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EFFECT OF EDGE-LOCALIZED MODE SIMULATION ON DETACHED PLASMA IN THE DIVERTOR SIMULATION EXPERIMENTAL MODULE OF GAMMA 10/PDX

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Abstract

Experiments were conducted in the divertor simulation experimental module (D-module) of GAMMA 10/PDX to investigate the dynamic behavior of detached plasma under intermittent high-density and high-temperature particle fluxes. A double-pulse electron cyclotron heating (ECH) scheme was employed to emulate edge-localized mode (ELM)-like transient loading conditions. Detached plasma was generated using radiator gas injection, and its response was diagnosed using electrostatic probes, Thomson scattering, microwave interferometry, and high-speed imaging. The experiments revealed that intermittent particle fluxes induced transitions between detachment and reattachment phases. Time-resolved diagnostics captured changes in electron temperature, density, and emission profiles, providing insight into the recovery mechanisms of detached plasma under transient conditions. These results contribute to the understanding of divertor plasma dynamics and support the development of advanced control strategies for future fusion reactors.

1. INTRODUCTION

Plasma detachment is a critical phenomenon in nuclear fusion research, as it significantly reduces both heat and particle fluxes to the divertor plate, thereby mitigating damage to plasma-facing components. In high performance fusion plasmas, particularly in H-mode tokamak operations, the occurrence of edge-localized modes (ELMs) introduces transient bursts of heat and particles that can strongly influence the detached plasma state. Understanding how detached plasmas respond to such intermittent loads is essential for the development of robust divertor solutions in future fusion reactors [1–7].
Linear plasma devices have played a pioneering role in exploring the physics of plasma detachment. Experiments using facilities such as Pilot-PSI, Magnum-PSI, and NAGDIS-II have provided valuable insights into the behavior of detached plasmas under high-flux and transient conditions, including ELM-like heat pulses [8–13]. These studies have primarily focused on the interaction between plasma and divertor materials, as well as the balance between ionization and recombination processes during detachment.

To further investigate detachment dynamics under high heat flux conditions (>20 MW/m²), a divertor simulation experimental module (D-module) was installed in the end cell (EC) of the GAMMA 10/PDX tandem mirror device. GAMMA 10/PDX confines plasma in the central cell (CC), with plasma escaping toward the EC and entering the D-module. In this module, detached plasma is generated using radiator gas injection, and its properties are diagnosed using electrostatic probes (ESPs), Thomson scattering (EC-TS), microwave interferometry (EC-MIF, MMIF), and high-speed imaging (HSCAM) [14–20].
Previous experiments in GAMMA 10/PDX have demonstrated that sudden increases in particle flux—mimicking ELM-like events—can alter the state of detached plasma [19]. However, these studies employed single-pulse operations of electron cyclotron heating (ECH) to increase core plasma density and temperature. In the present study, we introduce a double-pulse ECH scheme to simulate intermittent high-density and high-temperature fluxes into the D-module. This approach enables a more realistic emulation of ELM-like conditions and allows us to examine the dynamic response of detached plasma to transient particle loading.
By analyzing the behavior of the divertor simulation plasma under these conditions, we aim to clarify the mechanisms governing detachment recovery and reattachment, contributing to the broader understanding of divertor physics in fusion devices.

2. EXPERIENTAL APPARATUS

2.1. GAMMA 10/PDX tandem mirror device

To investigate the mechanisms of plasma detachment and its role in reducing heat and particle fluxes to the divertor plate, experiments were conducted in the D-module of GAMMA 10/PDX. The plasma conditions in this module are designed to emulate those of the scrape-off layer (SOL) and divertor region in ITER [1,2].
GAMMA 10/PDX is a tandem mirror device with its primary plasma confinement region located in the CC. Plasma escaping from the west-EC is directed into the D-module, which is installed in the EC for divertor simulation experiments (Fig. 1). The D-module features a V-shaped tungsten target plate equipped with five electrostatic probes (ESP #1–5) to measure local electron temperature and density near the divertor surface.
To diagnose upstream plasma parameters within the D-module, a Thomson scattering system and a microwave interferometer system (EC-MIF) are installed. Additionally, a movable electrostatic probe is positioned in front

