 4.13, it is evident that the thin film's temperature increased by a factor of seven, even in regions not expected to receive plasma radiation. Furthermore, four bright spots were observed on the boundary between the thin film and the frame holding it. These bright spots appeared at the same locations regardless of the ECH injection angle or magnetic field configuration, suggesting that the ECH microwaves might be causing a rise in temperature in certain structures on the frame.

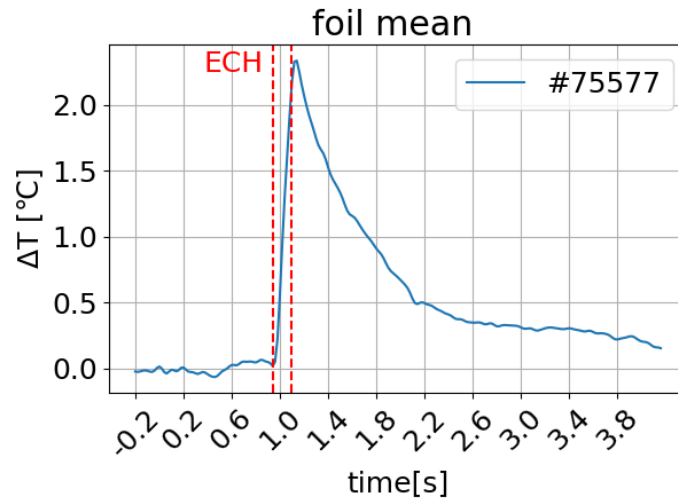


Figure 4.11: Temporal change in the average temperature of the thin film

4.4.4 Result of radiation measurement

IRVB measurements were performed in a neutral beam injected (NBI) plasma on the Heliotron J research device. A reproducible signal variation, induced by magnetic field generation, was observed. This variation was removed by subtracting

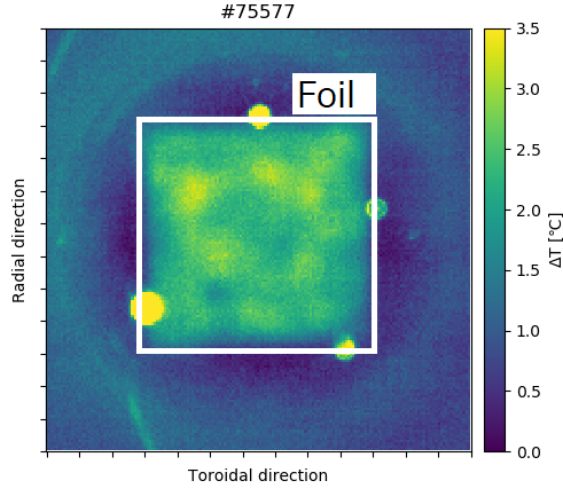


Figure 4.12: Condition of the thin film after the temperature rise induced by the ECH

data acquired with only the magnetic field on. Figure 4.13 compares radiation distribution simulated with EMC3-EIRENE and a typical spatial and temporal low-pass filtered temperature distribution increase from the background and only on the foil, ΔT . The temperature increase is observed during the discharge from the top to the lower right region of the foil while the temperature in the lower left does not show any response. This is as expected from the modeling shown in Figure 4.13(a). The upper region views the plasma core and has a larger ΔT increase than the other regions. The Absolute eXtreme UltraViolet (AXUV) intensity also has larger signals in the line of sight, where the plasma core is viewed [55,56]. Although the EMC3-EIRENE calculation result should not be directly compared to the IRVB results, due to the exclusion of radiation from the core, no response is found in the foil region with no plasma, as expected in the EMC3-EIRENE modeling.

The time evolution of the temperature on the foil is shown in Figs.4.14(a) and (b) with heating power from the magnetron and NBI. Here, the blue and orange lines are the ΔT averaged in the upper-half and lower-left regions of the foil, respectively. A seed plasma is produced with the assistance of 2.45 GHz non-resonant pre-heating and a high-temperature plasma is produced using NBI [57]. The ΔT gradually

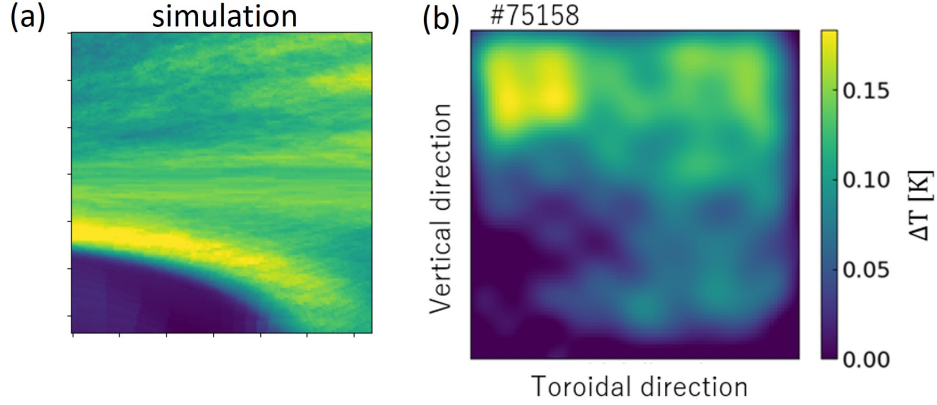


Figure 4.13: (a) Radiation distribution simulated with EMC3-EIRENE and (b) spatial distribution of temperature increase measured with IRVB in NBI plasma.

increases in the upper region at the timing of the magnetron turn-on and a sharp increase in ΔT is observed immediately after NBI injection. The magnetron is turned off at the same time as NBI injection, and hence only the plasma radiation should contribute to the ΔT response. The ΔT in the lower left (no plasma) region is kept around zero when the ΔT in the upper region increases. The maximum of the ΔT due to the plasma radiation, $\Delta T_{\max}^{\text{eff}}$, is 0.05 K. Note that pixel and time averaging are applied to reduce the NETD.

4.4.5 Comparison with AXUV

The $\Delta T_{\max}^{\text{eff}}$ is compared with the AXUV intensity in Fig. 4.15. The AXUV diode array with 16 channels measures the plasma radiation from the magnetic axis to the edge region. The AXUV signal is temporally integrated because the integrated value is related to the ΔT , and is spatially integrated to account for the effect of thermal diffusion in the foil. The error bars represent the standard deviation of the background signal level, estimated from data without plasma. Although the sensitivity of the AXUV depends on the wavelength of radiation [56, 58], it is proportional to the AXUV intensity. These results suggest that the IRVB can be used for plasma radiation measurements in small and medium size devices.

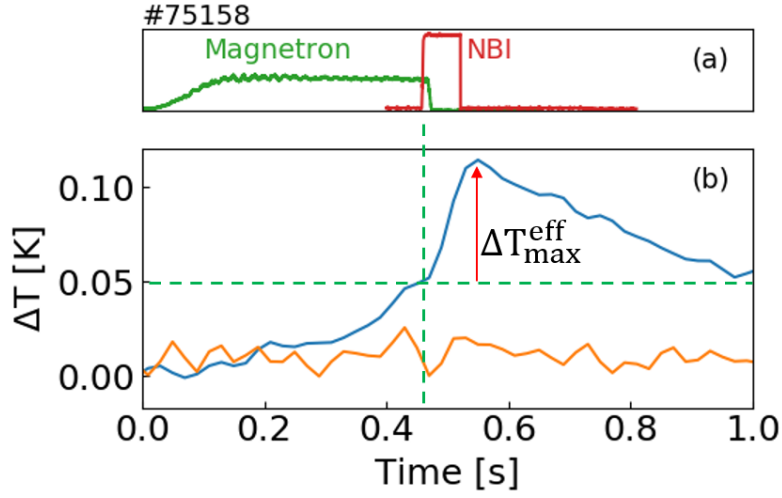


Figure 4.14: Time evolution of (a) magnetron and NBI power, and (b) the temperature of the foil. In (b), the blue and orange lines show the temperature increase in the upper and lower-left regions of the foil, respectively.

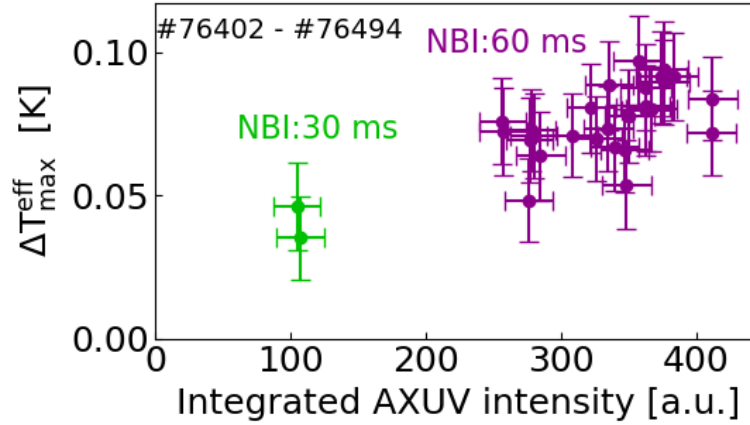


Figure 4.15: Comparison of the effective temperature increase in the foil with the integrated intensity of the AXUV. The offset of the temperature increase induced by the magnetron is considered.

4.4.6 Response to rotational transform

The radiation distribution was studied in different magnetic field configurations with different rotational transformations. The tops of Figure 4.16 show the correspondence between the magnetic surface and the IRVB measured line of sight at $\iota(0)/2\pi = 0.48$ and 0.58 , respectively. The bottoms of Figure 4.16 are the temperature distributions of the thin films in the respective configurations. The white dashed line in the center shows the area of toroidal channel 3 and radial channels from 0 to 6 when the thin film is divided into regions of $5\text{mm} \times 5\text{mm}$ each. This region corresponds to the IRVB measurement channel positions in top of Figure 4.16. At $\iota(0)/2\pi = 0.48$, Radial ch 4 shows an increase in the thin film temperature due to radiation from the edge magnetic islands. At $\iota(0)/2\pi = 0.58$, Radial ch 4 has a relatively low temperature increase. This may be due to the fact that the plasma region is smaller than that of $\iota(0)/2\pi = 0.48$.

The relationship between the temperature rise ΔT in toroidal ch 3 from radial ch 1 to 5 and the rotational transform is shown in Figure. 4.17. The tops of Figure 4.17 show the correspondence between the magnetic surface and the IRVB measured line of sight in each configurations. Regions of channel [3, 2] and [3, 5] are filled in red and purple, respectively. "all" means the average temperature increase over the entire thin film region. Each result corresponds to the [Toroidal, Radial] channel. Channel [3, 5] in $\iota(0)/2\pi = 0.48$ configuration is low, indicating the radiation outside the island is weak. Channel [3, 5] in $\iota(0)/2\pi = 0.55$ configuration is relatively high, indicating the radiation is expanded outside the LCFS. Channel [3, 2] in $\iota(0)/2\pi = 0.56$ configuration is high, indicating the radiation is large in the island. This result suggests that the radiation distribution is changing in dependence on changes in the magnetic field structure.

Comparison with EMC3-EIRENE calculations is important to confirm that the distribution reflects the magnetic island structure, and reproducible experiments with ECH discharges are needed to do so. In addition, it is necessary to eliminate noise due to the magnetic field in order to calculate the radiation distribution from the temperature distribution of the thin film. We will configure a measurement system that is not affected by noise due to ECH and magnetic fields, and conduct measurements in the future.

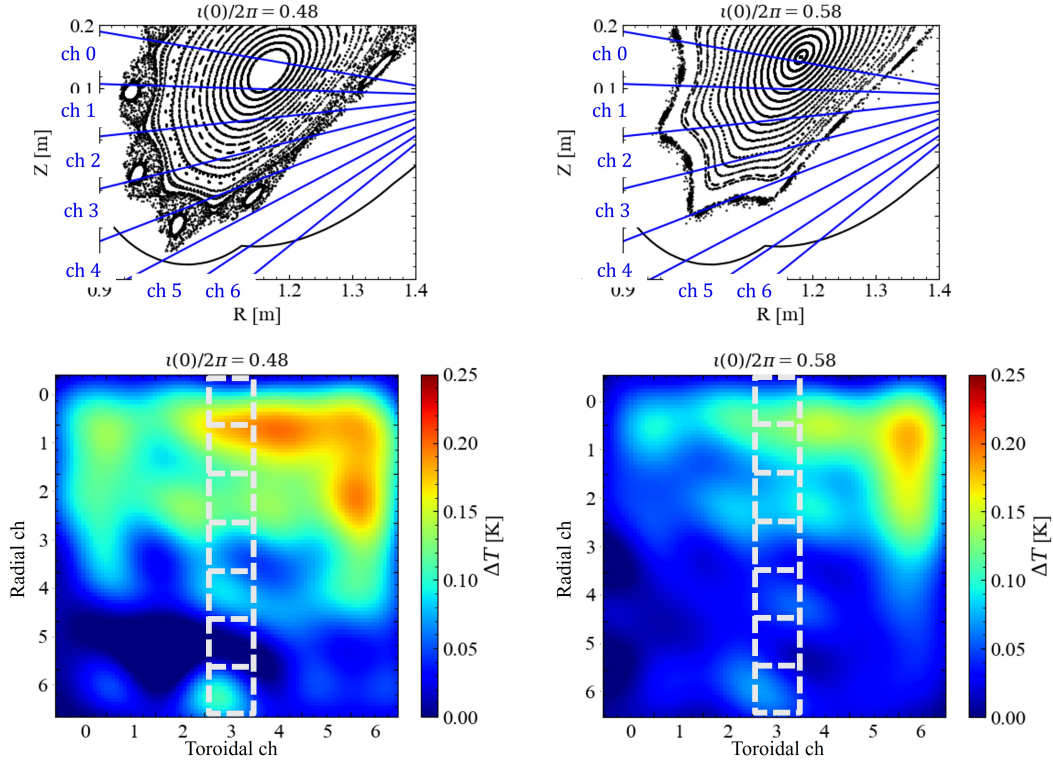


Figure 4.16: $\iota(0) = 0.48$ and 0.58 configuration and spatial distribution of temperature increase.

4.5 Summary

In this study, we developed an imaging bolometer to measure the radiation distribution of plasma in Heliotron J. Calibration experiments using an infrared camera confirmed a linear relationship between temperature and digital count values in the range of 20 °C to 40 °C. During the NBI startup experiments, a temperature increase was observed in the region expected to encompass the plasma core, while no significant temperature rise was detected in areas not anticipated to receive radiation.

