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Development of radiative divertor simulator using magnetic mirror device at KAIST

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1. Introduction

It is crucial to operate burning plasmas while satisfying the thermo-engineering constraints of plasma-facing components including the divertor plate in spite of high particle and energy flux transported from the core plasma. To find a solution for this problem, which is also compatible with high performance core plasma operation, we need to conduct dedicated research for the region between the last closed flux surface and the first wall, i.e., the edge region having open magnetic field lines. Linear devices have been employed to simulate the open field line of the tokamak and stellarator, including scrape-off-layer (SOL) and target region of the divertor [1], because of the similarity in its open magnetic field configuration. These devices can achieve high particle flux levels comparable to those near ITER divertor at relatively lower cost than closed magnetic field systems. Furthermore, linear devices are appropriate for the test bed for edge plasma research because they provide easier control and measurements of system variables such as upstream density, temperature, and neutral pressure.

Recently, magnetic mirror device, KAIMIR, was developed at KAIST [2]. The vacuum chamber of KAIMIR comprises a source chamber, a center chamber, an expander chamber, and two mirror nozzles located at both ends of the center chamber. The device can generate electron density $n_e \sim 10^{18–20}$ m^{-3} and electron temperature $T_e \sim$ 4–8 eV at the center chamber (Z=0.06 m) by adjusting the source power and magnetic field geometry. One of the primary research topics using this device is to simulate the radiative divertor, which reduces particle flux by puffing main ions or impurity gas near the target. To simulate the gas injection near the divertor while minimizing the effects on the upstream region, the pressure in the divertor simulation region should be independently controlled.

In this proceeding, we will describe the differential pumping system developed to control pressure of divertor region independently. Additionally, we will introduce preliminary experimental results showing the performance of the differential pumping system and the feasibility of radiative divertor simulation with the system in the KAIMIR.

2. Methods and Results

This section describes the magnetic mirror device KAIMIR, the developed differential pumping system, the diagnostic applied in this study, and the simulation of the radiative divertor using the system.

2.1 KAIMIR device

The KAIMIR device is a magnetic mirror device with a cylindrical geometry having a diameter of 0.5 m and a length of 2.5 m. As aforementioned, source, center and expander chambers are connected to each mirror nozzle. In the divertor simulation, the center chamber is considered as an upstream region and the expander chamber as a target region. Plasma is generated in the source chamber by a plasma gun [3], with the power supplied by a pulse forming network system. Helium is used as the discharge gas, fed into the plasma gun in the source chamber through either a piezoelectric valve ($Q_{inj.}$=3.9–13 slm) or a solenoid valve ($Q_{inj.}$=13–78 slm), where $Q_{inj.}$ is the gas flow rate. The operation pressure at the center chamber can be varied between 0.5–20 mTorr, depending on the gas flow rate, injection timing, and duration. The plasma generated by the gun is confined by an axial magnetic field produced by the electromagnetic coils, with maximum magnetic field intensities of ~0.1 T at the center and ~0.4 T at the mirror nozzles. The electron density and temperature reaches levels of n_e ~4×10^{19} m^{-3} and T_e ~6 eV with ~12 ms duration under the typical experimental condition, a source power of 0.088 MW, center and mirror nozzle magnetic field intensities of 0.0875 T and 0.35 T, respectively, and a neutral pressure of ~7 mTorr in the center chamber.

2.2 Differential pumping system

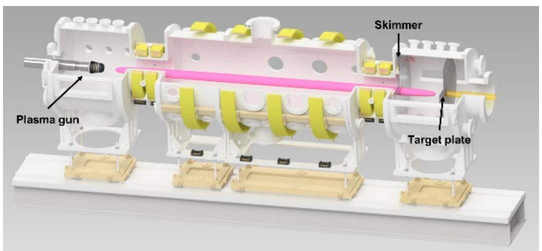

Figure. 1. Cross-sectional view of the computer-aided design model of the modified KAIMIR system.

An additional gas feed line and turbomolecular pump were added to the expander chamber to adjust the neutral pressure. To sustain the pressure difference, skimmer structure [4] was installed between the mirror nozzle and the expander, as shown in Figure 1.

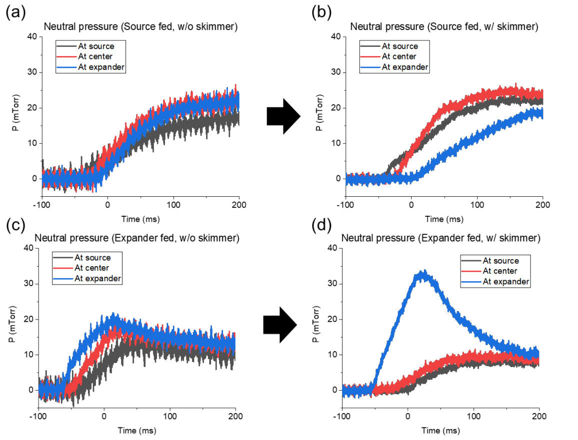

Figure. 2. Time trace of neutral pressure at each chamber when gas was fed into the source chamber (a) with and (b) without skimmer, and when gas was fed into the expander chamber (c) with and (d) without skimmer. In all cases shown, gas was fed from -100 ms to 0 ms at a gas flow rate of 13.3 slm. Here 0 ms refers to the discharge initiation time.

