

# MAGNETIC CHANNEL FLOW OF HIGH DENSITY PLASMAS IN THE HITOP DEVICE

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## Abstract

A high density (more than  $10^{14} \text{ cm}^{-3}$ ) and supersonic plasma flow is formed in the HITOP device to investigate various MHD phenomena. A plasma flow speed and an ion temperature are measured by using visible spectroscopy and Mach number of the flow is observed nearly equal to 1, which agree well with that by Mach probe. Spatial profiles of the plasma density and Mach number are measured in several magnetic field configurations. A cylindrical plasma is found to rotate eccentrically around the center axis in an expanding magnetic field configuration with the increase of plasma beta values and field curvatures.

## 1. Introduction

Magneto-hydro-dynamic (MHD) behaviors have been investigated for years and there are many interesting topics in this field such as a large amplitude Alfvén wave, MHD vortices, MHD shock waves, and MHD instabilities related to space and fusion plasmas. The solar flare explosion and the following substorm phenomena in the magnetosphere is one of the interesting MHD phenomena. Interaction between a high beta plasma flow and magnetic field plays an important role in the phenomena. It is also important to study MHD instabilities occurred in a high beta plasma to improve the plasma particle and energy confinement in fusion plasmas.

The HITOP (High density TOhoku Plasma) device has been developed to investigate these complex MHD behaviors at Tohoku University<sup>[1]</sup>. A high density plasma blows off with a supersonic velocity from a Magneto-Plasma-Dynamic (MPD) arcjet device<sup>[2]</sup> installed in the HITOP. This paper describes measurements of several plasma parameters and complex behaviors of the plasma flow observed in several magnetic channels.

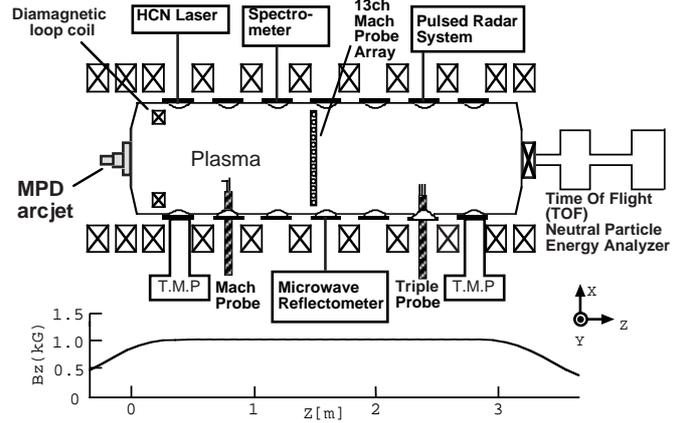
## 2. Experimental apparatus

Experiments are performed in the HITOP device, which consists of a large cylindrical vacuum tank (diameter  $D = 80$  cm, length  $L = 320$  cm) and eleven magnetic coils. A schematic view of the HITOP is shown in Fig. 1. Various types of magnetic field configurations is formed by adjusting the external coil current. A uniform magnetic field  $B_z$ , which is shown in the figure, can be generated up to 1 kGauss, which is limited by an available power supply capacity. The MPD arcjet, which is installed at one end of the HITOP, has a coaxial structure with a center thoriated tungsten rod cathode and an annular molybdenum anode, the inner diameter of which is 3 cm. A quasi-steady discharge continues for 1 ms with a pulse forming network (PFN) system and a fast puffing of helium gas. A high density plasma produced in the muzzle region of the MPD arcjet is accelerated in the axial ( $Z$ -axis) direction by the  $\mathbf{J} \times \mathbf{B}$  force, and expands in the large vacuum tank. Then, a high density, highly ionized, quasi-steady plasma flow is

produced in the HITOP. The discharge current  $I_d$  can be controlled by changing the charging voltage of capacitor banks of the PFN power supply. A discharge voltage  $V_d$  and  $I_d$  are kept nearly constant over 1ms. The maximum discharge current is 10 kA with a typical discharge voltage of 200 V.