When compared with radiation simulations conducted using the EMC3-EIRENE code, the results showed a general agreement in broader regions, such as the upper and lower sections, despite some detailed discrepancies. Furthermore, a correlation was identified between the increase in thin-film temperature and measurements from

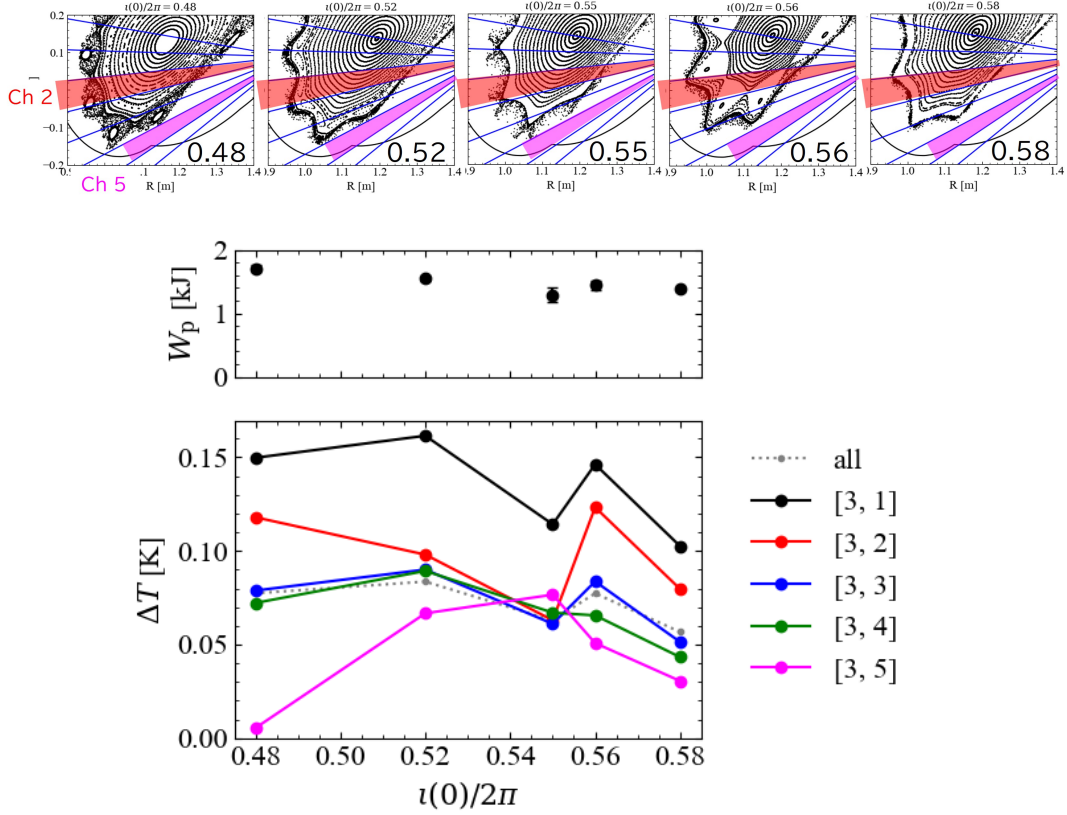


Figure 4.17: Temperature increase in [Toroidal, Radial] channel depend on rotational transform.

the AXUV diagnostics.

These findings suggest that IRVB measurements are feasible in Heliotron J, providing valuable insights into plasma radiation distribution.

The distribution of the temperature increase changes at different configurations of the magnetic field structure. In order to investigate the relationship with the magnetic island structure, it is necessary to compare the results with the radiation distribution simulation by EMC3-EIRENE. Radiation distribution measurements that are not affected by noise due to ECH and magnetic fields will be performed in the future. Higher sensitivity of IRVB and measurements in ECH plasmas are also needed.

A new thinner foil, using different materials such as titanium, is under devel-

opment since improvement of the IRVB sensitivity is required to measure spatial plasma radiation.

Chapter 5 Non-uniformity of fluctuation characteristics inside an edge magnetic island

5.1 Introduction

Understanding the impact of magnetic islands on plasma confinement in fusion devices is crucial. Typically, fusion plasma experiments strive to avoid the formation of rational surfaces or magnetic islands within the confined region, as these islands are believed to connect different flux surfaces via the X-point of the separatrix, thereby degrading plasma confinement. For instance, neoclassical tearing modes that produce magnetic islands can diminish plasma energy and potentially lead to disruptions in high beta plasmas [59]. Consequently, the suppression of magnetic islands using electron cyclotron current drive is often necessary [60].

Conversely, some studies have identified beneficial aspects of magnetic islands in relation to confinement characteristics. Within these islands, turbulence-driven transport is reduced, potentially enhancing confinement [26, 61]. The flow along magnetic field lines around the O-point of the island and the associated radial electric field structure have been examined [25, 62]. Discussions have emerged regarding the use of radial electric field shear around magnetic islands to control the foot position of electron internal transport barriers [63, 64]. Additionally, the interaction between magnetic islands and turbulence has been extensively reviewed [65].

Non-axisymmetric magnetic fields, including magnetic islands, are employed to manage heat and particle transport in the scrape-off-layer (SOL) and divertor regions, as well as in the confinement region. In the SOL and divertor regions, where parallel transport predominates, the geometry of a magnetic island can serve as a means to control heat and particle flow from the core to these regions. In tokamaks, resonant magnetic perturbation fields are introduced to control edge localized modes and mitigate heat and particle fluxes to the divertor [66]. In stellarator/heliotron

devices, the intrinsic three-dimensional field is utilized to test helical and island divertor concepts in large-scale devices [22, 67]. Attempts have been made to control magnetic islands through external perturbation fields in both tokamaks and stellarator/heliotron devices, with LHD achieving a relatively balanced energy state in the high-density region by managing particle transport in the peripheral region [24]. Additionally, the placement of magnetic islands has been reported to influence plasma performance during rotational transform experiments in W7-X [68].

However, the specific impact of magnetic island structure on fluctuations and fluctuation-driven transport requires further experimental investigation. At the periphery of the boundary between confined and unconfined regions, both parallel and perpendicular transport coexist and interact. Additionally, perpendicular transport, influenced by diffusive and non diffusive mechanisms like turbulence and blobs, impacts SOL plasma and broadens the divertor plate's footprint [69]. Previous research has shown that perpendicular transport often correlates linearly with the gradient of the SOL, but this relationship is modified by magnetic islands in the island divertor concept [70], suggesting that the effects of fluctuations and fluctuation-driven transport in edge magnetic islands are not yet fully understood.

This study aims to experimentally characterize the influence of edge magnetic islands on fluctuation characteristics and transport in the medium-sized fusion device, Heliotron J [71].

5.2 Experimental setup

5.2.1 Magnetic configuration

Heliotron J, a medium-sized helical-axis heliotron device, boasts a major radius (R) of 1.2 m, an average minor radius (a) ranging from 0.1 to 0.2 m, and a magnetic field strength on the magnetic axis of less than 1.5 T. It is equipped with a unique $L/M = 1/4$ continuous winding helical coil, where L represents the pole number and M the pitch number, along with two types of toroidal coils and three sets of vertical magnetic field coils. These components together produce a low magnetic shear configuration [34, 35, 43]. The device's magnetic configuration is adjustable, allowing for the alteration of current ratios in each coil. This adaptabil-

ity in Heliotron J enables the realization of island divertor-like SOL configurations by controlling the rotational transform. Here, the rational surface determines the last closed flux surface (LCFS) in Heliotron J. Figure 5.1 illustrates the connection length distribution in configurations with and without an edge magnetic island, while figure 5.2 displays the rotational transform profiles for each configuration. The chosen configuration, devoid of an edge magnetic island, is the low bumpiness configuration [39,41], where the rotational transform at the LCFS is approximately $4/7$. This configuration allows the probe to traverse the typical SOL in Heliotron J. In contrast, the island configuration features a rational surface with a rotational transform $\iota/2\pi = 4/8$ at the plasma's periphery, resulting in an island structure beyond the LCFS. Consequently, part of the magnetic island formed on this rational surface intersects with the vacuum vessel. The island exhibits a nested flux surface structure with a lengthy connection length (over 1000 m), akin to the core plasma region in vacuum conditions.

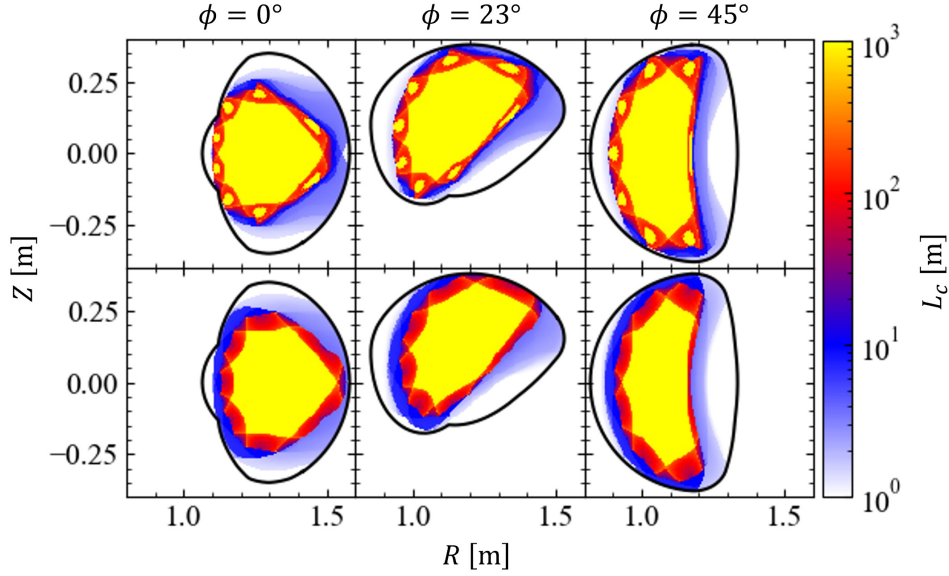


Figure 5.1: Connection length distribution in different configurations. Upper row shows the connection length in the island configuration, and lower row illustrates the connection length in the configuration without an island.

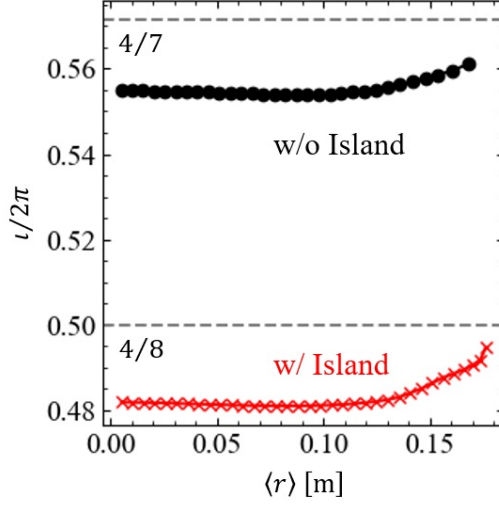


Figure 5.2: Rotational transform profiles. The black line shows the rotational transform profile for the configuration without magnetic islands, while the red line shows the rotational transform profile for the island configuration. The horizontal axis $\langle r \rangle$ corresponds to the average minor radius.

5.2.2 Multipin Langmuir probe

In this study, a Langmuir probe is employed to measure plasma parameters and their fluctuations in the peripheral region. Figures 5.3(a) and (b) illustrates the probe path, depicted as a green line, which traverses the O-point of the island in the island configuration and a simpler SOL in the configuration without the island. Figure 5.3(c) displays the connection length L_c along the probe path. The horizontal axis represents the distance Δr from the LCFS, with the observation region lying in the SOL outside the LCFS. The red and black lines in figure 5.3(c) represent L_c in the island and non-island configurations, respectively. In the island configuration, a long L_c region (1000m) is flanked by areas with shorter L_c (200m), whereas L_c remains consistently short in the configuration without the island.

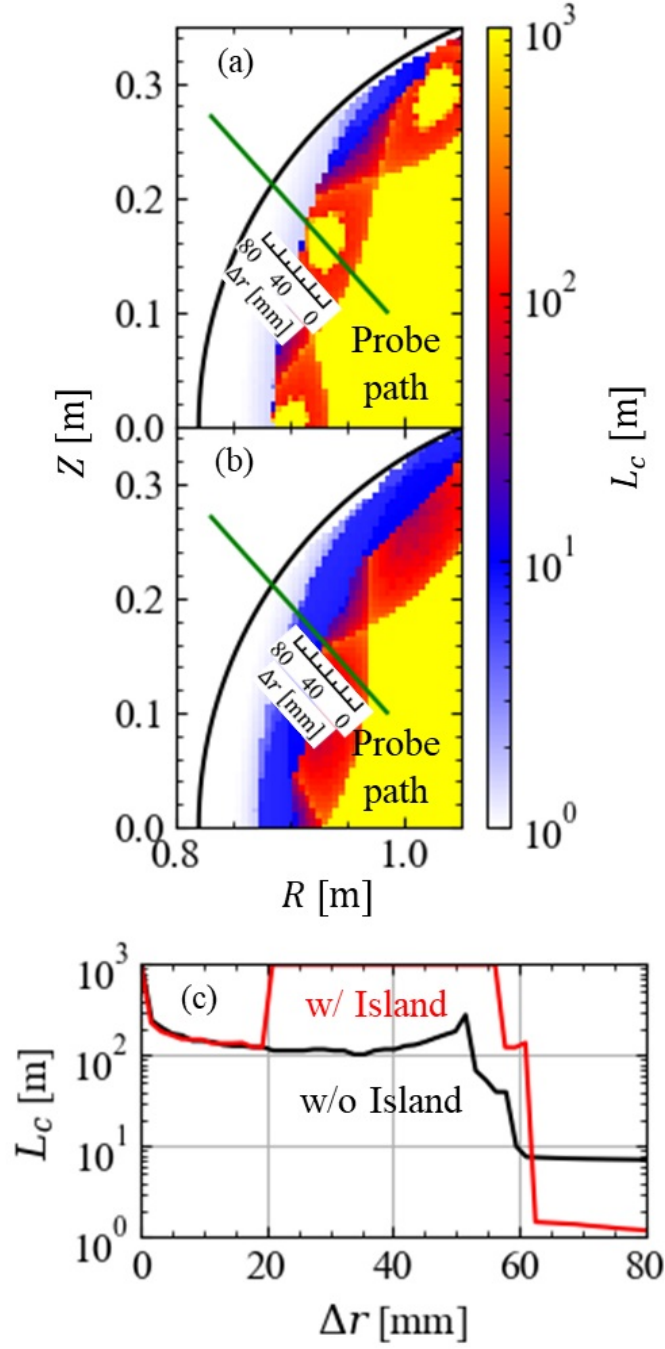


Figure 5.3: Connection length distribution of (a) the island configuration and (b) the configuration without an island around the probe path. Green line indicates the probe path. (c) Connection lengths on the probe path. Δr indicates the distance from the LCFS.

The probe head, designed specifically for measuring plasma fluctuations as well as plasma parameters, is depicted in figure 5.4. Constructed from boron nitride, the probe head features a 5-pin poloidal array organized in five columns with alternating poloidal radial positions. The cylindrical pins are tungsten, each with a diameter and length of 1 mm protruding from the probe head. Adjacent pins are spaced 2.5 mm apart in the poloidal direction and 3 mm radially. This setup enables triple probe operation to measure electron density n_e , temperature T_e and space potential V_s from the ion saturation current I_{s2} , floating potential V_{f2} and probe bias V_p . The radial electric field E_r can be determined by calculating the radial gradient of V_s . In addition, the probe can assess radial fluctuation-driven particle flux Γ_e from the poloidal electric field E_θ , measured by the poloidally separated floating potential (V_{f1}, V_{f2}) signals, and the ion saturation current I_{s2} signal. The green lines in figures 5.3(a) and (b) correspond to the center of the probe head.



Figure 5.4: Side view of the probe head and its channel setup.

The experiment was conducted in two magnetic configurations: with and without the edge magnetic island. The aim was to compare the impact of the magnetic island on turbulence fluctuation and turbulence-driven transport. Electron cyclotron heating (ECH) of 250 kW was applied. The probe underwent radial scans on a shot-by-shot basis to acquire radial profiles under fixed conditions. The shot set for the island configuration is #79880-#79909, and for the configuration without the island is #82989-#83017.

