

## Spatial Distribution of Lorentz Forces in an Applied-Field Magneto-Plasma-Dynamic Arcjet Plasma

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In order to clarify the electromagnetic acceleration mechanisms of an applied-field magneto-plasma-dynamic arcjet (MPDA), magnetic fields are measured in detail near the MPDA outlet. Plasma current density is calculated using the Maxwell equation ( $\text{rot}\mathbf{B} = \mu_0\mathbf{j}$ ), and then spatial distributions of Lorentz forces ( $\mathbf{j} \times \mathbf{B}$  forces) are evaluated. A uniform external magnetic field is deformed by a strong diamagnetic effect near the MPDA outlet, and as a consequence, a converging magnetic nozzle configuration is formed. It is found that an axial Lorentz force  $F_z (= j_r B_\theta - j_\theta B_r)$  is almost eliminated by the deceleration force (the  $j_\theta B_r$  force), which results from the diamagnetic effect. The deceleration force can be converted to the acceleration one in an externally-applied diverging magnetic field.

**Keywords:**

MPD arcjet, electric propulsion, Lorentz force acceleration, magnetic nozzle

A magneto-plasma-dynamic arcjet (MPDA) has been developed as one of high-enthalpy plasma sources for use in space propulsion [1] and in several industrial applications. The MPDA plasma is mainly accelerated axially by self-induced  $j_r \times B_\theta$  force and exhausted with a velocity of several tens of km/s with an ion acoustic Mach number  $M_i$  of around unity. When external magnetic field  $B_z$  is applied, the azimuthal  $j_r \times B_z$  force also acts on the plasma as shown in Fig.1.

In previous works, an increase in thrust achieved by applying a diverging magnetic field has been observed experimentally [2]. However, there has been no precise measurement of the electromagnetic force acting on the plasma, and the detailed acceleration mechanism has not yet been elucidated.

In order to clarify the behavior of electromagnetically-accelerated plasma, experiments have been performed in the HITOP (HIGH density TOhoku Plasma) device of Tohoku University [3]. A high-power, quasi-steady MPDA is installed at one end of the HITOP device. A quasi-steady helium discharge lasts for 1ms using a pulse-forming network power

supply. Time-varying magnetic fields in the plasma flow are measured directly by use of a movable magnetic probe array.

An axially-uniform external magnetic field  $B_0$  is applied as shown in Fig.2 (a). Figures 2(b) and (c) show 2-D vector plots of the magnetic fields  $B_r$  and  $B_z$  and plasma current densities  $j_r$  and  $j_z$ , which are calculated from the Maxwell equation,  $\text{rot}\mathbf{B} = \mu_0\mathbf{j}$ , by using three components of the measured magnetic field. A high-beta plasma generated in the outlet region of the MPDA counteracts the external magnetic field by the diamagnetic effect. Hence, the net field strength decreases to about one half of the applied-field strength and the azimuthal magnetic field  $B_\theta$  is also generated by the axial plasma current extending downstream. The resultant magnetic flux tube converges gradually downstream; *i.e.*, a slightly converging helical magnetic nozzle with a variable pitch is spontaneously formed.

The spatial profiles of Lorentz force  $\mathbf{F} (= \mathbf{j} \times \mathbf{B})$  derived from these data are shown in Fig.2 (d). It should be noted that the inward radial component of the Lorentz force  $F_r$  (pinch force) is much larger than the axial component  $F_z$ . Here the  $F_z$  is calculated using the following equation,

$$F_z = j_r B_\theta - j_\theta B_r \tag{1}$$

The second term in the right-hand side of eq. (1) comes from the interaction between  $j_\theta$ , which is arisen from the diamagnetic current and the Hall current, and  $B_r$  generated in the resultant converging magnetic field. This acts as a deceleration force counteracting the acceleration force of the first term of eq. (1). This result is consistent with the experimental result showing that  $M_i$  is always at almost unity in the case of a uniformly-applied magnetic field [3].