Vacuum conductance between the chambers was reduced from 12800 l s^{-1} to 880 l s^{-1} with the skimmer for He gas. Figures 2(a) and (c) present that the pressure evolution was similar when the skimmer was not installed. However, the pressure in the expander chamber differed from that in the source and center chambers with the skimmer installed. As shown in Figure 2(b), the pressure in the expander chamber was delayed by ~60 ms compared to the pressure in the source and center chambers when gas was fed into the source chamber. Similarly, Figure 2(d) shows that the pressure in the source and center chambers began to rise ~60 ms after the pressure evolution in the expander chamber started. These results indicate that the differential pumping system can be utilized to control the pressure of each chamber independently.

2.3 Ion saturation current density measurements

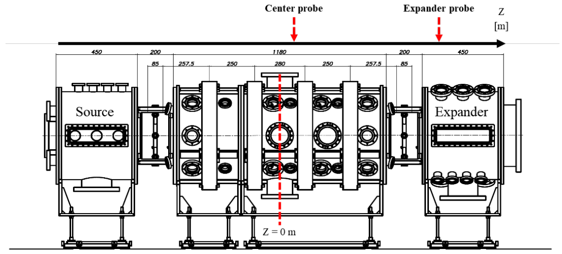

Figure. 3. Drawing of the KAIMIR system and axial locations of the Langmuir probes.

The ion saturation current density (j_{sat}) was measured using the Langmuir probes in the center (Z = 0.06 m) and expander chamber (Z = 0.89 m), with Z = 0 m referenced to the center of the chamber, as shown in Figure 3. A bias voltage of -150 V was applied to the probe tip, and the ion saturation current (I_{sat}) was measured across the shunt resistor (1 Ω). The voltage across the resistor was monitored by the isolation amplifier with a bandwidth of 100 kHz. j_{sat} was calculated by dividing the probe surface area (A_p = 1.01 mm^2 for center probe, A_p=28.9 mm^2 for expander probe) by the I_{sat}. This value can be a parameter for the plasma particle flux at each region since j_{sat} (~$q_e n_e v_{Bohm}$) is proportional to the particle flux (~$n_e v_{Bohm}$).

2.4 Feasibility of radiative divertor simulation

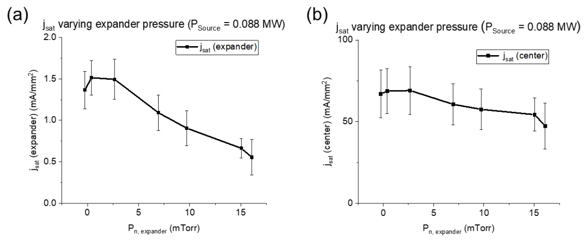

Figure. 4. Ion saturation current density, j_{sat}, (a) in the expander and (b) in the center chamber, while varying the neutral pressure in the expander chamber.

Radiative divertor was simulated by utilizing the differential pumping system. This system allows the expander pressure to be adjusted independently, enabling the reproduction of neutral pressure conditions similar to those in a radiative divertor (~20 mTorr [6]).

Figure 4(a) presents that the j_{sat} at the expander is reduced significantly as the pressure in the expander increases by the gas puffing to the expander, while j_{sat} at the center showed only a relatively small decrease in Figure 4(b). This result indicates that, with the support of the differential pumping system, the variation in neutral pressure of the expander chamber had minimal impact on the plasma in the center chamber. Additionally, the reduction in particle flux at expander suggests that the neutrals at the expander caused radiative loss, thereby reducing particle flux, which should be verified in the future.

3. Conclusions

The KAIMIR device was modified to simulate the radiative divertor. In the divertor simulation, center and expander chambers will be considered as upstream and target-simulating regions, respectively. A differential pumping system was developed to replicate the radiative divertor conditions. Using the system, a decrease in j_{sat} at the expander was observed when the gas was fed into the expander chamber while maintaining j_{sat} at the center, by independently controlling neutral pressure at the expander. This result demonstrates that the expander chamber pressure can be adjusted without significantly affecting the plasma in the center region. Furthermore, the result implies that the radiative divertor concept, suppressing particle flux through gas puffing in the target region, can be effectively simulated in this device.

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