The First Experiment of MPD Jet Injection into GAMMA 10 Plasma*)

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Results of the first experiment of short pulse plasma injection by MPD (magneto plasma dynamic) Jet into GAMMA 10/PDX's longer pulse plasma are reported. In the experiment, a new method for plasma start-up without using plasma guns was applied. In this method, the main plasma of GAMMA 10/PDX was produced by ECRH (electron cyclotron resonance heating) and ICRF (ion cyclotron range of frequency). Then, MPD Jet plasma was injected into the main plasma along magnetic field line. As a result, density of the main plasma was increased and the end-loss flux was doubled. Flow velocity of the plasmoid injected by the MPD Jet was evaluated from the change of plasma density in each cell of the tandem mirror. The result indicated that the flow speed is several km/s. It is found that the plasmoid worked as strong fueling device which dramatically raises the density of plasma. Therefore injection of MPD Jet plasma into tandem mirror can be a useful tool to study physical phenomena of divertor and PWI.

Keywords: tandem mirror, end loss flux, magneto plasma dynamic arcjet, divertor simulation

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1. Introduction

Efficiency of divertor cooling and the sustainability of plasma facing components are critical issues for fusion engineering. In a fusion reactor, control of extremely high heat and particle flux is important to maintain steady state operation. However, in torus devices, their complex structure of magnetic field and limited availability of diagnostic tools make it difficult to analyze physical phenomena in divertor region. On the other hand, linear devices such as tandem mirror have simpler magnetic field and more availability of diagnostics. Also, a tandem mirror is able to produce plasma of high temperature, which is relevant to the SOL plasma parameters of tokamak plasmas.

GAMMA 10/PDX [1–3] is the largest tandem mirror device in the world and is capable of producing long pulse of 200~400 ms mirror confined plasma with end-loss plasma flux of 100~400 eV in ion temperature and 10~40 eV in electron temperature with the help of powerful ICRF (ion cyclotron range of frequency) heating and plasma confinement with strong mirror magnetic field (~3 T). Recently, divertor simulation experimental module (D-module) was newly installed to a GAMMA 10/PDX. The D-module mainly consists of semi closed rectangular box, V-shaped target plate, and gas injection systems. So far, by using the high temperature end-loss flux and the D-module, a situation of tokamak divertor region is simulated and the change of plasma parameters due to the interactions between plasma, target plate, and impurity gas are being studied. In the latest research of the GAMMA 10/PDX divertor simulation, it was found that the density of the end-loss flux is still lower than the tokamak divertor plasma and therefore it will be preferred if more dense end-loss flux is obtained. Also, in studies of divertor and PWI, synergetic effect between the heat load from steady state plasma and the heat from short pulse plasma is an important topic.

In order to increase density of the end-loss flux and to simulate synergetic effect of steady heat and transient heat, application of MPD Jet [4] was put forward. As in Fig. 1, the MPD Jet has co-axial anode and cathode. In a

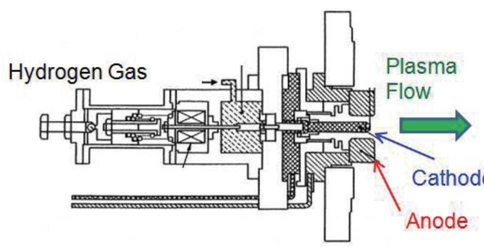

Fig. 1 Schematic view of the MPD Jet [4].

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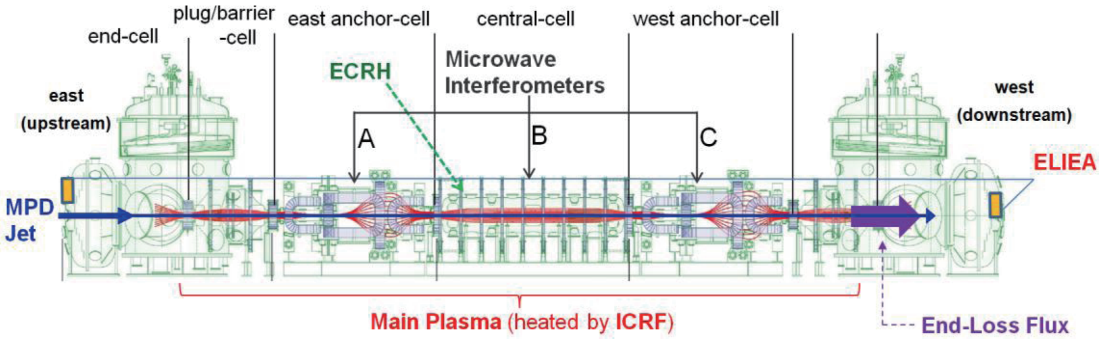

Fig. 2 Schematic view of GAMMA 10 vacuum vessels. Locations of MPD Jet, Mirror Confined Plasma, End Loss Flux, ECRH, and main diagnostics are shown as arrows.

discharge of the MPD Jet, electric current of ~ 6 kA flows between the anode and the cathode. Then, Lorentz force is induced within the current and magnetic field made by the current itself and the force thrusts ions and electrons into the direction of plasma flow. Since the tandem mirror has open ends, MPD Jet can inject plasma directly into the mirror confinement region. Therefore, the MPD Jet can be an effective tool to enhance the parameters of mirror confined plasma and the end-loss flux.