5.3 Experimental results

5.3.1 Heat pulse propagation in the island configuration

The presence of magnetic islands in plasmas is significantly influenced by plasma current and beta values, even in cases where a magnetic island exists in a vacuum [72]. Therefore, heating modulation experiments serve as an effective method for experimentally confirming the presence of magnetic islands. A magnetic island alters heat propagation, characterized by rapid propagation of heat pulses at the island's boundaries and relatively slower decay towards the O-point. This heating modulation technique has been previously utilized to investigate the island's impact on heat transport in core plasmas [73, 74]. In this study, a modulational ECH with a frequency of 100 Hz and a 30% power modulation was applied to the island configuration. This approach was intended to confirm the existence of the edge magnetic island during discharge, which in turn revealed the edge plasma's response reflecting the island's structure. Measurements were conducted under conditions with an average electron density of $0.8 - 1.0 \times 10^{19} \text{m}^{-3}$. The magnetic field intensity was adjusted to centralize ECH heating. The averaged electron temperature (T_e) profile, the modulated T_e amplitude profile, and the phase difference $\Delta\phi$ between the modulational ECH and T_e are presented in figure 5.5. In the island region of $\Delta r = 20 - 50$ mm, (b) a slight peak in the T_e profile, (c) a local drop in the modulated T_e amplitude profile, and (d) a larger $\Delta\phi$ value indicating delayed heat penetration into the island region were observed. These results suggest that heat transport is substantially affected by the island at the edge region, possibly due to heat propagation along the island's outer surface, aligning with past observations in the confined region [73, 74]. A comparison of heat pulse propagation between open field regions and magnetic island regions has not yet been conducted. It would be beneficial to compare the results of the heating modulation experiment between the island configuration and the configuration without an island in future work. The actual position of the magnetic island, as revealed by this experiment, remained largely consistent with its position in the vacuum state, indicating that the impact of plasma current and beta on the edge magnetic field structure is not significant in this experiment.

Furthermore, we take the calculation error of about 5 mm in defining the magnetic island location into consideration, which is estimated from coil current control precisions. Additionally, there may be an uncertainty of approximately 1-2 mm in the probe radial localization, taking into account the size and shape of a set of triple probe electrodes. Therefore, we assume that the position of the island boundary has an uncertainty of ± 5 mm based on the field tracing calculation in this study. This is represented as a hatched area in all relevant figures.

5.3.2 Radial profiles of steady-state plasma parameters

Under the same experimental conditions as the heat modulation experiment, this study also includes fluctuation measurements within the magnetic island. The edge plasma parameter profiles exhibit distinct characteristics in the configurations with and without the island. Figure 5.6 compares the profiles of electron density n_e , electron temperature T_e , spatial potential V_s and radial electric field E_r . The black and red lines in figure 5.6 represent the results for the configurations without and with the island, respectively. The edge n_e in the island configuration is more than twice that in the configuration without the island. This elevated n_e in the SOL is attributed to the presence of an island with a long connection length relative to the confinement region. The n_e within the island remains nearly constant. The T_e inside the island is lower on the wall side, and its profile is relatively flat, albeit not completely, differing from the flat T_e profile observed inside core plasma islands in other studies [25, 72, 75].

If parallel transport predominates over perpendicular transport, the temperature within the island should be uniform, a result of rapid parallel heat transport along magnetic field lines, as documented in core plasma experiments [25, 76]. However, this uniformity is not observed, indicating that transport within the magnetic island, located at the peripheral region of the confined area, is complex. The magnetic field structure of the island is inherently three-dimensional, and resultantly, heat sources from the core plasma and sinks to the divertor are localized in specific regions due to the configuration's three-dimensionality. These conditions may realize the situation that perpendicular transport would also play a significant role, as well as parallel transport, inside the island localized in the edge region, indicating

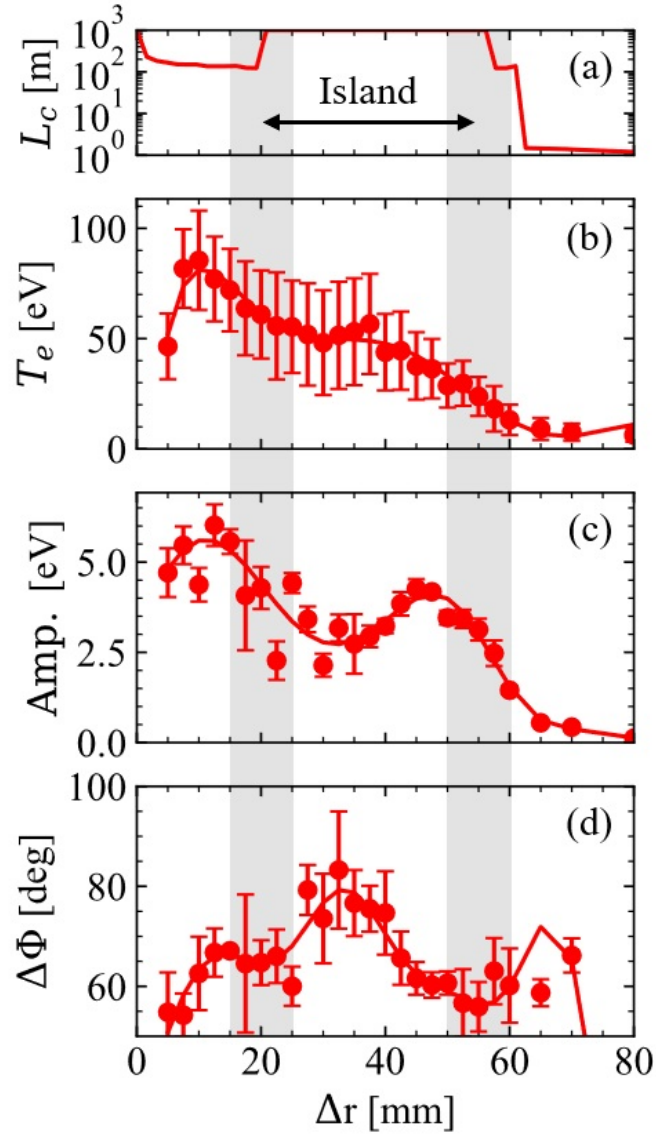


Figure 5.5: Profiles of (a) connection length distribution, (b) time averaged T_e , (c) amplitude, and (d) phase delay. The two vertical grey hatched area indicate the boundaries of the magnetic island. Δr indicates the distance from the LCFS.

the observed parameter non-uniformity along the magnetic field line. The T_e difference between the inner and outer island boundaries can be understood in the context described above. However, further experimental investigation and numeri-

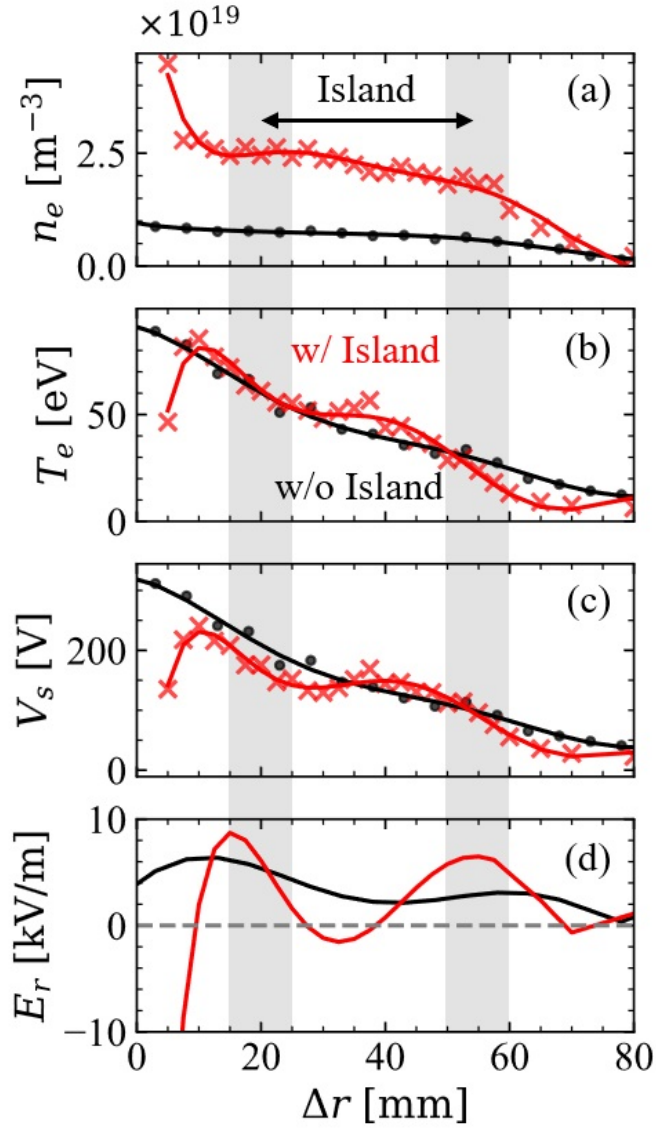


Figure 5.6: Radial profiles of (a) electron density, (b) electron temperature, (c) space potential, and (d) radial electric field. Black line represents the configuration without magnetic islands, while the red line represents the island configuration. Δr indicates the distance from the LCFS.

cal study would be beneficial. This is beyond the scope of the present manuscript and will be a part of future work.

One should note that a temperature reduction at $\Delta r = 5$ mm in the island configuration is observed, and there are a few factors that should be considered, although it is difficult to conclude the reason. Firstly, the operation range of the triple probe measurement should be considered. Generally, the triple probe needs to be biased more than $3T_e$, and in this experiment, 200 V was applied. However, the temperature at $\Delta r = 10$ mm is already at the maximum measurable temperature of 70-80 eV. As the probe approaches the core plasma, the electron temperature is expected to increase and hence the triple probe measurement might not be reliable when the temperature at $\Delta r = 5$ mm is higher than at 10 mm. Additionally, we must consider the interaction between plasma and probe material, which may reduce the temperature at the measurement position due to sputtering. Both factors are likely to contribute to the electron temperature reduction at the closest position to LCFS.

Moreover, the island region exhibits a notable impact on the electric field. In the configuration without the island, V_s decreases monotonically as the probe moves away from the LCFS. Conversely, in the island configuration, variations in both V_s and E_r profiles are observed inside the island. These differences could potentially generate poloidal flow and influence transport within the island. In magnetic islands located in the confined region, a reversal of the radial electric field has been observed, along with a structure where the poloidal flow is reversed around the O-point of the magnetic island [25,62]. These findings, however, do not align with the current observations. The exact mechanisms remain unclear, but one hypothesis is that the magnetic island may be influenced by parallel flows in the open magnetic field line region surrounding it [77].

5.3.3 Fluctuation characteristics in configuration with and without islands

Influence of magnetic island on broadband fluctuation characteristics

The presence of a magnetic island notably impacts broadband turbulence in the edge region. Figure 5.7 presents typical frequency spectra of the ion saturation current (I_s) and floating potential (V_f) fluctuations. These results, obtained at

$\Delta r = 20$, indicate distinct differences between the two configurations. In the I_s spectrum, the island configuration exhibits stronger fluctuations around 10 kHz compared to the non-island configuration and displays a notable peak at 250 kHz. The V_f spectrum in the island configuration shows increased fluctuations across a broader frequency band than in the configuration without the island. The low coherence between I_s , V_f and the magnetic probe signal, as shown in figure 5.7, suggests that the magnetohydrodynamic instability component of these fluctuations is not significant in this analysis.

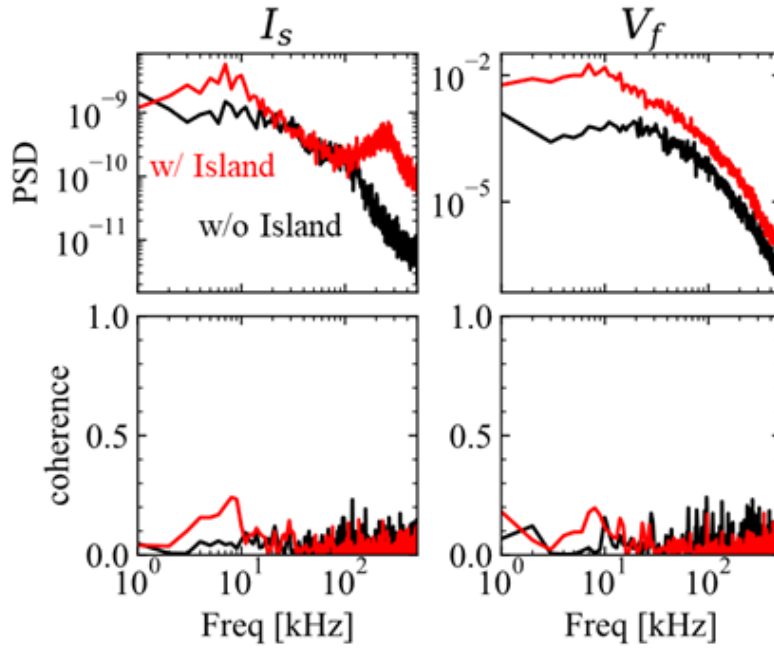


Figure 5.7: Typical PSD of I_s and coherence between I_s and a magnetic probe. Typical PSD of V_f and coherence between V_f and a magnetic probe.

The presence of a magnetic island influences the spatial structure of the fluctuation characteristics. Figure 5.8 illustrates the spatial distribution of I_s and V_f power spectrum density for configurations with and without a magnetic island. In the configuration without a magnetic island, I_s and V_f fluctuations decrease radially outward. Conversely, in the magnetic island configuration, I_s fluctuations around 10 kHz are pronounced near the magnetic island region, and V_f fluctuations below

10 kHz are elevated in parts of the island. Figure 5.9 shows the normalized fluctuation intensity profiles for each configuration, including frequencies ranging from 1 kHz to 100 kHz. The angular brackets $\langle \dots \rangle$ here mean ensemble average over a time interval of 20 ms. In the non-island configuration, the normalized fluctuation intensities, $\tilde{I}_s/\langle I_s \rangle$ and $\tilde{V}_f/\langle T_e \rangle$, remain constant in the SOL region. However, in the island configuration, $\tilde{I}_s/\langle I_s \rangle$ significantly increases from the center to the outer region of the magnetic island, and $\tilde{V}_f/\langle T_e \rangle$ locally intensifies in parts of the island. Despite a flat profile and small gradient within the island's inner region, as depicted in figure 5.6, fluctuations are not locally suppressed, differing from previous findings where fluctuation profiles in magnetic islands within the confinement region were locally diminished [27]. This observation suggests that the fluctuations are not solely driven by local gradients-induced turbulence but may also be influenced by other factors, such as turbulence spreading.

