Divertor plasma simulating facility using AF-MPD thruster for testing divertor cooling channel mockup

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1. Introduction

Most of current and future tokamak devices adopt divertor concept to remove helium ashes and impurities from the fusion plasma; helium ashes formed by D-T fusion reactions dilute the fusion fuel while impurities generated by plasma-wall interactions decrease the temperature of the core plasma. In order to efficiently remove the helium ashes and impurities, strong magnetic fields intersect with divertor plate and therefore, the divertor target gets high heat and particle fluxes. In ITER, the heat flux of 10 $MW{\cdot}m^{-2}$ and the particle flux of 10^{24} $m^{-2}{\cdot}s^{-1}$ are expected to hit the divertor target [1,2]. In DEMO, the incoming heat and particle fluxes to the divertor target are probably much higher than those of ITER and it is beyond the current technology level.

Several approaches have been made to address this divertor problem. For instance, the enhancement of the critical heat flux (CHF) of the divertor has been tried by developing innovative heat sink designs such as swirl tube and hypervapotron while some have tried to find materials robust to high heat and particle fluxes. Several advanced divertor designs including super X-divertor [3] and small-angle slot divertor [4] have been proposed to reduce the incoming heat and particle fluxes while some study how to achieve the detached divertor regime without affecting the core plasma performance.

The Korean government agreed that the divertor problem is important and launched a new research center focusing on divertor in 2017; the Center for Innovative Divertor (CID) has been started to develop innovative divertor cooling techniques, divertor armor materials, and advanced divertor designs. The CID is composed of three teams – Postech, UNIST, and KAERI. The Postech team focuses on the divertor heat sink design to enhance the CHF of the divertor. The UNIST team studies advanced divertor design using Tokamak SOL simulation codes such as SOLPS. The KAERI team has developed a divertor plasma simulating facility for the demonstration of Postech team's cooling channel design and for studying divertor armor materials.

2. KAERI divertor plasma simulating facility

There are three types of heat load test facility – electron beam, ion beam, and arc torch. The electron beam is good to achieve high heat flux but it cannot provide particle flux while the ion beam can provide high heat and particle fluxes with high cost. Arc torch can provide high heat and particle fluxes at reasonable cost but the operation pressure is too high for using hydrogen gas (close to atmospheric pressure).

We think applied-field magnetoplasmadynamic (AF-MPD) thruster is promising to provide high heat and particle fluxes because it is operating at high input power (around few hundreds kilowatts) and the size of the plasma plume is few centimeters similar to the spatial scale of the heat flux profile. In addition, it is operating at relatively low pressure with strong magnetic field, similar to actual fusion divertor region.

We then set the target plasma parameters of our divertor plasma simulator as follows:

1) plasma density: ~10^{14} cm^{-3}
2) plasma temperature: few eV
3) plasma flow speed: 20 km/s (= 80 eV for Ar)
4) particle flux: >10^{24} $m^{2}{\cdot}s^{-1}$
5) heat flux: 20 $MW{\cdot}m^{-2}$

Based on the existing AF-MPD thruster in Germany [5], we designed and fabricated our plasma source as seen in Fig. 1. Our plasma source consists of copper anode, thoriated tungsten (2%) cathode, and three Al_2O_3 ceramic insulators. The diameters of the anode and cathode are 80 mm and 12 mm, respectively. The plasma source was designed to be water-cooled.

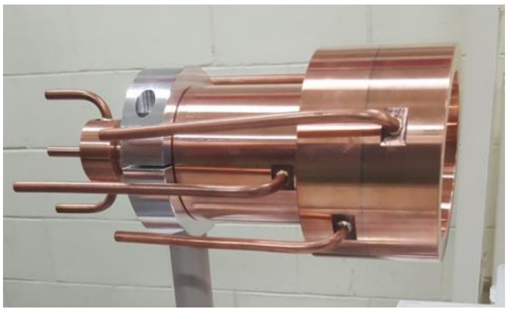

Figure 1. Photo of our plasma source.

In order to provide axial magnetic field, we built a ring type permanent magnet made of NdFeB. The inner and outer diameters are 160 mm and 240 mm, respectively and the thickness is 100 mm. The strength of the magnetic field at the center of the magnet is 0.15 T measured by the Hall probe. The magnet is placed on the translation stage so that we can adjust the magnet position relative to the plasma source.

Figure 2 shows the plasma source and magnet installed inside the vacuum chamber. The cylindrical vacuum chamber with 1.5 m diameter and 1.5 m length was constructed to accommodate full-scale divertor cooling channel mockup. The vacuum chamber is pumped by two cryopumps which have a pumping speed of 5000 L/s for argon.

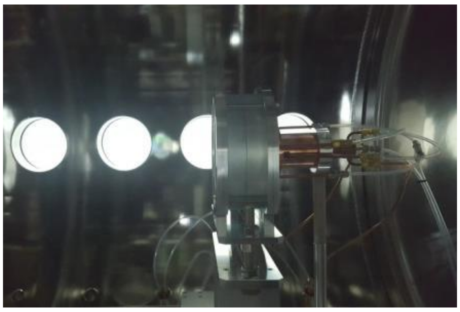

Figure 2. Photo of the plasma source and magnet installed inside vacuum chamber.