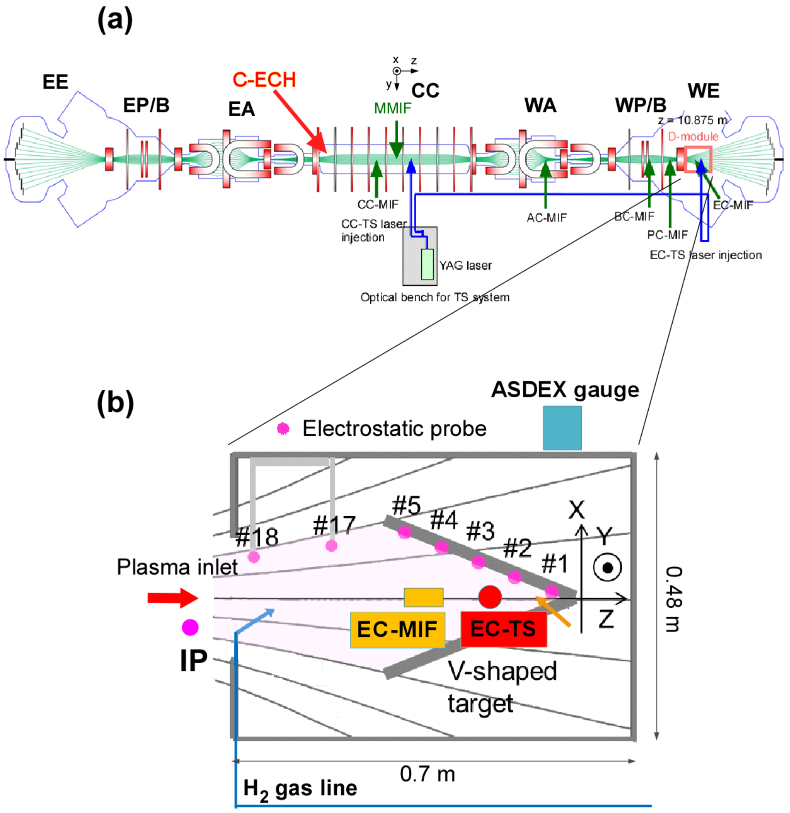

FIG. 1. Schematics of the experimental setup of GAMMA 10/PDX (a), and the divertor simulation experimental module (b).

of the D-module to monitor inlet plasma conditions. To generate higher-density and higher-temperature particle fluxes into the D-module, central-ECH (C-ECH) is applied to the CC.
Figure 1(b) shows the configuration of the D-module within the EC. Prior to C-ECH injection, the typical electron temperature and density in the CC are approximately 30 eV and 2×10^{18} m^{-3}, respectively, while those in the D-module range from 1 to 30 eV and 0.01 to 1×10^{18} m^{-3}.

2.2. Dual-path Thomson scattering system

The details of the dual-path TS system installed in GAMMA 10/PDX are provided in references [18-19]. The YAG laser was split into two paths using a polarization control system and introduced into both the CC and EC using the same number of laser shots during a single plasma shot. Both the CC-TS and EC-TS employed a multipass system. The CC-TS system comprises three spherical mirrors for collecting 90° TS light, seven five-channel polychromators, and high-speed oscilloscopes, allowing the measurement of electron temperatures and densities at seven radial positions. The EC-TS system utilizes 160° backscattered TS light and can measure the electron temperature and density at the center of the D-module plasma.

2.3. Microwave interferometer systems

The MIFs were set up at various locations, including the CC (z = -0.6 m), AC (z = 5.2 m), barrier cell (BC, z = 8.6 m), plug cell (PC, z = 9.7 m), and EC-MIF (z = 10.786 m), to measure the electron line densities. The frequency of the microwaves in the CC-, AC-, BC-, and PC-MIFs was 70 GHz, whereas that in the EC-MIF was 64 GHz. The EC-MIF is a heterodyne interferometer system with a local integrated array (LIA) system [22] that employs only one LIA channel aligned in the z-direction for this experiment. The length of interferometer chords across the plasma in the D-module is approximately 0.26 m, and the average plasma density in the D-module is calculated by dividing the measured line density by 0.26 m.

2.4. High-speed camera system

In the D-module of GAMMA 10/PDX, a HSCAM equipped with an Alva Prism was employed to observe two-dimensional (2D) spatial profiles of plasma radiation [20]. The Alva Prism enables simultaneous multi-wavelength imaging by dispersing light onto different regions of the camera sensor, allowing for spectral discrimination of emission lines such as Hα and Hβ.
This configuration allows for real-time visualization of dynamic plasma behavior, including detachment transitions, recombination fronts, and localized emission structures. By applying narrowband filters in combination with the Alva Prism, the HSCAM system can selectively capture specific Balmer series emissions, which are essential for diagnosing recombination processes and evaluating the degree of plasma detachment.
The HSCAM system was positioned to view the D-module from the side, enabling clear observation of the plasma column and its interaction with the tungsten target plate. Time-resolved imaging during ECH and SMBI injections provided insight into transient phenomena such as ELM-like particle flux bursts and reattachment events.