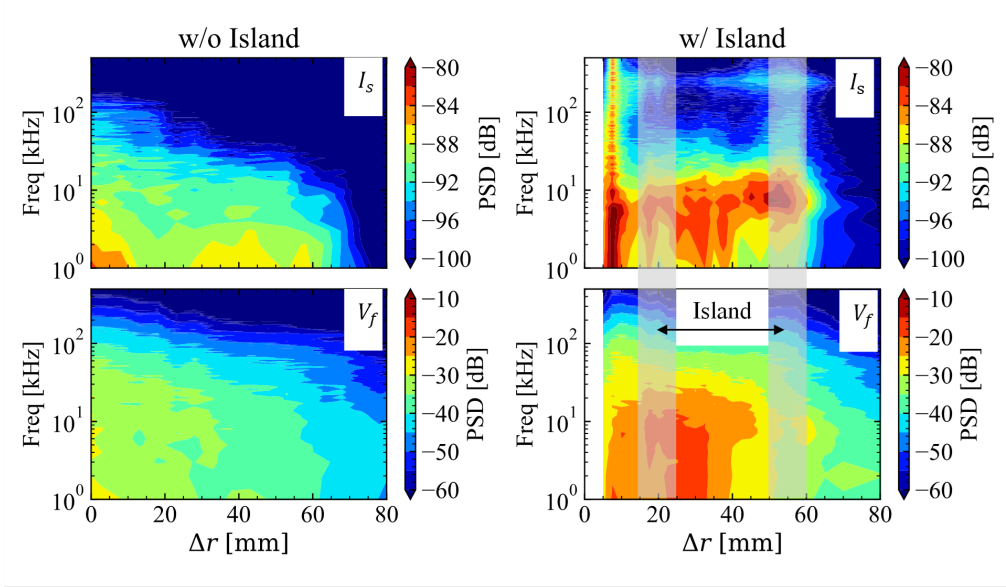


Figure 5.8: Spatial distribution of I_s and V_f spectra. The upper row shows the radial power spectrum density profile of I_s , and the lower row shows V_f . Here, the left column corresponds to the configuration without a magnetic island, and the right column corresponds to the island configuration. Δr indicates the distance from the LCFS.

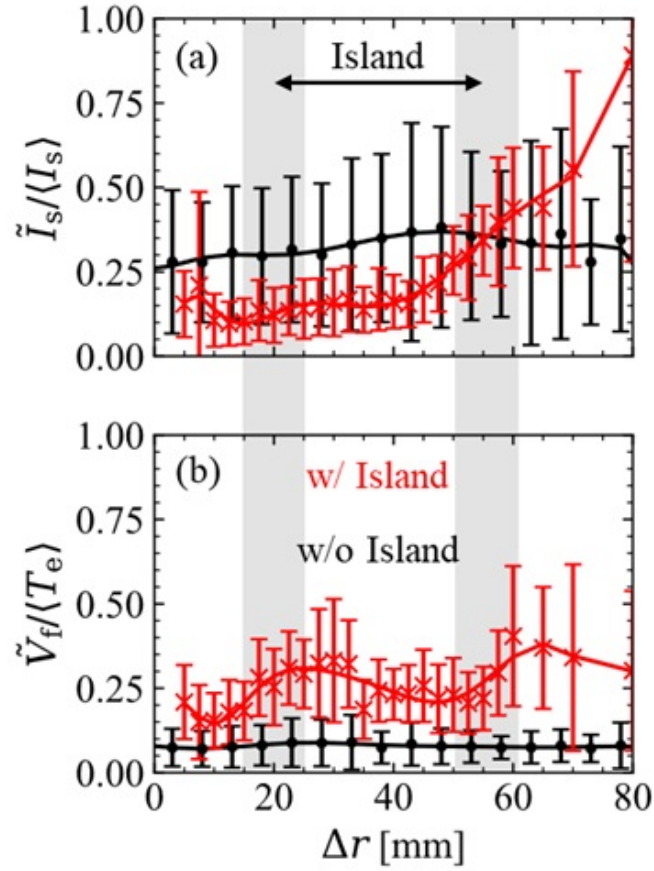


Figure 5.9: Radial profiles of normalized fluctuation intensities of (a) $\tilde{I}_s/\langle I_s \rangle$ and (b) $\tilde{V}_f/\langle T_e \rangle$. Δr indicates the distance from the LCFS.

Impact of magnetic islands on intermittent transport

Differences in statistical characteristics of the fluctuations are observed in the comparison between configurations with and without an island. Figure 5.10 compares the distributions of skewness S and kurtosis K of I_s with and without an island. In the configuration without an island, both S and K are positive, suggesting that intermittent, out ward transport, like plasma blobs, could occur in the SOL region, as observed in many tokamaks and stellarators [31, 78]. However, in the island configuration, both S and K are close to zero inside the island, i.e. the

PDF is close to Gaussian. Outside the island region, these values drop at the outer bound ary and become larger, suggesting blob-like and hole-like behavior around $\Delta r = 50$, with more hole-like behavior inside and more blob-like behavior outside. This indicates that inter mittent transport is suppressed inside the island, while it is enhanced outside the island.

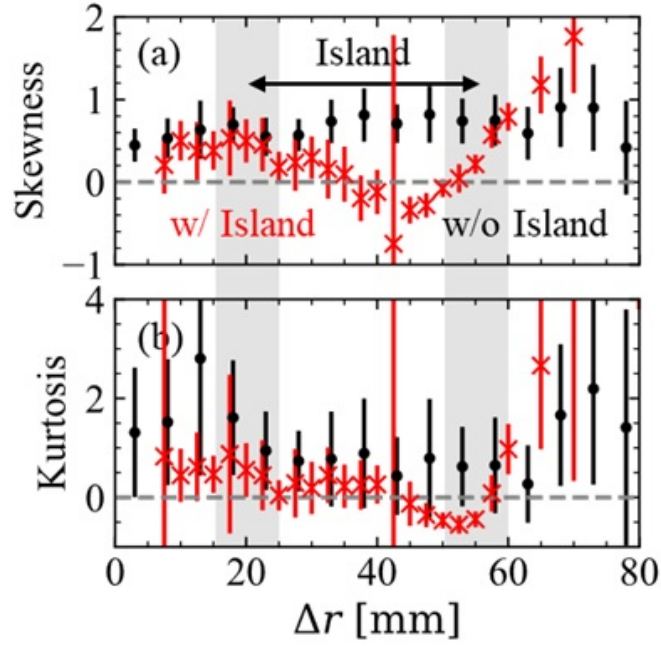


Figure 5.10: Radial profiles of (a) skewness and (b) kurtosis of I_s . Δr indicates the distance from the LCFS.

Coexistence of different turbulence mechanisms in a magnetic island

The analysis of the driving mechanism of density fluctuation within the magnetic island reveals that both gradient-induced driving and turbulent spreading contribute to these fluctuations. Figure 5.11 displays the profile of I_s , its gradient $-dI_s/dr$, fluctuation intensity $\langle \tilde{I}_s^2 \rangle$, and the spread of the fluctuation $\langle \tilde{I}_s^2 \tilde{E}_\theta \rangle$. Here, E_θ is calculated under the assumption of negligible electron temperature fluctuation since they are difficult to evaluate with the Heliotron J probe system. The validity

of this assumption is discussed in section 5.4. $\langle \tilde{I}_s^2 \tilde{E}_\theta \rangle$ serves as an indicator of the radial direction in which the fluctuation spreads, with positive values indicating outward radial spreading and negative values indicating inward radial spreading. In the non-magnetic island configuration (represented by the black line), the profiles of $\langle \tilde{I}_s^2 \rangle$ and $\langle \tilde{I}_s^2 \tilde{E}_\theta \rangle$ structures are largely monotonic, although there are regions where $-dI_s/dr$ is almost zero. In contrast, the magnetic island configuration (represented by the red line) shows a symmetric profile of $-dI_s/dr$ about the magnetic island, with a large value at the outer edge and a minimal value near the center. The intensity of fluctuations is enhanced at the outer edges but remains consistent at the center without a clear minimum. The profile of $\langle \tilde{I}_s^2 \tilde{E}_\theta \rangle$ suggests outward spreading from the magnetic island and inward spreading towards its interior.

To identify the driving mechanism of particle flux within the magnetic island, the turbulence drive ω_D and spreading ω_S terms are evaluated, based on the methodology outlined in the literature [79, 80] (figures 5.12(a) and (b)). According to these studies, the time evolution of free turbulent energy $\langle \tilde{n}^2 \rangle$ is given by:

$$\frac{1}{2} \frac{\partial}{\partial t} \langle \tilde{n}^2 \rangle = - \left\langle \frac{\partial n}{\partial r} \right\rangle \langle \tilde{v}_r \tilde{n} \rangle - \frac{1}{2} \frac{\partial}{\partial r} \langle \tilde{v}_r \tilde{n}^2 \rangle \quad (5.1)$$

where $\tilde{n} = n - \langle n \rangle$. The first term on the RHS of this equation is associated with local turbulence drive due to the background gradient, and the second term is a nonlocal nonlinear term related to turbulence spreading. By normalizing with the local turbulence amplitude $\langle \tilde{n}^2 \rangle$, the rate of turbulence drive ω_D and spreading ω_S are defined as:

$$\omega_D = - \frac{2 \left\langle \frac{\partial n}{\partial r} \right\rangle \langle \tilde{v}_r \tilde{n} \rangle}{\langle \tilde{n}^2 \rangle} \quad (5.2)$$

$$\omega_S = - \frac{\frac{\partial}{\partial r} \langle \tilde{v}_r \tilde{n}^2 \rangle}{\langle \tilde{n}^2 \rangle} \quad (5.3)$$

Here, assuming $n \propto I_s$ and neglecting electron temperature fluctuation, we obtain:

$$\omega_D = - \frac{2 \left\langle \frac{\partial I_s}{\partial r} \right\rangle \langle \tilde{I}_s \tilde{E}_\theta \rangle}{B_T \langle \tilde{I}_s^2 \rangle} \quad (5.4)$$

$$\omega_S = - \frac{\frac{\partial}{\partial r} \langle \tilde{I}_s^2 \tilde{E}_\theta \rangle}{B_T \langle \tilde{I}_s^2 \rangle} \quad (5.5)$$

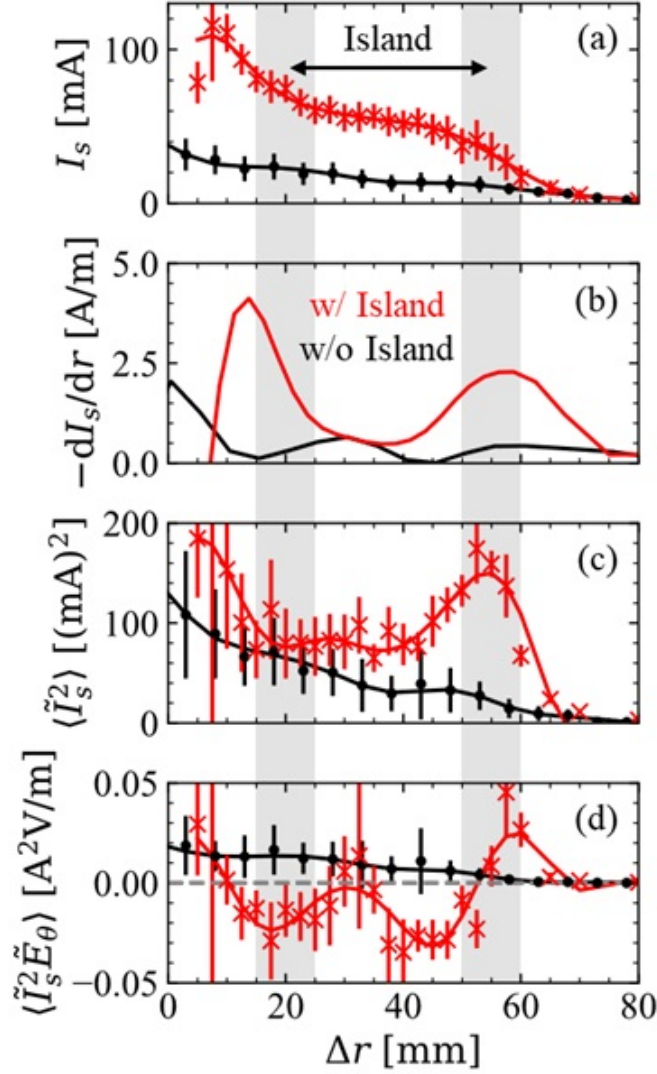


Figure 5.11: Radial profiles of I_s , $-dI_s/dr$, $\langle \tilde{I}_s^2 \rangle$, and $\langle \tilde{I}_s^2 \tilde{E}_\theta \rangle$. The black line represents the configuration without a magnetic island, while the red line represents the island configuration. Δr indicates the distance from the LCFS.

The angular brackets $\langle \dots \rangle$ here mean ensemble average over a time interval of 2 ms.

In the configuration without the island, both the turbulence drive rate (ω_D) and the turbulence spreading rate (ω_S) are nearly constant across the SOL region. However, in the island configuration, ω_D remains constant within the island but

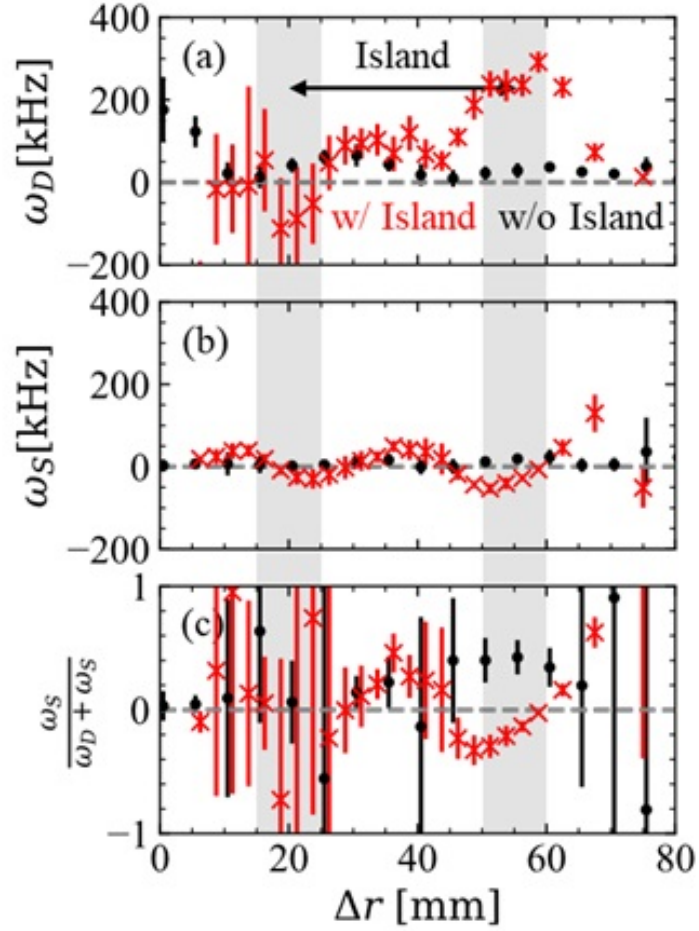


Figure 5.12: Radial profiles of (a) $\tilde{I}_s$ intensity, (b) $\tilde{E}_\theta$ intensity, and (c) averaged $\tilde{I}_s^2 \tilde{E}_\theta$. Δr indicates the distance from the LCFS.

is significantly higher at its outer boundary. Conversely, ω_S turns negative at both boundaries of the island and peaks at the center. The contributions of turbulence spreading are assessed using $\omega_S/(\omega_D + \omega_S)$ (figure 5.12(c)). In the island configuration, the influence of turbulence spreading increases both within and at locations radially distant from the magnetic island. These findings indicate that the edge magnetic island substantially affects the behavior of turbulence driving and spreading, with various turbulence mechanisms coexisting and displaying distinct spatial structures in the SOL region.