2. Experimental Apparatus

A schematic view of GAMMA 10/PDX and the experimental apparatus is shown in Fig. 2. In the east region of the machine, MPD Jet is placed. The middle region is a place for production of main plasma. Area of divertor simulation experiment exists in the downstream region. In standard experiments of GAMMA 10/PDX, initial plasma is ignited by MPD Jet in order to help ICRF systems ramp up the main, high temperature plasma. In this research, the ECRH (electron cyclotron resonance heating) wave is used to ignite the initial plasma and this makes it possible to inject MPD Jet plasma into the main, hot plasma [5]. After the main plasma is completely built up in the central cell, the MPD Jet injects plasma from the east end cell in the pulse of 1 ms. Then, time changes of the plasma density in three positions; east anchor cell, central cell, and west anchor cell are measured by microwave interferometers in order to evaluate the efficiency and the penetration speed of the MPD Jet plasma.

Arrays of ELIEA (end-loss ion energy analyzer) attached at the inner wall of the end cells are used to investigate the change of ion current density which is flowing along magnetic field line. Figure 3 is a schematic diagram of ELIEA. ELIEA consists of the ion repeller grid, the secondary electron repeller grid, and the collector plate. In the measurement of ELIEA, positive voltage is given to the ion repeller grid. Then, when an ion in the end-loss flux enters the ELIEA device, it will be led to the collector plate if its kinetic energy is not high enough to penetrate the potential well. The ion repeller voltage in this research is fixed to measure ions whose energy is lower than 3 keV.

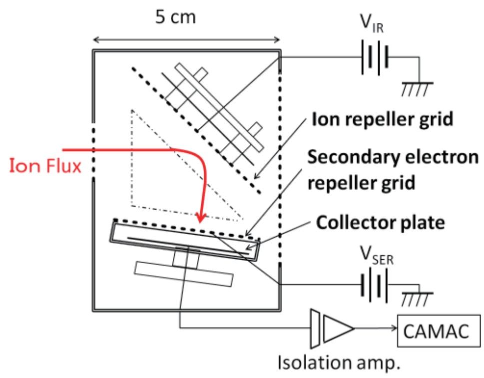

Fig. 3 Schematic diagram of ELIEA device.

Table 1 Plasma parameters in GAMMA 10/PDX and performances of MPD Jet at upstream region.

	Ti (eV)	Te (eV)	Ne (m^{-3})	Heat Flux (MW/m^2)
main plasma	4000	100	10^{18}	-
end-loss	400	40	10^{17}	1.0
MPD Jet	4	4	10^{20}	5.7

Important parameters of typical GAMMA 10/PDX plasmas and the performance of the MPD Jet are listed in Table 1. In GAMMA 10/PDX, ion temperature of the main plasma usually reaches to 4 keV, and from the main plasma, the end-loss flux of 400 eV is produced. Compared with these high temperature plasmas, the plasma injected by MPD Jet is cold; however, its density is even higher than the GAMMA 10/PDX main plasma. Therefore two things are expected in the plasma injection experiment; increase in the densities of main plasma and the increase of the total energy flowing toward downstream region (west end cell).

3. Experimental Results

In this experiment, the plasma was started up by using ECRH in order to use the MPD Jet after the start up of the main plasma. Therefore, as the first step, the compari-

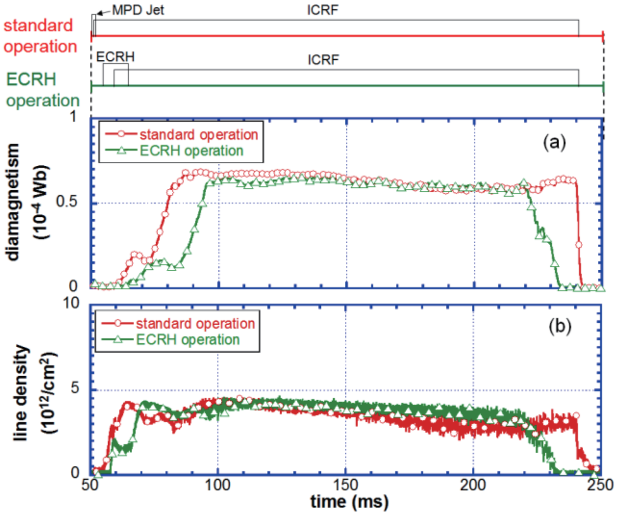

Fig. 4 Time sequences of MPD Jet, ICRF and ECRH with parameters of the main plasma in two operation modes; (a) diamagnetism and (b) electron line density.