2.5. Central-Electron Cyclotron Heating

The C-ECH, generated by a 28 GHz, 500 kW gyrotron, was installed at z = -2.45 m in the east CC for effective electron heating. The C-ECH employs a mirror and two polarizers to change the injection position and polarization to improve the heating performance and transport effect.

3. PLASMA DETACHMENT EXPERIMENTS WITH C-ECH

The hydrogen plasma is produced and heated by ion cyclotron range of frequency wave from t = 51 to 440 ms, with additional hydrogen gas puffing for radiator gas in D-module from t = 50 to 450 ms at a pressure of 1200 mbar for the detached plasma experiment. C-ECH is injected at t = 300-310, and 320-330 ms in double pulse with a power of 130 kW. Figure 2 shows the time evolutions of diamagnetisms (red dotted line), line densities of the CC (CC-MIF, blue line) and EC-MIF (green line), indicating the double pulse C-ECH injection periods (yellow hatch). It is clearly confirmed that the electron line densities increased and diamagnetism slightly decreased with double pulse C-ECH injection. The electron densities and temperatures with and without C-ECH are approximately 6 eV and 2.3×10^{17} m^{-3}, and 3 eV and 1.2×10^{17} m^{-3}, respectively, in D-module (Fig. 3). The quick increase of ion flux with C-ECH injection was also observed (Fig. 4), which is comparable to the behavior of

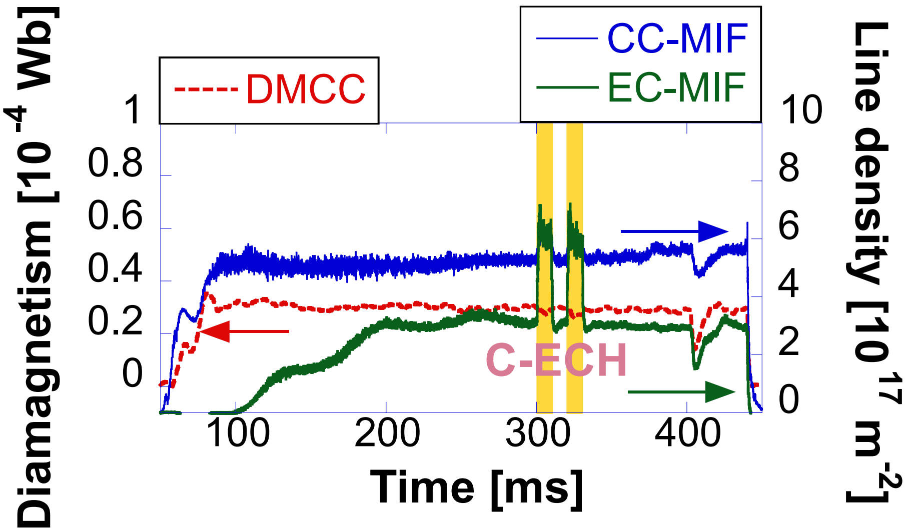

FIG. 2. Time evolutions of diamagnetisms (red dotted line), line densities in CC (blue line) and EC (green line) with C-ECH injection.

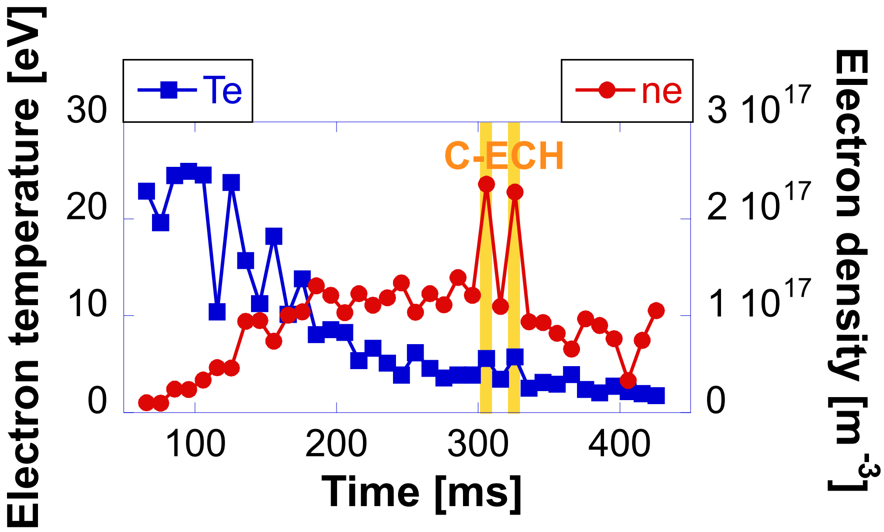

FIG. 3. Time evolutions of electron temperature (blue line) and electron density (red line) at ESP#3.