Electron temperature and density profiles are measured by Langmuir probes. Plasma flow velocity is measured by a Mach probe which has two probe tips, one of which faces the plasma flow direction and the other faces the perpendicular direction. A Mach number  $M$ , defined as a ratio of the plasma flow velocity to the ion acoustic velocity, is obtained from ratio of the two ion saturation currents. A 13ch Mach probe array is set at 1.6 m downstream of the MPD outlet in the HITOP to measure temporal evolutions of spatial profiles of the density and the Mach number. A spectroscopic technique is used to measure an ion temperature  $T_i$  and a flow velocity  $U_p$  from the Doppler broadening and spectral shift of HeII line spectrum. An emission from the plasma is transferred to a 1m Czerny-Turner spectrometer with a grating of 2400 grooves/mm. A spectrum is detected with an image intensifier tube coupled with a CCD camera (ICCD). HeII line spectra are obtained in every 0.1 msec time interval during a shot with the spectral resolution of 0.02 nm.

Several other diagnostics are installed in the HITOP device as shown in Fig. 1. A time-of-flight (TOF) neutral particle energy analyzer is attached at the end of HITOP along the Z-axis. Ion temperature and flow velocity of the plasmas are obtained from the TOF data. An HCN laser interferometer is being installed to measure electron density profiles. A microwave reflectometer and a multi-channel magnetic probe array are also utilized to measure the density and magnetic field fluctuations associated with MHD activities such as instabilities and a magnetic reconnection in the plasma.



**Fig. 1.** Schematic view of the HITOP device and a spatial profile of the uniform magnetic field ( $B_z = 1$  kG).

### 3. Experimental results

In Fig. 2 are shown the  $I_d$  dependences of ion saturation currents,  $J_{perp}$ , and the ratio,  $J_{para}/J_{perp}$  measured at  $Z = 1.6$  m in the uniform configuration of  $B_z$ . Here,  $J_{perp}$  and  $J_{para}$  are those collected by Mach probe surfaces, of which the normal is perpendicular and parallel to the plasma flow, respectively. The electron density  $n_e$ , calculated from  $J_{perp}$  assuming the electron temperature  $T_e$  is constant at 10 eV, increases almost linearly with the increase of  $I_d$  and  $B_z$ . The electron density and temperature are also measured by a triple probe and are  $3 \times 10^{14}$   $\text{cm}^{-3}$  and 10 eV, respectively, when  $I_d$  is 10 kA. Mach number is calculated from the ratio as  $M = \kappa \times (J_{para}/J_{perp})$ , where  $\kappa = 0.4$  assuming  $T_e = T_i$ , and is almost constant around  $M = 1$ .

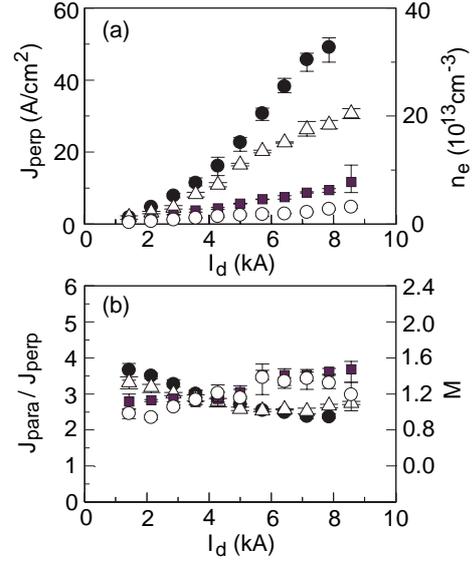
A radial profile of the plasma column is measured by the Mach probe array.

Figure 3 shows a temporal evolution of  $J_{perp}$  radial profile at  $I_d = 5.5$  kA. The plasma column is kept stationary with its axis coincident with the chamber axis. As the magnetic field increases, the half-maximum plasma diameter  $d_p$ , gradually decreases and reaches 5 cm at  $B_z = 1$  kG, which is nearly equal to the average diameter of the anode.