5.3.4 Turbulence-driven particle flux

Figure 5.13 summarizes the profiles of the fluctuation amplitudes of ion saturation current ($\tilde{I}_s$), poloidal electric field ($\tilde{E}_\theta$), and the electron particle flux ($\Gamma_e(\propto \tilde{I}_s \tilde{E}_\theta)$), evaluated in the frequency range from 1 kHz to 100 kHz. In the configuration with out the island, all fluctuation amplitudes decrease monotonically as the probe moves radially outward from the LCFS. In the island configuration, $\tilde{I}_s$ is consistent within the island but peaks at its outer boundary. Meanwhile, $\tilde{E}_\theta$ peaks inside the island. The differing peak positions of $\tilde{I}_s$ and $\tilde{E}_\theta$ result in two peaks in Γ_e at two distinct locations: the island's central region and outer boundary. This observation suggests that fluctuation characteristics within the edge magnetic island are not uniform, leading to a spatial structure in the fluctuation driven particle flux inside the island, even though the profile shape remains relatively flat within the magnetic island.

5.4 Discussion

Here, we examine the structure of turbulent fluctuations within the magnetic island in Heliotron J. Key observations in the magnetic island include:

- The presence of small gradients.
- An approximately equal contribution from turbulence driving and spreading at the center of the magnetic island.
- A decrease in turbulence spreading towards the outer edge, with values becoming negative.
- A peak in $\tilde{E}_\theta$ at the center, aligning with the peak of the turbulence-driven particle flux.

Despite small gradients at the center of the edge magnetic island, fluctuations are more pronounced compared to the configuration without a magnetic island. The sources of these fluctuations appear to be a different spatial structure towards the boundary of the magnetic island. While turbulence driving and spreading have similar values in the inner part of the edge magnetic island, there are distinct driving

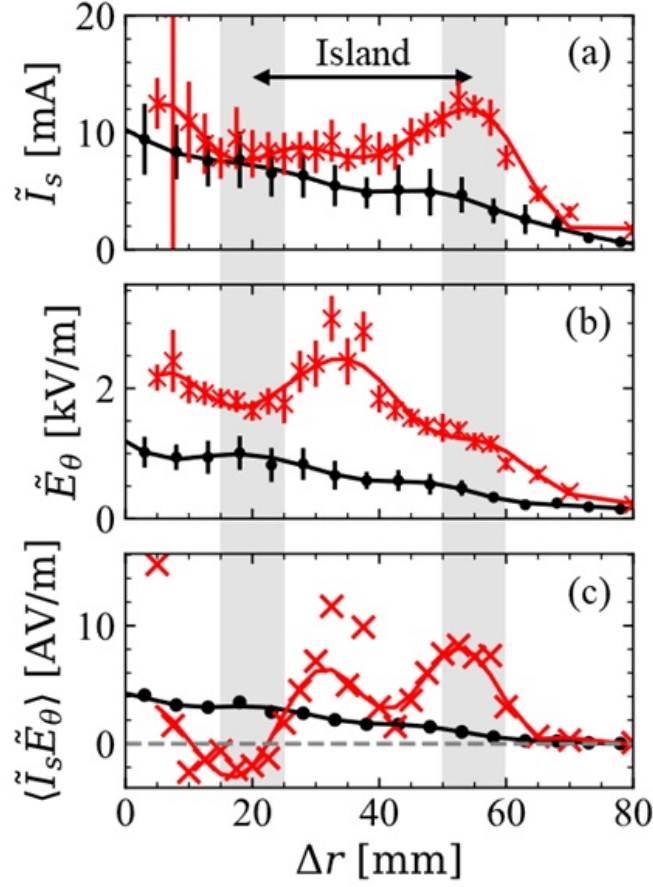


Figure 5.13: Radial profiles of (a) $\tilde{I}_s$ intensity, (b) $\tilde{E}_\theta$ intensity, and (c) averaged $\tilde{I}_s \tilde{E}_\theta$. Δr indicates the distance from the LCFS.

mechanisms for fluctuations within and near the magnetic island, each characterized by non-uniform spatial features. The long connection length, akin to that of the confinement region, may facilitate the coexistence of multiple mechanisms driving these fluctuations. Our interpretation is that there are two types of turbulence: turbulence spreading, which originates and spreads from other radial regions (likely from the core plasma inside LCFS), and turbulence driven by local gradients within the island. Moreover, the detection of poloidal electric field fluctuations at the center of the magnetic island, as illustrated in figure 5.13, indicates the presence of a driving factor for these fluctuations, resulting in a central peak. This suggests that density

fluctuation and poloidal electric field fluctuation within the magnetic island are not directly proportional but are instead decoupled. The driving mechanism behind these poloidal electric field fluctuations cannot be fully understood using current methods of analyzing turbulence driving and spreading. As a preliminary conclusion, it appears that at least three distinct types of fluctuation mechanisms may coexist within the island, resulting in subdominant perpendicular transport in addition to dominant parallel transport. However, further experiments are necessary to confirm this hypothesis and to measure the effects at multiple toroidal/poloidal positions.

At the outer boundary of the magnetic island:

- Large gradients are evident.
- Density fluctuations are significant, indicating the potential for inward and outward spreading of these fluctuations.
- There is a possibility of observing hole-like features inside and blob-like features outside the island.
- The influence of turbulence driving is more pronounced.
- The turbulence-driven particle flux is considerably high.

At the outer boundary, turbulence is believed to be driven by the steep gradient resulting from varying connection lengths. Similar to phenomena observed around the LCFS of other confinement devices, particles might be transported into the magnetic island as 'holes' and expelled outward as 'blobs.' The proximity of the pressure gradient's position to the peak of the radial electric field aligns with the theoretical prediction [79] that blobs occur at the maximum value of the radial electric field. It has been suggested that fluctuations initiated by the gradient at the boundary of the magnetic island could propagate through the X-point towards the O-point [81]. This study's results imply that fluctuations beginning at the outer boundary of the magnetic island might spread into the island. However, elucidating this phenomenon is challenging with the current probe measurement system, which is one dimensional. Therefore, it is still necessary to use multidimensional measurements to comprehend the spatial structure of these fluctuations.

In this study, E_θ is calculated under the assumption of negligible electron temperature fluctuations since they are difficult to evaluate with the Heliotron J probe system. This assumption is supported by the observation in other devices, showing that the electron temperature fluctuations are usually small and are approximately in phase with the potential fluctuations to the degree of spatial precision of the probe head [27, 70, 79]. Furthermore, even if electron temperature fluctuation was significant, this would not affect the observation of the non-uniformity of fluctuation properties and transport inside the magnetic island, which is the main claim of this study, for the following reasons. Firstly, ion saturation current fluctuation (density fluctuation) is not substantially affected by temperature fluctuation, suggesting that temperature fluctuation is unlikely to contribute significantly to the observed non-uniformity of density fluctuation inside the island. Additionally, while temperature fluctuation could contribute more significantly to floating potential fluctuation, even if the potential fluctuation is uniform and the non-uniformity is attributed to temperature fluctuation, the non-uniform temperature fluctuation would induce non-uniform transport inside the island.

While the precise physical mechanisms are not fully explained at this stage, these observations affirm the presence of various non-uniformities in and around the magnetic islands, even with one-dimensional probe measurements. Given the three-dimensionality introduced by magnetic islands, future research necessitates two-dimensional, and ideally, three-dimensional measurements. These approaches are crucial for comprehending heat and particle transport in the SOL and divertor regions, which exhibit strong three dimensional characteristics. These findings are significant for understanding heat transport and control in the divertor region, a critical aspect for the realization of fusion reactors.

5.5 Summary

In this study, we investigated the impact of magnetic islands on fluctuation characteristics and transport within a medium sized helical device, Heliotron J. We utilized modulational ECH to examine the edge plasma response in a magnetic island configuration. The results revealed a slight peak in the averaged electron

temperature (T_e) profile, a localized drop in the amplitude profile, and an increased value of the phase difference ($\Delta\phi$), indicating heat deflection by the magnetic island structure. Comparing edge plasma parameter profiles in configurations with and without a magnetic island, we observed higher and constant electron density (n_e) in the island configuration. The T_e inside the island was lower on the wall side. Variations in spatial potential (V_s) and radial electric field (E_r) were also observed within the island, potentially influencing poloidal flow and transport.

The presence of magnetic islands distinctly affects the turbulence mechanism, resulting in varying behaviors in fluctuation intensity, statistical properties, fluctuation spreading, and fluctuation-driven transport. The normalized density fluctuation intensity increases from the inner to the outer region of the magnetic island, while the normalized potential fluctuation intensity is enhanced in parts of the island. Intermittent transport, as indicated by skewness and kurtosis values, is suppressed within the island, where PDFs are close to Gaussian. However, outside the island region, intermittent transport is enhanced, and the PDF deviates from Gaussian. The density fluctuation is more pronounced at the outer boundary, with the direction of fluctuation spreading reversed at the boundary of the magnetic island. The turbulence driving term remains constant within the island but increases significantly at the outer boundary. In contrast, the turbulent spreading term is negative at both boundaries, peaking at the center of the island. The poloidal electric field fluctuation peaks inside the magnetic island, and the fluctuation-driven particle flux shows peaks in both the center and the outer boundary of the island. These findings suggest that various fluctuation mechanisms coexist and generate spatially modulated transport even within the structure of an edge magnetic island.

Chapter 6 Change in the magnetic structure at the edge region and spontaneous plasma oscillation

6.1 Introduction

An edge magnetic structure, such as a divertor, is vital for any magnetic confinement system to control heat and particles for long-pulse operations. Impurities can easily enter the confinement region in the limiter configuration, where the solid wall is in contact with the confinement region. However, impurity penetration is reduced in the divertor configuration, where the confinement region is separated from the solid wall, resulting in improvement plasma control, and poloidal divertors are a standard option used in tokamaks, including ITER [82]. Studies have demonstrated the control of the edge magnetic field structure with resonant magnetic perturbation to reduce the divertor heat load associated with the edge localized mode (ELM) [66, 83]. Furthermore, real-time ELM control has been achieved [84, 85]. The edge plasma is controlled using perturbation coils and a local island divertor in the Large Helical Device (LHD), and a superdense core mode has been discovered [24, 86].

Advanced stellarator/heliotron devices with low magnetic shear exhibit non-axisymmetric magnetic field configurations, featuring edge magnetic islands that form a divertor configuration. The Wendelstein 7-AS (W7-AS) device performed well in terms of recycling and impurity control in a magnetic island divertor configuration [18, 22, 22, 87, 88]. The Wendelstein 7-X (W7-X) device has achieved long-pulse discharges by incorporating a magnetic island divertor and water-cooling system [23]. Heliotron J, a stellarator/heliotron device, with flexible magnetic configuration control, can form magnetic island divertor or helical divertor configu-

rations [71, 89], and has achieved a high H-factor in magnetic configurations with a rotational transform slightly lower than low-order rational surfaces [90]. Island divertor configurations for quasi-symmetry devices, such as the Helically Symmetric eXperiment (HSX) and quasi-axisymmetric stellarator (CFQS), have been proposed [91, 92].

It should be noted that advanced, low-magnetic-shear devices are susceptible to changes in the edge magnetic field structure due to plasma current. Researchers have attempted to achieve a more stable configuration in W7-AS that can maintain the island divertor regardless of a change in the rotational transform by plasma current [87]. Modeling calculations have been performed to describe the change from an island divertor to a limiter configuration by plasma current in W7-X [93], and experimental results showed that the heat flux profile on the divertor target moved and shifted to a limiter-like profile during plasma current rump-up discharge [94, 95]. A movement of the footprint position induced by plasma current has been observed in Heliotron J while maintaining the divertor configuration [96].

Numerical calculations have predicted changes in the rotational transform and edge magnetic field structure due to an increase in plasma current to maintain the divertor configuration, and there has been a focus on controlling the plasma current. However, the control has not been fully achieved, and the maintenance of the divertor configuration cannot be guaranteed because of the imperfect controllability and predictability of the core plasma behavior. When the divertor configuration cannot be maintained and transitions to the limiter configuration, changes in edge transport are expected. However, predicting the plasma response under such conditions is challenging, and experimental validation remains insufficient. For future stellarator/heliotron device operations, experimental investigations are required to identify phenomena that could arise under plasma conditions where the divertor configuration cannot be maintained.

This study reports the transition of the edge magnetic field structure from a divertor configuration to a limiter configuration resulting from plasma current in Heliotron J, a medium-sized low-magnetic-shear device. The rest of the paper is organized as follows. Section 6.2 explains the basic characteristics of the Heliotron J configuration and the possible transition of the magnetic field configuration from

a divertor configuration to a limiter configuration. Section 6.3 discusses the experimental observation of changes in the particle flux on the divertor probe and radiation profile that indicate the transition of the edge magnetic structure. In addition, this section describes a spontaneous oscillation observed at 2 kHz, with electron density, plasma current, and magnetic fluctuations accompanying the transition. Section 6.4 discusses the underlying mechanisms of the transition and oscillation by comparing the present observation with previous observations of other devices. Finally, section 6.5 summarizes the major study findings and future research scope.

6.2 Magnetic configuration

The divertor structure in Heliotron J is determined by the rational surface. The standard configuration forms a divertor configuration through a rational surface ($\iota/2\pi = 4/7$) (Figure 6.1(a), blue line, Figure 6.1(c)). The rotational transform increases with an increase in the co-directed plasma current, which is defined by an increase in the poloidal magnetic field. Furthermore, the $4/7$ rational surfaces move inward into the confinement region, appearing as a shrinkage of the confinement region and an expansion of the scrape-off layer (SOL) [97]. Conversely, in the magnetic configuration (Figure 6.1(b), red line, Figure 6.1(c)), an increase in the rotational transform was expected to move the rational surfaces away from the confinement region, resulting in an expansion of the confinement region and SOL shrinkage. Such a configuration would enable a transition from a divertor to a limiter configuration.

A change in the edge magnetic field structure against plasma current was predicted based on the field line tracing code, assuming a filament current on the magnetic axis. Figure 6.1(d) shows the rotational transform profile with the on-axis current. Only regions with a minor radius of $r \leq 0.08$ m are illustrated because the core region widely varied and was unreliable owing to an unrealistically center-focused filament current. In the standard configuration indicated by the blue line, as the rotational transform increased, its profile approached the rational surface ($4/7$) that defines the last closed flux surface (LCFS), shrinking the confinement region. Furthermore, an increase in the rotational transform moved its profile away

from the rational surface $(4/8)$ that defines the LCFS, expanding the confinement region in the magnetic configuration indicated by the red line.