electron density. The plasma was in the detached condition before C-ECH injection. With C-ECH, the increase in electron density and temperature showed that the plasma transitioned to the attached condition. The transition time of detached to attached condition was approximately 1 ms which was calculated by a rise time of EC-MIF. The fall time of 1 ms in EC-MIF after cut of C-ECH shows the change from the attached state to the detached state. These changes were also observed in the second C-ECH pulse. Figure 5s show Hα and Hα/Hβ intensity ratio images at t = 290-300 ms (a) and (f), 300-310 ms (b) and (g), 310-320 ms (c) and (h), 320-330 ms (d) and (i), and 330-340 ms (e) and (j), respectively, measured by HSCAM. The increase in ion flux and electron density with C-ECH injection indicates that the higher temperature electron flux increased plasma ionization, leading to a total increase in ion flux in the D-module. The intermittent higher electron density and temperature condition of the core plasma affects the D-module detached plasma condition, transitioning it to an attached plasma state during the C-ECH injection periods.

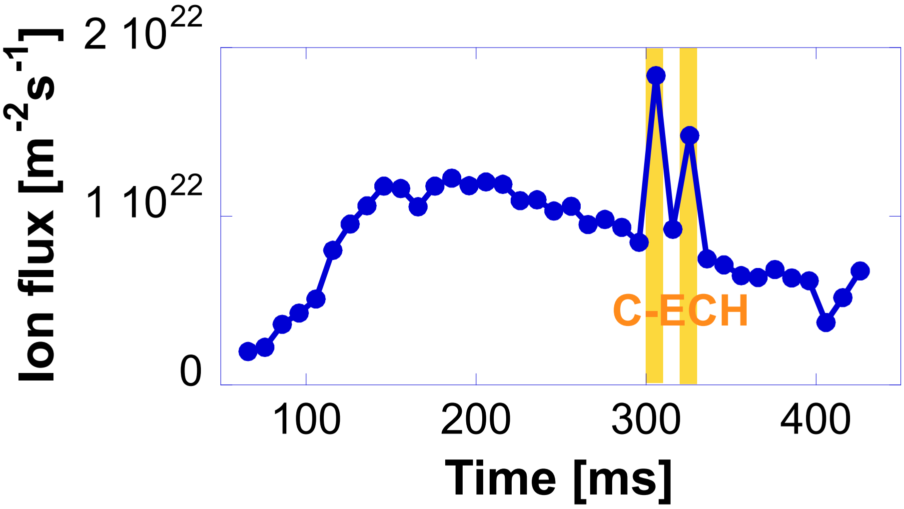

FIG. 4. Time evolutions of ion flux at ESP #3.

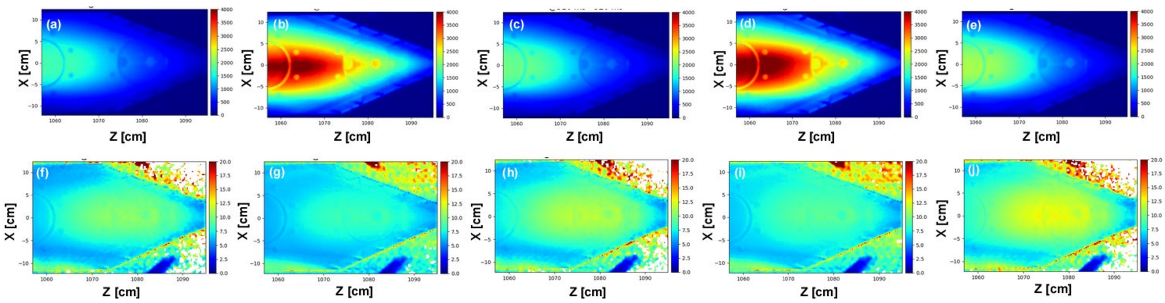

FIG. 5. Hα and Hα/Hβ intensity ratio images at t = 290-300 ms (a) and (f), 300-310 ms (b) and (g), 310-320 ms (c) and (h), 320-330 ms (d) and (i), and 330-340 ms (e) and (j), respectively, measured by HSCAM.

4. CONCLUSION

We revealed that the double pulse of higher temperature and density particle fluxes into the detached simulation plasma in D-module leads to higher ion flux. This double pulse higher electron temperature injection transitions the plasma from a detached to an attached condition twice. In the next step, we plan to use four-wavelength simultaneous measurements on HSCAM to investigate the overall hydrogen atomic and molecular processes in D-module. Additionally, we intend to conduct detailed emission spectroscopy of atoms and molecules along the magnetic field lines.

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