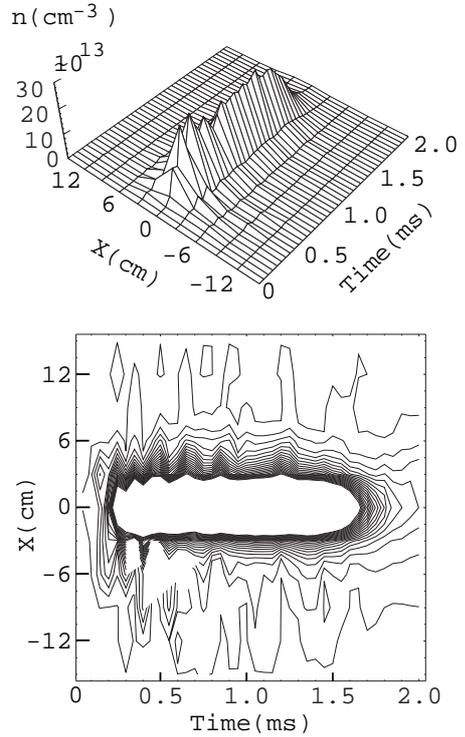
Temporal evolutions of the ion temperature  $T_i$  and the flow velocity  $U_p$  are measured by a spectrometer as shown in Fig. 4.  $T_i$  and  $U_p$  are almost constant during a shot and are 10 eV and 25 km/sec, respectively, when  $I_d$  is 8 kA. The Mach number is calculated from the measured  $T_i$  and  $U_p$  as  $M = U_p / ((T_i + T_e) / m_{He})^{1/2} = U_p / (2T_i / m_{He})^{1/2}$  assuming  $T_e = T_i$ . The Mach numbers thus obtained are almost equal to those by Mach probe measurements.  $U_p$  as well as  $T_i$  increases gradually as  $I_d$  increases. This is the reason why the Mach number is kept constant as  $I_d$  increases.

Density profile measurements are performed in several magnetic configurations. Figure 5 shows  $J_{perp}$ , and  $J_{para}/J_{perp}$ , as a function of  $I_d$  in expanding magnetic field configurations, where  $B_{z0}$  at  $Z = 0$  m changes from 0.23 kG to 1.3 kG with  $B_{z1}$  at  $Z = 1.6$  m keeping constant at 0.23 kG. The on-axis density increases with  $I_d$  in a low mirror ratio  $R = B_{z0}/B_{z1}$  but it starts to decrease above  $I_d = 4.5$  kA in a high mirror ratio as shown in the figure. A temporal evolution of  $J_{perp}$  radial profile with  $I_d = 6.5$  kA is shown in Fig. 6. From simultaneous measurements of the density peak position by use of several probes located at several axial and azimuthal positions, it is found that the plasma plume rotates eccentrically around the chamber axis. The eccentric radius increases as mirror ratios and beta values at  $Z = 1.6$  m increase. A ballooning instability<sup>[3]</sup> is a candidate, but more detailed experiment are necessary to conclude it. Rotation frequency changes with the radial electric field in the plasma, which is controlled by end-plate biasing technique. Spatial profiles of the plasma potential are measured by scanning a triple probe. The rotation direction and its velocity are consistent of  $\mathbf{E} \times \mathbf{B}$  drift motion.

In conclusion, a high density (more than  $10^{14}$  cm<sup>-3</sup>) and transonic plasma flow is formed in the HITOP device. The electron density and



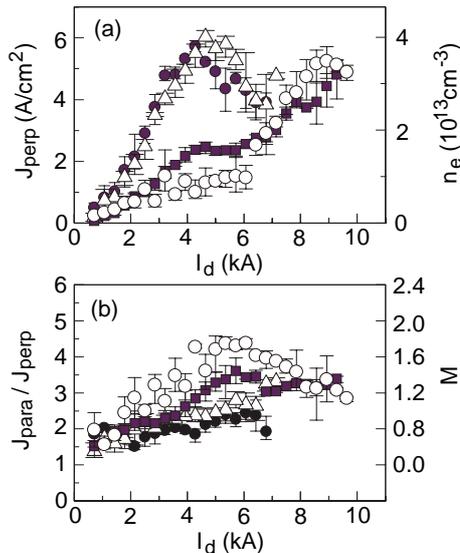
**Fig. 2.** Dependences of (a)  $J_{perp}$  and (b)  $J_{para}/J_{perp}$  on  $I_d$  in the uniform B-field.; closed circles:  $B_z = 1$  kG, open triangles:  $B_z = 0.73$  kG, closed squares:  $B_z = 0.4$  kG, open circles:  $B_z = 0.23$  kG.