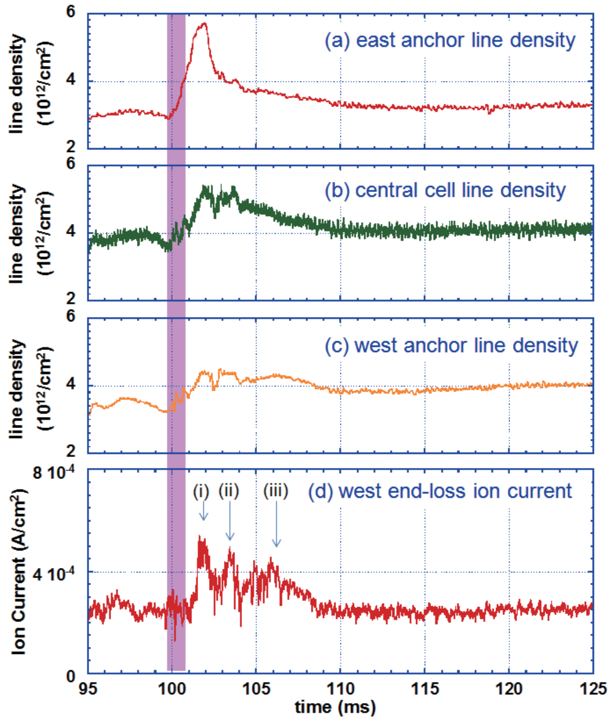

Fig. 5 Results of the MPD Jet plasma injection experiment. The upper three plots show the time evolution of electron line density in (a) the east anchor cell, (b) the central cell, and (c) the west anchor cell. Plot (d) is time profile of the end-loss ion current measured by ELIEA in the west end-cell.

son between the ECRH startup operation and the standard operation was performed.

Results of two plasma start up modes are shown in Fig. 4. Both diamagnetism and electron line density in the central cell have shown almost same behavior as standard experiment modes except for the beginning and the ending of the discharge. In the beginning of discharge (70 ~ 90 ms), plasma parameters were different in each operation modes because the amount of neutral gas was different. The power input in the ECRH operation mode was around 100 kW (from ECRH wave) which is much smaller than that of standard operations; several MW (from MPD Jet discharge). This difference of energy has made a gap of ionization rate and neutral gas amount in two operation modes. Therefore, except the beginning and the ending of discharges, it should be reasonable enough to consider that the main plasma in ECRH startup operation have similar parameters and characteristics to those in the standard experiments.

After the main plasma was ignited by ECRH and ICRF, injection of the MPD Jet was performed. In Fig. 5, time evolution of electron line-densities (in position A, B and C described in Fig. 2) and downstream ion current during the experiment were plotted. In the time sequence, MPD Jet injection pulse was from t = 99.9 ms to 100.9 ms. Obviously, line densities and the end-loss ion current were increased by the injection of MPD Jet. It is noted that, in each three cells, peaks of density are slightly different. For example, line density in east anchor cell (Fig. 5 (a)) shows one large peak at t = 102 ms. However, in the central cell (Fig. 5 (b)), line density shows two peaks; roughly at t = 102 ms and t = 103.5 ms. Also, the line density of the west anchor cell and the end- loss ion current, three peaks were observed at t = 102, 103.5, and 106.5 ms.

The maximum amount of density increase was achieved at the east anchor cell; the cell locates at the most upstream, closest to the MPD Jet. On the other hand, the increases at the central cell (Fig. 5 (b) and the west anchor cell (Fig. 5 (c)) are smaller. This indicates that the effect of the MPD Jet plasma was weakened as particles flow in the large tandem mirror. As Fig. 5 (d), the current density of end-loss ion was around 2.5 $\times 10^{-4}$ (A/cm^2) and it was increased to around 5.0 $\times 10^{-4}$ (A/cm^2). Therefore the value of end-loss ion current was doubled by MPD Jet.

4. Discussion

To evaluate the flow speed of plasma injected by MPD Jet is critical for this research in two reasons. First, since GAMMA 10/PDX is a mirror machine, it have mirror magnetic field and therefore, for the experiment of plasma injection by MPD Jet, mirror reflection of injected plasma needs to be considered. In our experimental apparatus, the magnetic field strength at the MPD Jet is 0.01 T, while the maximum field strength of GAMMA 10/PDX is 3.0 T. In this case, the mirror ratio R = 300 and thus, plasma particles injected by MPD Jet will apparently feel very strong effect of mirror reflection. The flow speed of injected plasma determines how much part of injected plasma can penetrate the mirror. Second, because the injected plasma penetrates the main plasma, effects of interaction between the plasmoid and the main plasma, such as particle collisions should be considered. Here, the flow speed will determine the frequency of collisions and of course, will affect the flow speed.