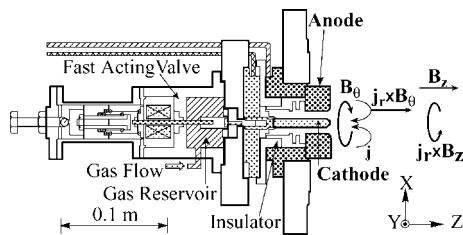


Fig. 1 Cross section of MPDA and directions of Lorentz forces.

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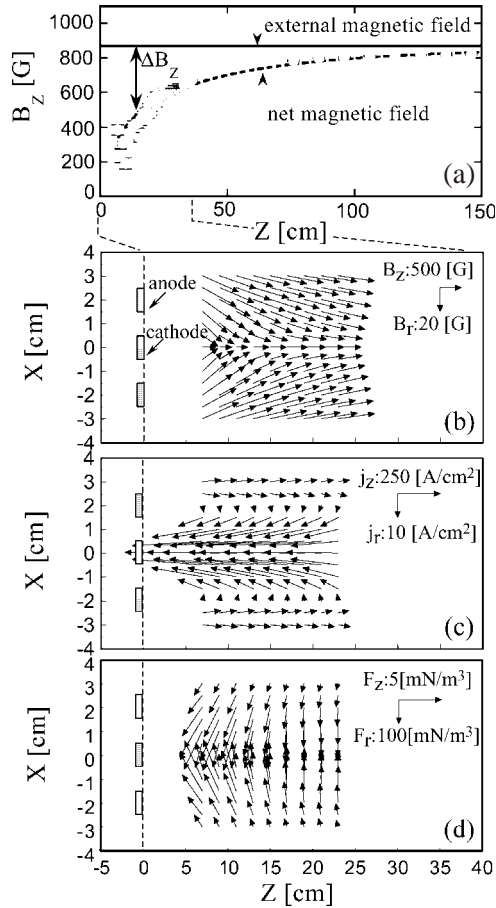


Fig. 2 (a) Axial profile of net magnetic field strength, and 2-D vector plots of (b) magnetic field, (c) plasma current density and (d) Lorentz force.  $B_0 = 870$  G (uniform), Discharge current  $I_d = 7.2$  kA and mass-flow-rate of helium = 0.1 g/s.

For efficient plasma acceleration, the sign of  $B_r$  of the second term in eq. (1) should be reversed by applying a diverging magnetic field.

Figure 3(a) shows an externally-applied diverging field and the measured net field strength. Though a converging nozzle is still formed by the strong diamagnetic effect in the upstream region, it converts to a diverging field in the downstream region; *i.e.*, a magnetic Laval nozzle is spontaneously formed. Spatial distribution of the Lorentz

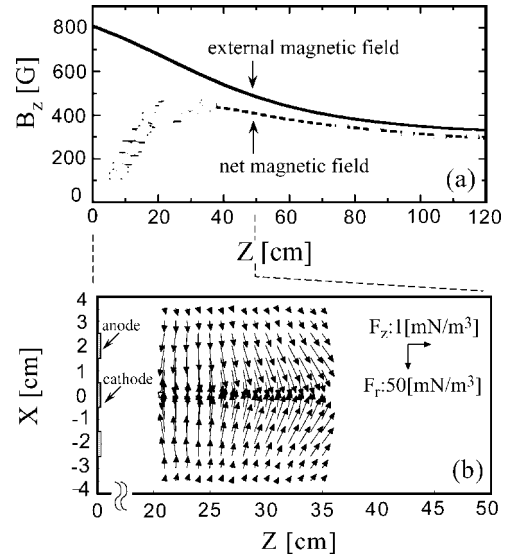


Fig.3 (a) Axial profile in the externally-diverging field and (b) 2-D vector plot of Lorentz force.  $I_d = 7.2$  kA and mass-flow-rate of helium = 0.1 g/s.

forces in the externally-applied diverging field is shown in Fig. 3(b). It is noteworthy that the direction of  $F_z$  converts from negative to positive in the region where the net magnetic flux tube changes from a converging one to a diverging one. This result shows that the Lorentz force distribution in the MPDA plasma can be controlled by adjusting the externally-applied field configuration. For more efficient plasma acceleration, the Laval-nozzle shape should be optimized by taking into account both the electromagnetic force and the pressure force. This is a crucial ongoing task for further progress in the plasma acceleration research.

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