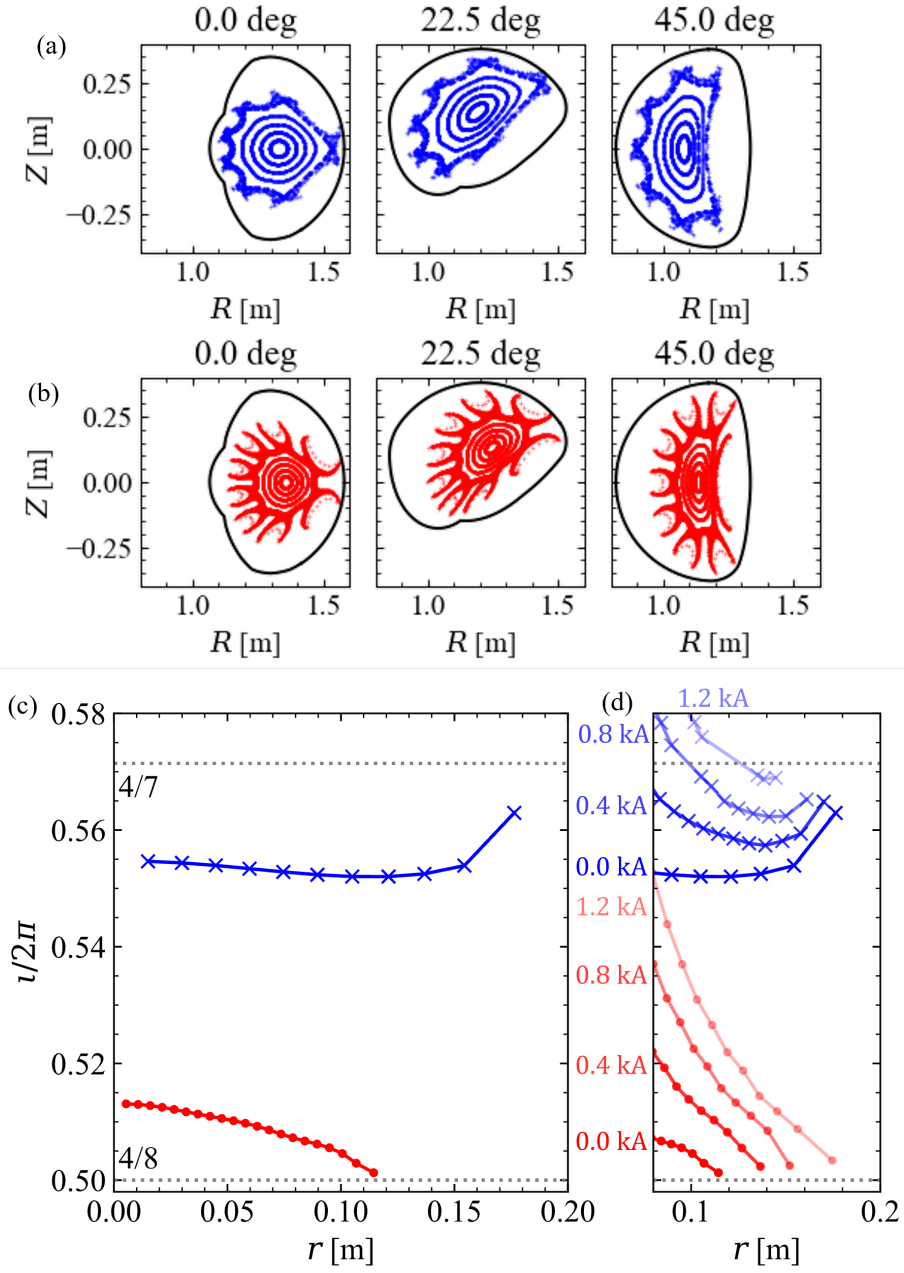


Figure 6.1: Poincare plot of (a) the standard configuration close to the $\iota/2\pi = 4/7$ rational surface and (b) the configuration close to the $\iota/2\pi = 4/8$ rational surface. The toroidal angle defined from the corner section of Heliotron J. (c) Rotational transform profile of standard and 4/8 configurations in a vacuum and (d) with plasma current.

Figure 6.2(a) shows the Poincare plots of the LCFS and its expansion caused by an increase in the plasma current. At a plasma current of 1.2 kA, the LCFS attached to the divertor probe, forming a limiter configuration. The dashed line in the lower right corner of Figure 6.2(a) indicates the position of the probe. The observation range of the probe was $R = 1.33 - 1.47$ m and from $Z = -0.36$ m to $Z = -0.24$ m in the section of $\phi = 67.5^\circ$. Figure 6.2(b) shows the profile of the connection lengths L_c on the divertor probe. In a vacuum (black line), L_c peaked around $R = 1.47$ m. As the plasma current increased, this peak shifted to a position with a smaller R . At 1.2 kA (green line), the LCFS attached to the divertor probe, resulting in a transition to a limiter configuration. The L_c on the probe exceeded 1000 m in the limiter configuration.

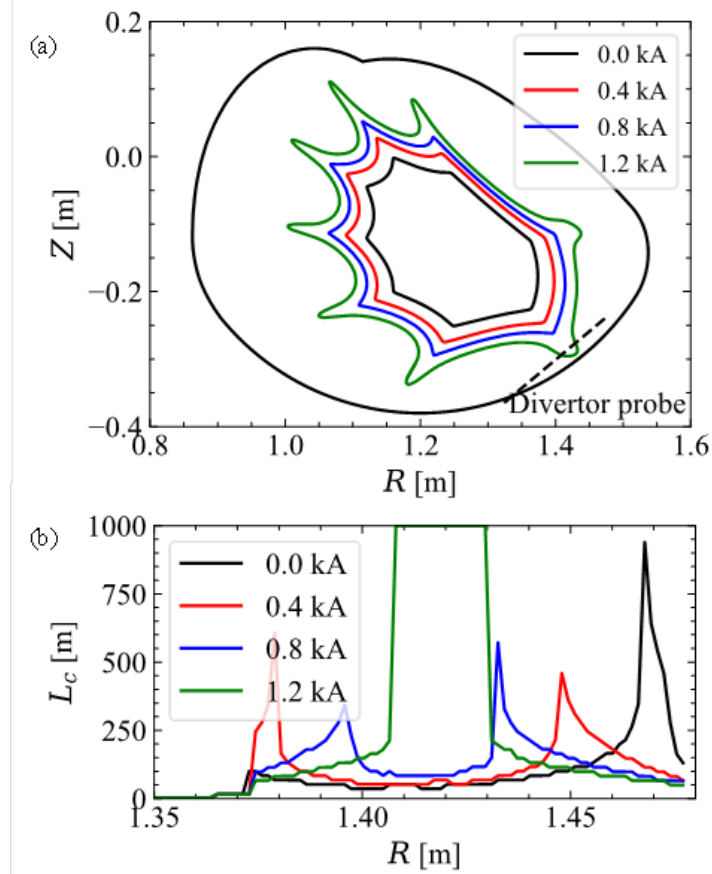


Figure 6.2: (a) LCFS and (b) connection length L_c on divertor probe for configuration close to the 4/8 rational surface. The on-axis current was varied in four cases.

The plasma current criteria required to transition to the limiter configuration are related to the size of the confinement region in a vacuum. Figure 6.3(a) shows the rotational transform profiles with slightly increased rotational transforms.

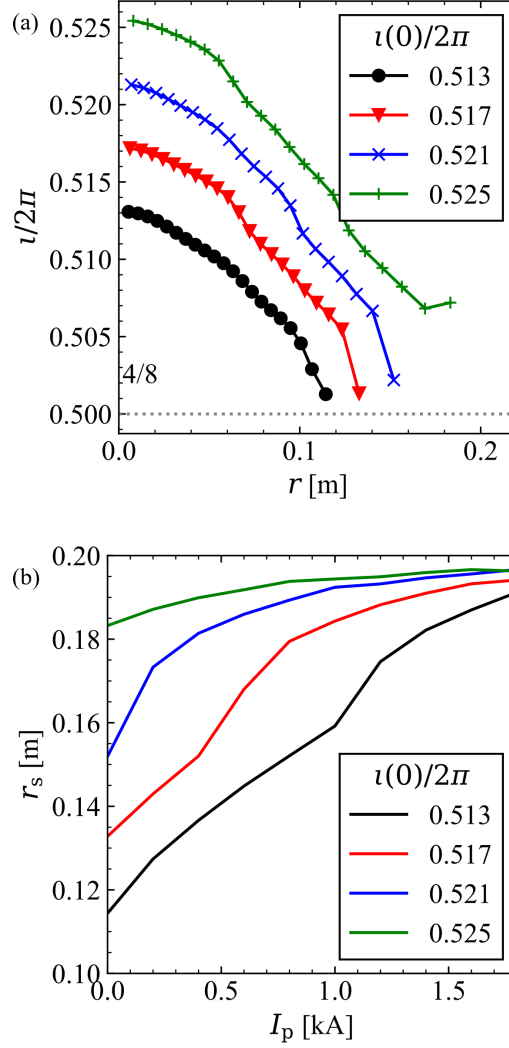


Figure 6.3: (a) Vacuum rotational transform profile of the configuration close to the $4/8$ rational surface (black) and slightly modified configurations via poloidal magnetic field (red, blue, and green). (b) Dependence of the LCFS radius r_s on plasma current I_p .

These configurations can be generated by altering the poloidal magnetic field

by a percentage from the configuration shown in Figure 6.1(b). A high rotational transform configuration features a large plasma volume, and, consequently, a transition should require less plasma current with a high rotational transform among these configurations. Figure 6.3(b) summarizes the dependence of the LCFS radii on plasma current for each configuration, based on the field tracing calculation. Here, we experimentally examined the plasma current dependence of the transition criteria.

6.3 Experimental results

6.3.1 Change in edge magnetic field structure

The response of the edge magnetic field structure to the plasma current was investigated by controlling the ECCD through adjustments in the ECH injection angle, in the configuration close to the 4/8 rational surface shown in Figure 6.1(b). Figures 6.4(a)-(e) shows the discharge waveforms for the different ECH injection angles ($N_{\parallel} = 0.0$ and 0.38) with the same magnetic configurations. The plasma was produced and heated using an ECH of 230 kW. Although the electron density $\bar{n}_e$ and stored energy W_p were practically the same, the plasma current I_p was approximately 0.8 kA for $N_{\parallel} = 0.0$ and approximately 2 kA for $N_{\parallel} = 0.38$, flowing in a direction that increased the rotational transform. The bootstrap current was dominant in the discharge of $N_{\parallel} = 0.0$ [47,49], whereas the plasma current comprised bootstrap and EC-driven current in the discharge of $N_{\parallel} = 0.38$. The plasma current and electron density oscillated at 2 kHz from 248 to 276 ms in the discharge with a higher plasma current.

Figures 6.4(d) and (e) show color maps of the time evolution of the ion saturation current I_{is} measured using the divertor probe during low and high I_p discharges, respectively. The I_{is} peak position remained largely unchanged at a low I_p discharge (Figure 6.4(d)). Oppositely, the peak position of the I_{is} shifted from $R = 1.47$ m to approximately $R = 1.40$ m at a high I_p discharge (Figure 6.4(e)). This indicated that the peak location of the heat and particle flux shifted with an increase in the plasma current.

The divertor plasma responses were qualitatively consistent with the simple mag-

netic field tracing calculation assuming an on-axis current (Figures 6.4(f) and (g)), indicating a change in the edge magnetic structure. At an on-axis current of 0.0 kA, the peak of the connection length L_c should have been observed at $R = 1.47$ m, predicting the location of the divertor footprint, where heat and particle flux are concentrated. As discussed in Section 6.2, the confinement region expanded with an increase in the plasma current, transitioning from a divertor configuration to a limiter configuration. During this transition, the connection length calculation predicted that the divertor footprint shifted from $R = 1.47$ m to the region of $R = 1.41 - 1.43$ m, consistent with the experimental observation. However, a discrepancy of several centimeters existed between the L_c profile and the peak position of the I_{is} after the transition to the limiter configuration. This may have been due to the assumption of only a filament current on the magnetic axis, without considering the radial plasma current profile, and the assumption of the vacuum vessel without any components, such as the divertor probe. Similar to I_p and $\bar{n}_e$, an I_{is} oscillation was observed at 2 kHz. The details of the oscillation are provided in Section 6.3.2.

During the transition to the limiter configuration, an expansion of the confinement region along with the magnetic field structure was observed in the radiation profile. Figure 6.5(a) shows the line-of-sight positions of the Absolute eXtremes UltraViolet (AXUV) in Heliotron J and the estimated LCFS as calculated using the field line tracing code with changes in the on-axis currents from 0 to 1.2 kA. The AXUV detector is sensitive to wavelengths from soft X-rays to UV light [29] and has 16 channels, with channel 1 viewing the innermost radial position and channel 16 viewing the outermost radial position. Figure 6.5(b) shows the AXUV profile prior to and after the transition to the limiter configuration. Prior to the transition, the SOL region was outside channel 5, with the signal intensity monotonically decreasing outward. After the transition to the limiter configuration, the signal intensity monotonically decreased in the region outside channel 8, indicating that the SOL region had shifted outward. The AXUV profile expanded outward towards the minor radius, suggesting that the expansion of the confinement region was due to changes in the edge magnetic field structure.

The same behavior that indicates the response of the edge magnetic field struc-

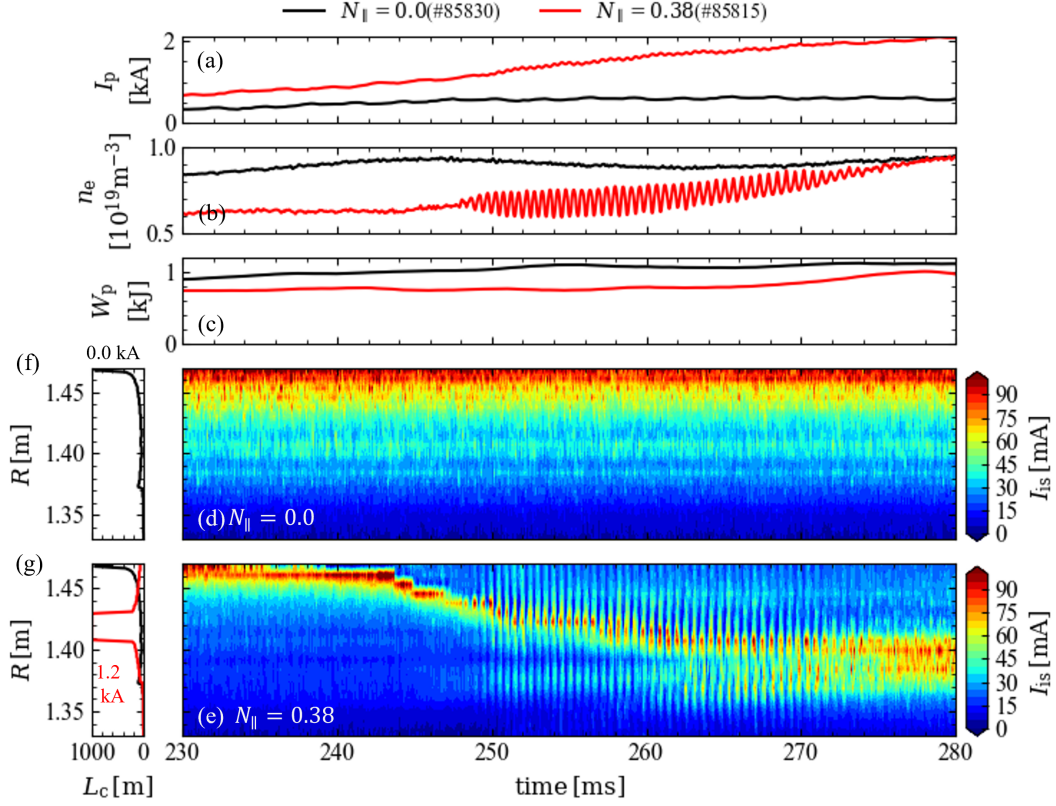


Figure 6.4: (a) Waveform of plasma current I_p . (b) Line-averaged electron density $\bar{n}_e$. (c) Stored energy W_p . The black and red lines indicate the discharge waveforms of $N_{\parallel} = 0.38$ and 0.0 , respectively. (d) Connection length L_c at 0.0 kA (black) and 1.2 kA (red). (e) Time evolution of the profile of the ion saturation current I_{is} on the divertor probe

tures were observed in other configurations with different rotational transforms in a vacuum. Figures 6.6(a)-(d) show the time evolution of the I_{is} profile of the divertor probe and the plasma current I_p for four configurations, with slightly different rotational transforms in the range of $0.513 - 0.525$ (Figure 6.3). For each configuration, a transition of the edge magnetic structure, appearing as the I_{is} peak shift, was observed. Furthermore, the transition, indicated by the vertical gray line, occurred earlier depending on the increase in the rotational transform. The configuration transition marked by the gray line was identified as the time when the I_{is} at the