For igniting the plasma, we use an ignition power supply which can provide up to 600 V voltage and 10 A current. The plasma is typically ignited at about 400 V and immediately after the ignition, the plasma voltage decreases to 200 V. Figure 3 shows the plasma in this stage. As we increase the plasma current, the plasma voltage slowly decreases and the plasma changes to the arc mode when the plasma current becomes higher than 4 A. Then, the plasma voltage drastically decreases to 50 V. After we achieve the arc plasma, we use high current power supply which can provide up to 500 A. Figure 4 shows the plasma at this stage.

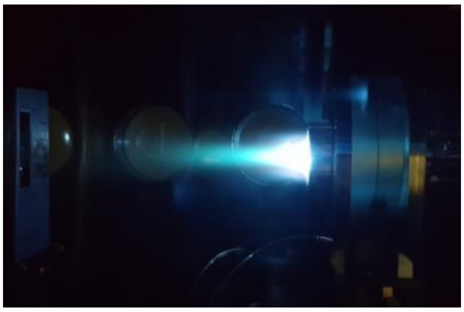

Figure 3. Photo of plasma ignited by ignition power supply (I_p = 1 A)

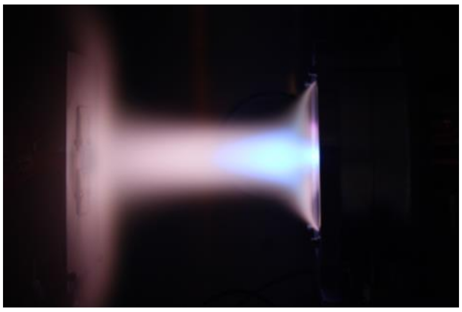

Figure 4. Photo of the plasma sustained by high current power supply (I_p = 100 A)

The current-voltage characteristic of our plasma is shown in Fig. 5. As seen here, the plasma voltage drastically drops to 50 V when the plasma enters to the arc mode. Then, the arc voltage gradually decreases to 33 V as the current increases to 100 A. After this current, the arc voltage slowly increases as shown in Fig. 5.

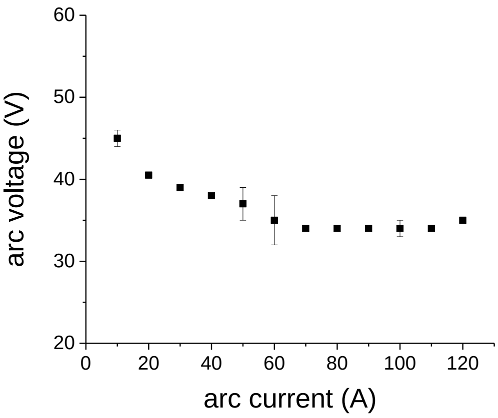

Figure 5. I-V characteristic of our plasma source

3. Heat flux and particle flux measurement

For measuring heat flux provided by our plasma source, we built a single channel calorimeter as shown in Fig. 6. It consists of a copper block (20 × 20 × 70 mm^3) and water cooling tube. Three K-type thermocouples are embedded in the copper block with 20 mm interspace and the copper block is cooled by water at one end. Thus, the heat flux can be calculated from the conduction equation which is given by $dQ/dt = \kappa A \Delta T_c/\Delta x$ where κ is the thermal conductivity, A is the area, and ΔT_c is the temperature difference between the two nearby thermocouples. Since κ for copper is about 400 W/m·K, the heat flux q can be expressed as $q = 0.04 \times \Delta T_c$ $MW{\cdot}m^{-2}$.

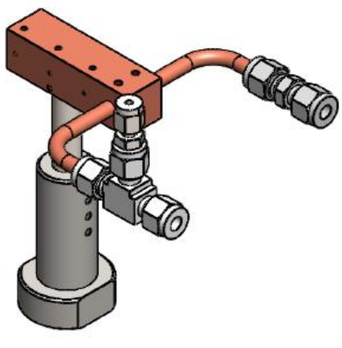

Figure 6. Sketch of a single channel calorimeter for measuring the heat flux.

We also measured the temperatures of inlet water and outlet water using K-type thermocouples. Using the measured temperature difference (ΔT_w), we can calculate the heat transferred to water as $dQ/dt = c{\cdot}m{\cdot}\Delta T_w$ = 4200 J × (2 kg/60 s) × ΔT_w. Thus, the heat flux $q = dQ/dt/A$ = 0.35 × ΔT_w $MW{\cdot}m^{-2}$.

For instance, when the plasma current is 160 A, the ΔT_c is ~75 K and ΔT_w is ~4 K. They indicate that the heat flux of our plasma source at I_p = 160 A is 1.5 $MW{\cdot}m^{-2}$.

In order to measure the particle (ion) flux, we will use Langmuir probe array. The fabricated Langmuir probe array is shown in Fig. 7. 8 Langmuir probe tips made of carbon fiber composite with a diameter of 6 mm are placed in the zigzag configuration. The spatial resolution is about 25 mm. This is actually identical to the KSTAR divertor Langmuir probe array installed on the central divertor in 2018 campaign. The probe array will be placed in front of the plasma source and will be biased negative 200V to measure the ion saturation current. We then obtain the ion flux profile of our plasma source.

Figure 7. Photo of the Langmuir probe array.

4. Concluding remarks

At present, the heat flux of our divertor simulating facility is 1.5 $MW{\cdot}m^{-2}$ at I_p = 160 A. We think the heat flux would be increased as we increase the plasma current in the future. In order to continuously increase the plasma current, we need to improve the cooling system of the plasma source and calorimeter. After we improve the cooling system we will increase the I_p up to 500 A this year and will test the divertor cooling channel mockup designed and fabricated by Postech team.

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