In past research, result of Mach probe measurement showed that the flow speed of plasma injected by the MPD Jet is about 4~6 km/s at the upstream region [6]. Since the total length of GAMMA 10/PDX is 27 m, it takes about 4.5~7 ms for particles to travel from upstream to downstream. Therefore the plasmoid will arrive to the west end cell at t = 104.5~107.5 ms. However, in Fig. 5 (d), the ion current in the downstream showed peak not only at t = 106.5 ms (peak (iii)), but also t = 102 and 103.5 ms (peak (i) and (ii)). The appearance of the peak (iii) at t = 106.5 ms can be explained as the arrival of injected plasmoid. However, for the preceding two peaks, effect of ionization by injected electrons needs to be considered. Since electrons are light and move much faster than ions, they can enter to the main plasma instantly after the discharge of MPD Jet. Then, the electrons collide with neutral gas in each cell and ionization will occur. As a result, the plasma density in the cells increases as seen in Figs. 5 (a)~(c). After the ionization, newly ionized particles are strongly heated by ICRF waves. Therefore the ions obtain large velocity. It is known that in GAMMA 10/PDX, such newly ionized particle reaches to the end cell in 1~2 ms. Therefore, newly ionized particles get ahead of the plasmoid and thus, ion current in the end-cell increases at t = 102 ms, like Fig. 5 (d). For the peak (ii), effect of mirror confinement is a plausible cause. That is, when the fast electrons ionized neutral particles in the central cell, newly ionized particles actually can go to both west and east. Then, particles moved toward east are reflected by mirror magnetic field and therefore the ion current in the west rises.

In order to analyze the effect of collisions on flow speed of injected plasma, discharges of MPD Jet in three discharge conditions; injection into plasma, into neutral gas, and into vacuum were performed. Positions and appearance time of the observed peaks of line densities are plotted in Fig. 6 (a). In the graph, the flow speed of injected plasma in each discharge conditions can be roughly evaluated from the slope of the plots. The fastest flow speed was observed in the condition of injection into vacuum. Then, in the case of injection into neutral gas, the flow velocity was slower, and the injection into plasma showed the slowest one. It indicates that there apparently is the slowing down of the flow speed due to the collisions between gas and plasmoid, and the effect is stronger in the collision with plasma particles. Figure 6 (b) is the floating potential of the west end plate. At t = 99.9 ms, the floating potential went down dramatically. This indicates that there certainly were electrons which move very fast, therefore the occurrence of ionization during the MPD Jet injection became more concrete.

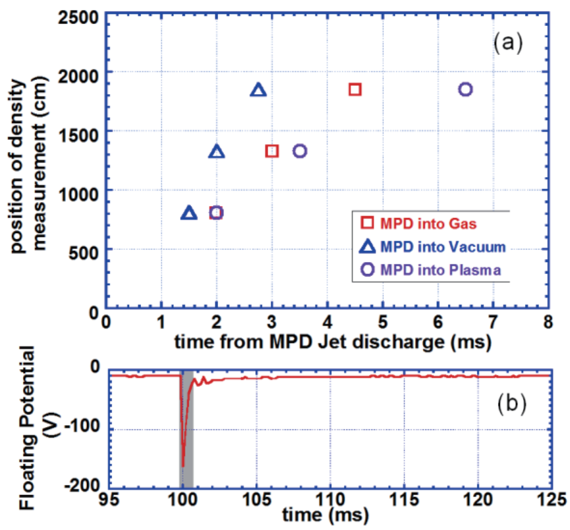

Fig. 6 (a) Positions and the appearance times of line density peaks in each cell are plotted. square: MPD Jet injection in to neutral gas, triangle: injection into vacuum, circle: injection into plasma. (b) floating potential of the west end plate during MPD discharge into vacuum.

5. Summary

In order to expand the operation range of plasma parameters and to give a transient change of plasma for GAMMA 10/PDX divertor simulation experiment, plasma injection along the magnetic field was tested by using MPD Jet. As a result, end-loss ion current was largely increased and therefore the operation range of plasma parameter was expanded. Since the mean free path of the injected plasma was short compared with the total length of the tandem mirror in this research, effect of the injection of MPD Jet plasma mainly worked as a fueling device for the tandem mirror. Although the achieved density of the end-loss plasma is still lower than tokamak divertor plasma, the result will be a good guide for a future expansion of divertor studies in tandem mirror.

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