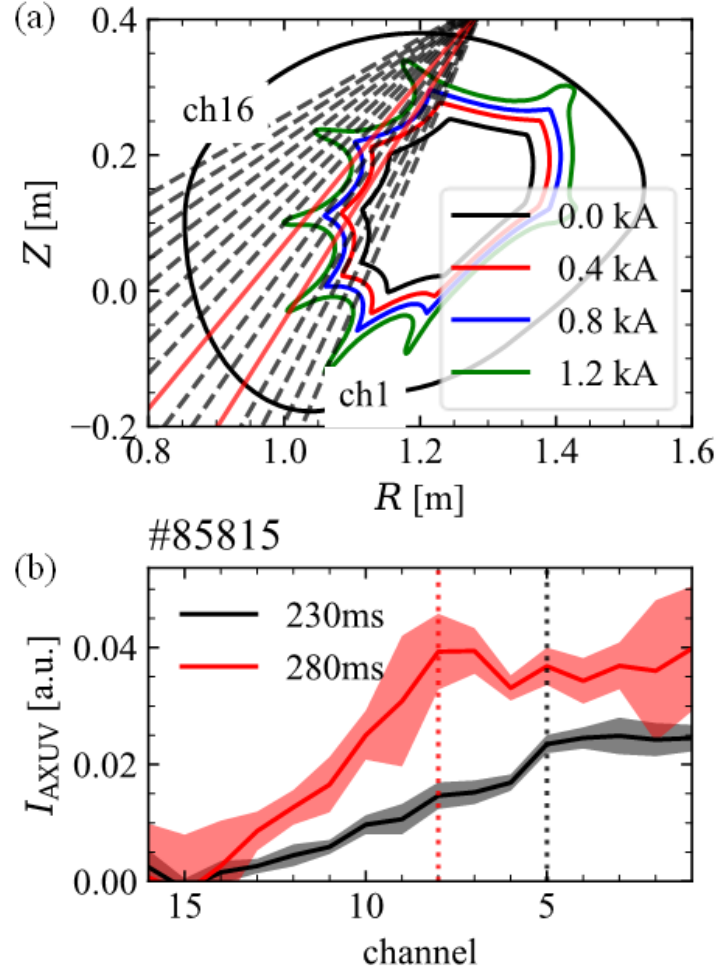


Figure 6.5: (a) Line-of-sight positions of the AXUV and estimated LCFS positions. The lines of sight for Channels 5 and 8 are indicated by red lines. (b) AXUV profile.

position where the confinement region contacts the divertor probe exceeded the average value of all the channels.

Figure 6.6(e) shows the relationship between the central vacuum rotational transform and plasma current at the transition time to the limiter configuration. The required plasma current was dependent on the vacuum rotational transform. Figure 6.6(f) compares the averaged minor radius r_s of the LCFS at the time of the limiter transition against I_p during the experiments across different magnetic configurations. The solid lines indicate the calculated r_s , assuming an on-axis current

for each configuration, similar to Figure 6.3(b). The vertical dotted lines indicate the I_p values at the transition from the divertor to the limiter configuration for each magnetic configuration. The X markers indicate the intersection points between the calculated and observed values. All the X markers were within the r_s range of 0.185 – 0.190 m (hatched area). Here, the divertor plasma responses were qualitatively consistent with the magnetic field tracing calculation assuming an on-axis current. However, since the difference in the magnetic axis positions for all magnetic configurations was less than 0.01 m, the r_s in the limiter configuration remained almost the same size. This demonstrates that a configuration with a larger central rotational transform has a larger confinement region (Figure 6.6(a)), and, therefore, easily undergoes a transition to the limiter configuration even at a lower plasma current. The similar criteria at the plasma minor radii, regardless of the configuration, strongly show that the transition is determined by plasma current, leading to a configuration transition.

6.3.2 Oscillation accompanying the change in the edge magnetic field structure

The spontaneous oscillation associated with changes in the magnetic field structure was observed during the transition in the magnetic configurations close to the 4/8 rational surface. The oscillation accompanied fluctuations in the electron density, plasma current, magnetic probe signals, AXUV, and divertor probe signals. Figure 6.7(a) shows the oscillation waveforms at the measured signal. Each signal synchronously oscillated at approximately 2 kHz. Figure 6.7(b) shows the power spectrogram density (PSD) of $\bar{n}_e$ where the 2 kHz oscillation and its higher harmonics were observed from 248 to 276 ms. The toroidal mode number was $n = 1$ (Figure 6.7 (c)) according to the toroidal array of magnetic probes. Here, the poloidal mode could not be determined because of technical issues with the poloidal magnetic probe array.

The divertor footprint position responded to the oscillations. Figure 6.8 shows the time evolution and profile of the I_{is} of the divertor probe during the oscillations. The I_{is} signals were subjected to low-pass filtering at 20 kHz. The plasma current I_p and averaged I_{is} were almost in phase (Figures 6.8(a) and (b)). During the

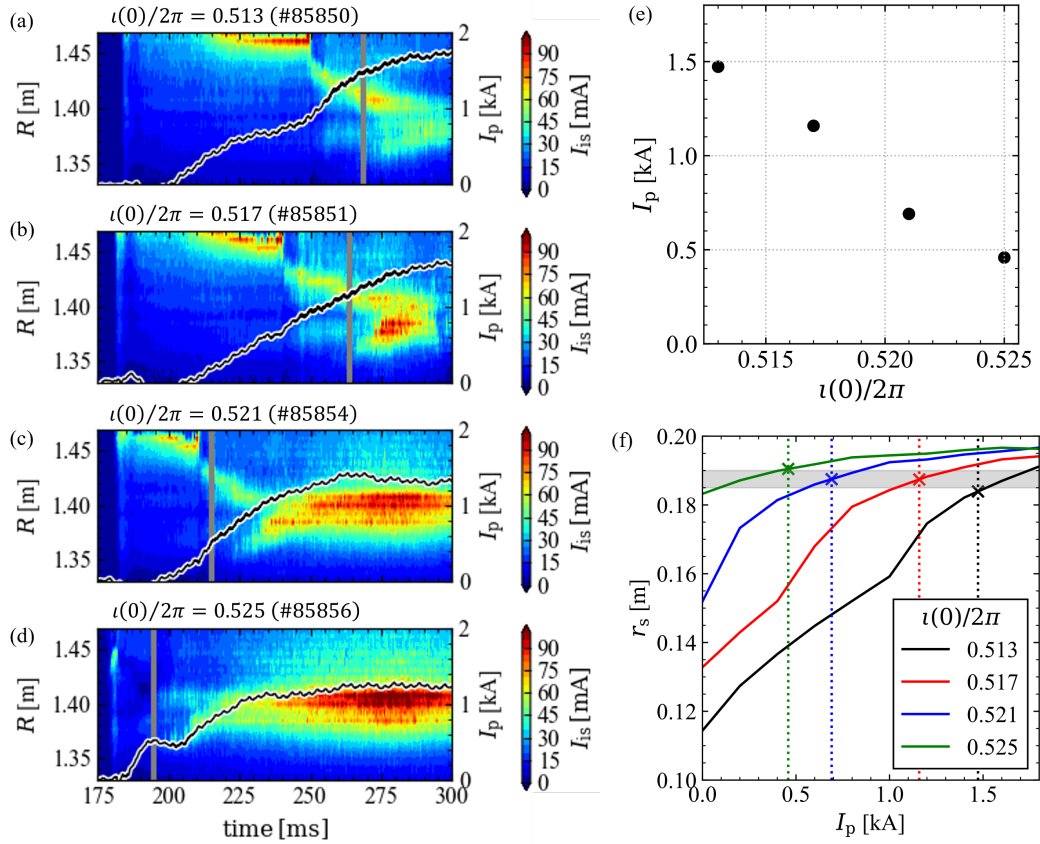


Figure 6.6: (a)-(d) Time evolution of the I_{is} profile on the divertor probe and the plasma current I_p (black line) for different configurations with varying rotational transforms. The vertical gray line indicates the time of the transition to the limiter configuration. (e) Dependence of the plasma current at the time of the transition to the limiter configuration on the rotational transform. (f) Comparison between the calculation and experimental result of an increase in minor radius r_s of the LCFS by I_p .

oscillations, the I_{is} profile exhibited two distinct phases; the first was similar to the connection length L_c profile at the on-axis current I_{axis} of 0.4 kA, which was the divertor configuration. The other phase was of 1.2 kA, which was the limiter configuration (Figures 6.8(c) and (d)).

Figure 6.9 compares the conditionally averaged I_{is} profiles at the local maximum and minimum in the period of the channel-averaged I_{is} waveform with the L_c profile.

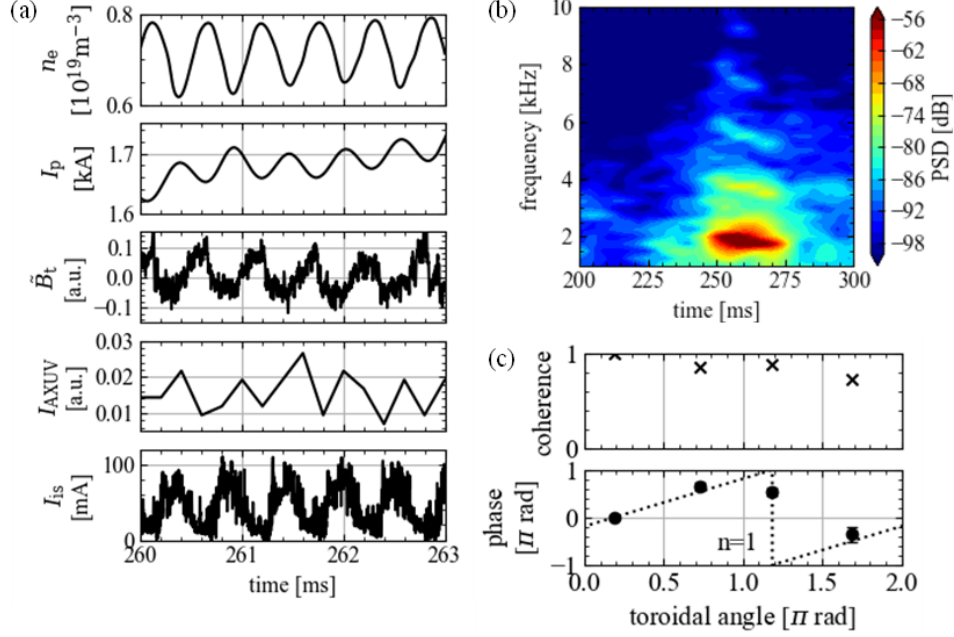


Figure 6.7: (a) Waveform of $\bar{n}_e$, I_p , $\tilde{B}_t$, AXUV and I_{is} of the divertor probe. (b) Spectrogram of $\bar{n}_e$. (c) Coherence and phase difference between toroidal magnetic probes.

The peak positions of I_{is} at $R = 1.38$ m and $R = 1.45$ m were consistent with the peak positions of L_c at $I_{axis} = 0.4$ kA at the time of the I_{is} minimum. The peak position of I_{is} was placed at $R = 1.41$ m and was within the region of $L_c > 1000$ m at $I_{axis} = 1.2$ kA, where the plasma should exhibit the limiter configuration at the time of the I_{is} maximum. This suggests that the plasma oscillated between both configurations.

The values of the plasma and on-axis currents differed from those in the experimental observation. This discrepancy was likely because differences in the plasma current profile led to substantial variations in the edge magnetic field structure even at the same plasma current [96], which cannot be reproduced by simple magnetic field tracing calculations only with the on-axis current. The second peak at $R = 1.37$ m at the time of the I_{is} maximum cannot be explained by the L_c profile, which might be relevant to the perpendicular transport in the SOL.

The radiation profile measured with the AXUV array revealed oscillation. Fig-

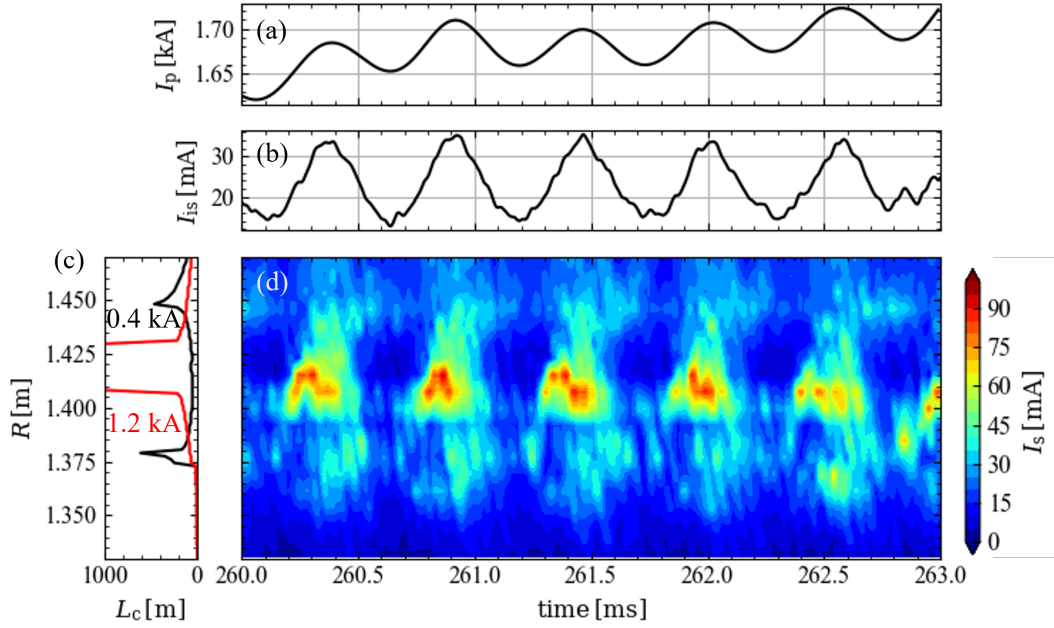


Figure 6.8: (a) Waveform of plasma current I_p . (b) Averaged ion saturation current I_{is} . (c) Connection length L_c profile. (d) Time evolution of I_{is} profile.

Figure 6.10(a) shows the profile of the conditionally averaged AXUV signal at the maximum and minimum timing of the divertor probe. Figure 6.10(b) shows the normalized oscillation intensity $\tilde{I}/I$. Figure 6.10(c) shows the coherence with channel 10, and Figure 6.10(d) shows the phase difference profile. The $\tilde{I}/I$ was minimal at channel 5, increased toward the edge, and reached its maximum at channel 12. The phase inversion point was located on the channel 5 sightline where the LCFS was observed prior to the oscillation. This suggests that the oscillation was larger in the region farther from the LCFS compared to oscillation closer to it.