**Fig. 3.** A temporal evolution of  $n_e$  spatial profiles in a uniform  $B_z$ -field.  $B_z = 1$  kG,  $I_d = 5.5$  kA.

temperature increase as the discharge current and the magnetic field strength and are nearly  $3 \times 10^{14} \text{ cm}^{-3}$  and 10 eV, respectively, at  $I_d = 10 \text{ kA}$  on the axis of the vacuum chamber. The plasma flow speed and ion temperature are measured by visible spectroscopy and are 25 km/sec and 10 eV, respectively. Mach numbers of the flow obtained by the spectrometer agree well with those by the Mach probe. The spatial profiles of the plasma density and Mach number are measured in several magnetic field configurations. A cylindrical plasma is found to rotate eccentrically around the center axis with the increase of a beta value and a field-line curvature. The rotation frequency changes with the radial electric field in the plasma. Experiments on the merging of two rotating plasma flows are being scheduled.

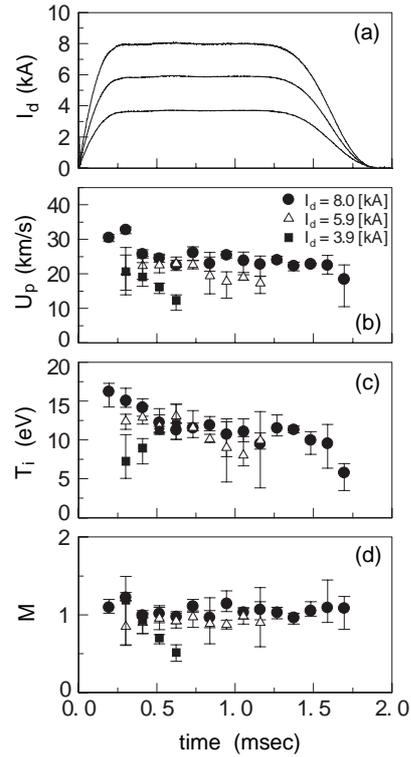
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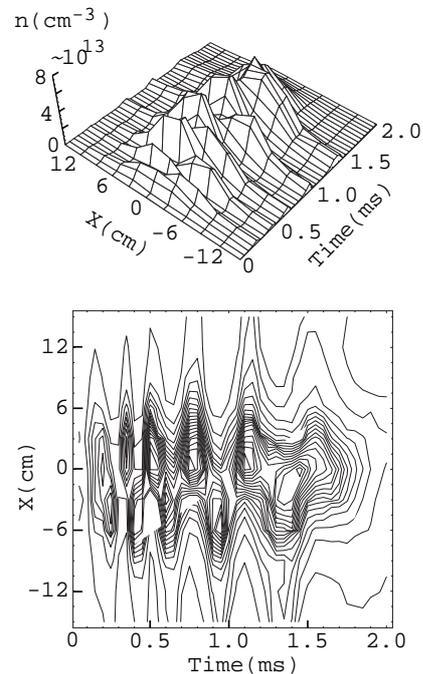
**Fig. 5.** Dependences of (a)  $J_{perp}$  and (b)  $J_{para}/J_{perp}$  on  $I_d$  in an expanding magnetic configuration.; closed circles:  $B_{z0} = 1.3 \text{ kG}$ , open triangles:  $0.73 \text{ kG}$ , closed squares:  $0.4 \text{ kG}$ , open circles:  $0.23 \text{ kG}$ , where  $B_{z1} = 0.23 \text{ kG}$  in all cases.

## References

- [1] A. Ando et al.: *Proc. of ICPP96*, (Nagoya), Vol.2, 2014 (1996).
- [2] K. Kuriki and M. Inutake: *Phys. Fluids.*, **17**, 92 (1974).
- [3] R. Hatakeyama et al.: *Nucl. Fusion* **23**, 1467 (1983).



**Fig. 4.** Temporal evolutions of (a)  $I_d$ , (b)  $U_p$ , (c)  $T_i$  and (d)  $M$  for three different  $I_d$ .



**Fig. 6.** A temporal evolution of  $n_e$  spatial profiles in an expanding magnetic configuration.  $B_{z0} = 1.3 \text{ kG}$ ,  $B_{z1} = 0.23 \text{ kG}$ ,  $I_d = 5.5 \text{ kA}$ .