6.4 Discussion

Using an advanced helical device, Heliotron J, we experimentally demonstrated that the transition of the edge magnetic field structure from a divertor configuration to a limiter configuration can occur during a discharge. The increase in plasma current modified the rotational transform, leading to a transition to the limiter

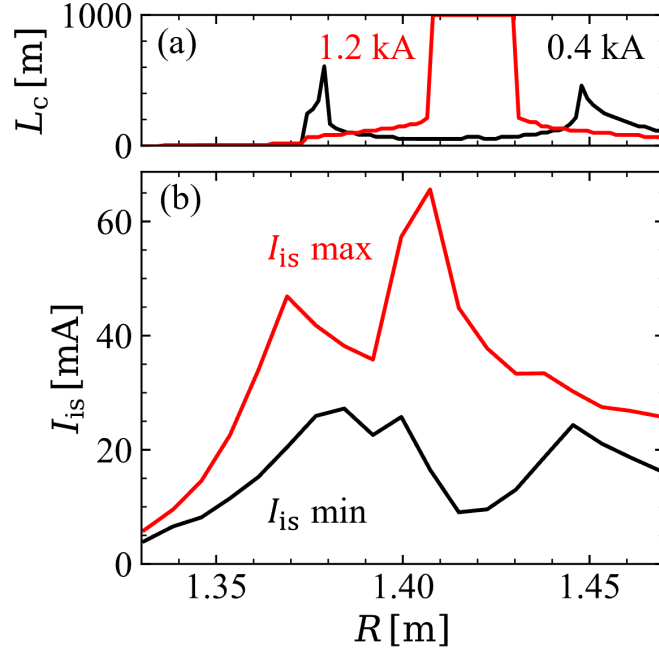


Figure 6.9: (a) L_c profile. (b) Conditional average I_{is} profile.

configuration from the divertor configuration with low-order rational surfaces. The transition was qualitatively consistent with the on-axis current model. However, the quantitative agreement was insufficient as compared in Figures 6.4(e) and (g).

Experimental results suggesting a change in the edge magnetic field structure by an increase in the plasma current have been observed in W7-X, and the heat flux profile of the divertor target was quantitatively consistent with the field line tracing calculation, including an on-axis current, in the case of a low I_p (< 10 kA) [94, 95]. However, it has been pointed out that comprehensive equilibrium fields need to be used for simulations with a high I_p [94]. The upper limit of the plasma current to which the calculation with the on-axis current can be applied should be lower in Heliotron J than in W7-X because of the lower magnetic field strength. In the future, we hope to achieve consistency between the experimental result and calculations, including equilibrium, in Heliotron J.

The expansion of the confinement region by an increase in the plasma current

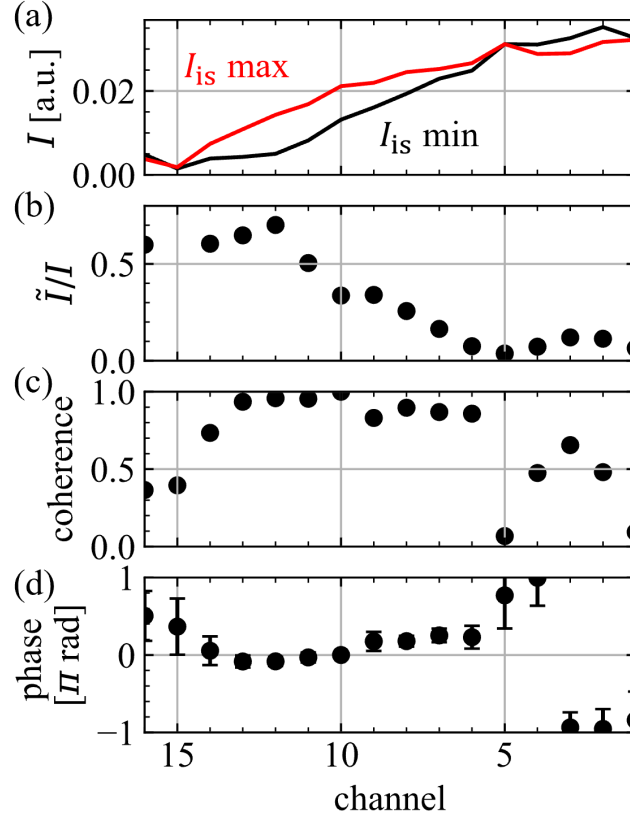


Figure 6.10: (a) Conditional averaged AXUV profile. The black and red lines indicate the conditionally averaged profile at the time of the minimum and maximum divertor I_{is} , respectively. (b) Normalized oscillation intensity, (c) coherence and (d) phase difference profiles.

was observed. According to the magnetic field line tracing calculation, as shown in Figure 6.6(f), the r_s increased from 0.12 m to 0.18 m, expanding by a factor of 1.5, meaning the plasma volume more than doubled in the magnetic configuration with $\iota(0)/2\pi = 0.513$. However, as shown in Figures 6.4(b) and (c), the line-averaged density and stored energy did not change significantly. Here, changes in the path length of the interferometer and plasma volume during the discharge were not considered. Therefore, the plasma current impact of the confinement region expansion by the increase in the plasma current on confinement performance remains unclear. In the future, we hope to measure the profile of electron temperature and density

in the confinement region and confirm the extent of their spatial expansion.

During the transition, the plasma spontaneously oscillated with an $n = 1$ mode structure, accompanying a synchronous divertor footprint oscillation. A possible cause is a difference in plasma boundary conditions between the divertor and limiter configurations. The transition to the limiter configuration from the divertor configuration should substantially modify the wall-plasma interactions, including recycling and impurity from the vacuum wall, causing a drop in the electron temperature. This would lead to a decrease in the bootstrap current [98], causing a return to the divertor configuration, where impurities are pumped out, the electron temperature recovers, and the plasma current increases again, transitioning back to the limiter configuration, thereby completing a loop. The plasma current continuously increases on average despite the spontaneous oscillation and the transient decrease in plasma current due to recycling/impurity effects. Thus, the system could eventually remain in the limiter configuration without returning to the divertor configuration, leading to the disappearance of the oscillation. However, in Heliotron J, the L_p/R_p time is approximately 100 – 200 ms [47], where L_p and R_p are the plasma inductance and resistance. This is much longer than the oscillation period of 0.5 ms. It is possible that the plasma current oscillation is localized in the edge region, where the electron temperature and density are relatively low.

A similar oscillation phenomenon in the edge plasma, known as impurity radiation-condensation instability [99], has been reported where instability due to impurities couples with drift. This results in oscillations with an $n = 1$ spatial structure and several-kHz frequency in the edge region [100]. However, since no impurity gas puffing was performed in this study, the influence of impurities is expected to be minimal. In the future, we will investigate this scenario by measuring the electron temperature, the impurity radiation line in the edge region, and their phase differences.

Another possible explanation is a self-sustained divertor oscillation (SSDO) associated with magnetic islands. In LHD, a 40-Hz SSDO was observed as a result of interactions between the edge magnetic islands and an X-point remnant bootstrap current [101, 102]. The magnetic island was driven by external perturbation fields and maintained during the entire discharge. Although oscillations of plasma current

were observed in the present study, the magnetic islands should have disappeared under our experimental conditions, which is an essential difference between the cases and is unrelated to the LHD observation. Finally, the oscillation frequency was 2 kHz, which significantly differed from that in the LHD observation.

While bootstrap current, impurity radiation-condensation instability, and magnetic islands with X-point remnant bootstrap current are presented as possible mechanisms for the oscillation, no sufficient experimental evidence has been obtained for any of them. To verify each possibility, observations of electron temperature, density, radiation profiles, and magnetic island width during the oscillation are necessary.

6.5 Summary

Here, a transition from the divertor configuration to the limiter configuration was observed in Heliotron J when the co-directed plasma current increased the rotational transform at the configuration of the rotational transform profile close to the 4/8 rational surface. Observations using AXUV and divertor probes revealed changes in the plasma profile such as radiation and particle flux, indicating an expansion of the confinement region, as well as a shift in the divertor footprint, associated with the transition. Such changes in the edge magnetic structure were qualitatively consistent with calculations performed using a field line tracing code based on the assumption of an on-axis current. Furthermore, plasma currents at which the transition was observed in certain magnetic configurations with different vacuum rotational transforms were consistent with the qualitative trends predicted by the calculations. This supports the idea that the plasma current modifies the edge magnetic structure.

At the time of the magnetic structure transition, oscillations with a toroidal mode number $n = 1$ were observed at approximately 2 kHz. These oscillations were detected in various diagnostics, including electron density, plasma current, and magnetic fluctuations. Although the comparison with the calculations, assuming an on-axis current, was qualitative, divertor probe measurements suggested that the plasma could oscillate between both configurations. Furthermore, AXUV

measurements revealed that the radiation profile in the edge region was oscillating. The transition to the limiter configuration altered the transport in the edge region, causing the edge plasma to oscillate as a transient response. In the future, we will compare measurements from several upgraded multiple diagnostic instruments to extensively clarify the spatial structure of the oscillations, including the core region, and investigate the underlying physical mechanisms.

Plasma oscillations may pose a risk of worsening the load on the divertor. This manuscript highlights the significance of plasma current control in stellarator/heliotron devices.

Chapter 7 Conclusion

This study aims to elucidate edge plasma transport in the island divertor configuration. The edge plasma is influenced by the core plasma, impurities from the solid wall and 3D transport induced by magnetic islands in the island divertor configuration. The fluctuation characteristics within the magnetic island were investigated using a Langmuir probe. Additionally, the phenomenon of spontaneous changes in the island divertor configuration was examined. An imaging bolometer was applied to measure the radiation distribution.

The summary of each chapter is as follows.

Chapter 1 provides an overview of the energy challenges and the significance of fusion power generation. The edge plasma is need to be controlled to maintain a high temperature plasma in the core region of a magnetically confined fusion plasma. The divertor plays a critical role in preventing impurities, sputtered from the solid wall upon contact with the plasma, from penetrating the core plasma. The island divertor employed in low magnetic shear stellarator/heliotron devices. The concept of the island divertor involves utilizing magnetic islands formed at rational surfaces in the plasma periphery, in contact with the solid wall, to function as a divertor.

Previous studies have indicated that within the magnetic island, a flow structure centered around the O-point can develop, with reduced thermal transport and decreased turbulent transport compared to the surrounding area. The aim of this study is to investigate the transport within the magnetic island in the island divertor configuration and to examine the changes in the magnetic field structure caused by plasma currents, which are of concern during the operation of advanced stellarator/heliotron devices with island divertor configurations.

Chapter 2 discusses the tools used for measuring edge plasma, specifically the Langmuir probe, imaging bolometer, and AXUV. The measurement principles of

the Langmuir probe are described in detail. Additionally, data analysis methods, including fast Fourier transform (FFT) and statistical analysis, are also discussed.

Chapter 3 provides an overview of the Heliotron J device. It begins by describing the general characteristics of the device and the properties of its magnetic configuration. The Heliotron J device employs a helical-axis heliotron configuration, aiming to achieve a balance between good particle confinement and MHD stability. It is equipped with a unique $L/M = 1/4$ continuous winding helical coil (HF), where L represents the pole number and M the pitch number, along with two types of toroidal coils (TA and TB) and three sets of vertical magnetic field coils (MV, AV and IV). These components together produce a low magnetic shear configuration. The device's magnetic configuration is adjustable, allowing for the alteration of current ratios in each coil.

The chapter also details the heating systems and diagnostic tools used in this study on the Heliotron J device.

Chapter 4 describes the development of an imaging bolometer to measure the plasma radiation distribution. Through calibration experiments with the infrared camera, a linear relationship between temperature and digital count values was confirmed in the range of 20° C to 40° C . During the NBI startup experiment, the temperature in the region corresponding to the plasma core increased, while the temperature in the region where no radiation was expected remained unchanged.

Comparison with radiation simulations using the EMC3-EIRENE code showed that, although there were some minor differences, the overall trends in the upper and lower regions were consistent. The increase in thin-film temperature was found to correlate with the AXUV measurement. These results suggest that IRVB measurements are feasible on Heliotron J.

The distribution of the temperature increase changes at different configurations of the magnetic field structure. In order to investigate the relationship with the magnetic island structure, it is necessary to compare the results with the radiation distribution simulation by EMC3-EIRENE. Radiation distribution measurements that are not affected by noise due to ECH and magnetic fields will be performed in

the future. Higher sensitivity of IRVB and measurements in ECH plasmas are also needed.

Chapter 5 discusses the non-uniformity of fluctuations within the magnetic island. To clarify the impact of the magnetic island, experiments were conducted under configurations with and without the island. Measurements were performed using a movable multi-point Langmuir probe.

The presence of the magnetic island was first confirmed by observing the localized attenuation and delay in the propagation of thermal pulses at the position of the magnetic island in a vacuum. In the steady-state plasma distribution, the electron density in the magnetic island region was found to be consistently high and nearly constant. Additionally, while the electron temperature inside the magnetic island showed a region of constancy, it decreased near the wall.

The magnetic island influences the mechanisms of turbulence, altering the normalized fluctuation intensity, statistical characteristics, fluctuation diffusion, and fluctuation-driven transport. The normalized density fluctuation intensity increases from the inner to the outer region of the magnetic island, while the normalized potential fluctuation intensity is enhanced in parts of the island. Intermittent transport, as indicated by skewness and kurtosis values, is suppressed within the island, where PDFs are close to Gaussian. However, outside the island region, intermittent transport is enhanced, and the PDF deviates from Gaussian. The density fluctuation is more pronounced at the outer boundary, with the direction of fluctuation spreading reversed at the boundary of the magnetic island. The turbulence driving term remains constant within the island but increases significantly at the outer boundary. In contrast, the turbulent spreading term is negative at both boundaries, peaking at the center of the island. The poloidal electric field fluctuation peaks inside the magnetic island, and the fluctuation-driven particle flux shows peaks in both the center and the outer boundary of the island. These findings suggest that various fluctuation mechanisms coexist and generate spatially modulated transport even within the structure of an edge magnetic island.

In Chapter 6, the changes in the magnetic field structure and spontaneous oscil-

latory phenomena due to plasma current are discussed.

The transition from the divertor to limiter configuration has been observed in Heliotron J when the co-direction plasma current increases the rotational transform at the configuration of the rotational transform profile close to the $4/8$ rational surface. Observations using AXUV and divertor probes revealed changes in the plasma profile, indicating an expansion of the confinement region, as well as the shift of the divertor footprint, associated with the transition from the divertor configuration to the limiter configuration. These changes in the edge magnetic structure qualitatively agree with calculations using a field line tracing code based on the assumption of the on-axis current. Furthermore, plasma currents at which the limiter configuration transition was observed in some magnetic configurations with different rotational transforms were consistent with the qualitative trends predicted by the calculations, supporting the idea that the plasma current modifies the edge magnetic structure.

At the time of the magnetic structure transition, spontaneous oscillations with a toroidal mode number $n = 1$ were observed at around 2 kHz. These oscillations were detected in various diagnostics, including electron density, plasma current, and magnetic fluctuations. Although the comparison with the calculations, assuming the on-axis current, was qualitative, divertor probe measurements suggested that the plasma could oscillate between the divertor and limiter configurations. Additionally, AXUV measurements indicated that the plasma profile in the edge region was oscillating. The transition to the limiter configuration would alter the transport in the edge region, causing the edge plasma to oscillate as a transient response.

In this study, the edge plasma transport in the island divertor configuration was discussed. The edge plasma transport in the island divertor configuration is complex due to the effect of the magnetic island. This study will contribute to the control of the edge plasma with magnetic islands. Future work will focus on further investigating plasma transport using advanced diagnostic techniques in the island divertor configuration. Experimental validation will be pursued, alongside comparisons with numerical analyses such as those using EMC3-EIRENE. These efforts are expected to contribute to optimizing magnetic field configurations from

the perspective of island divertors.

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Achievements

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