Magnetic nozzle plasma thruster
~ Helicon and Helicon MPD thruster ~

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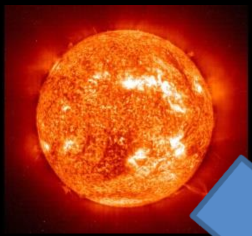
Students in Iwate and Tohoku Universities

Here I would like to briefly review the results on the magnetic nozzle plasma thruster in Iwate University (2007-2012), in the Australian National University (sabbatical year 2010-2011), and in Tohoku University (2013-).

電気推進機 (プラズマ推進機)



ソーラーパネル

電力

プラズマ生成・加速

燃料ガス

プラズマ流噴射

推力

推力 = 推進機から放出した運動量

化学推進機

化学燃料を燃焼し一気に噴射する

特徴：莫大な推進力 (数千 kN).
燃料使用量が多い.

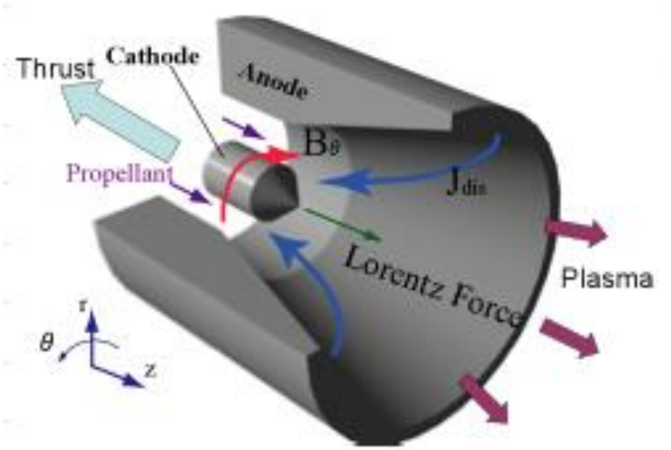
僅かな燃料 (Xe, Ar等)をプラズマ化し，イオンを電気的な力で加速することで，超高速で噴射

特徴：小さい推進力 (μN – 1 N).
燃料使用量が少ない.

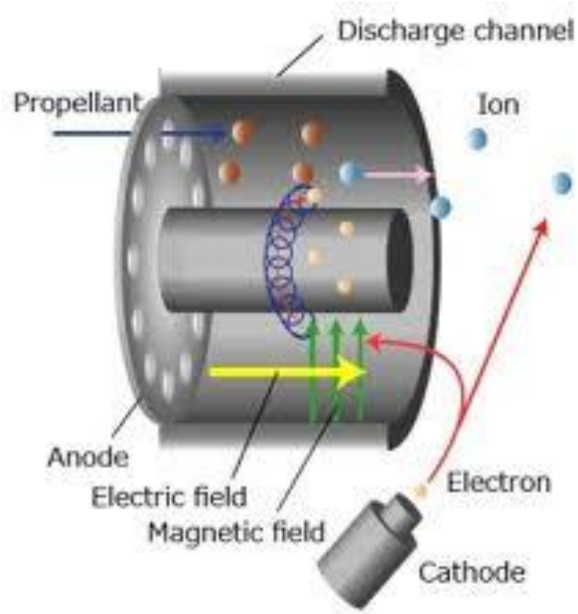
Conventional electric propulsion

Electromagnetic acceleration

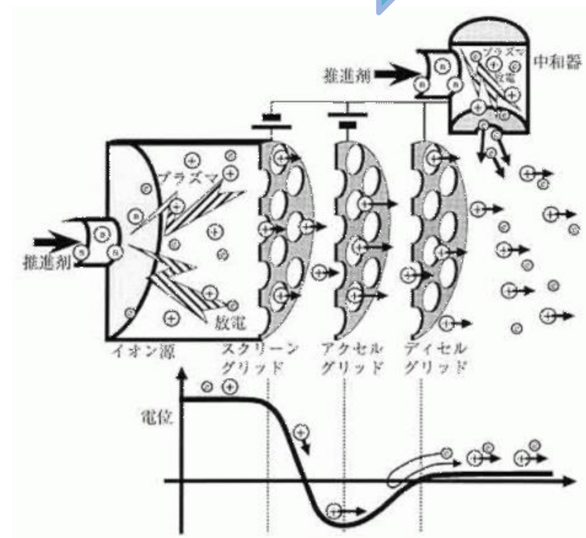
Electrostatic acceleration



MPD arcjet thruster



Hall effect thruster



Ion gridded thruster

Magnetic nozzle

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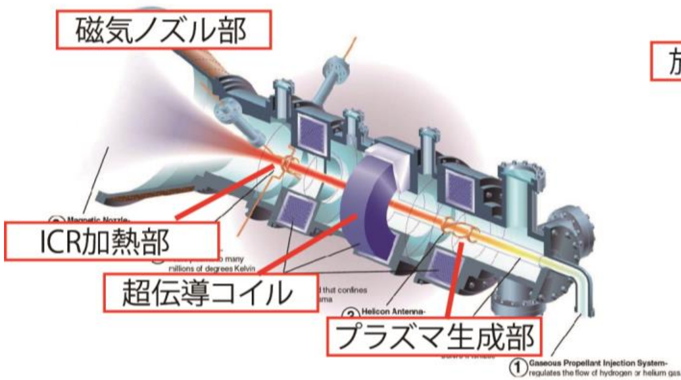
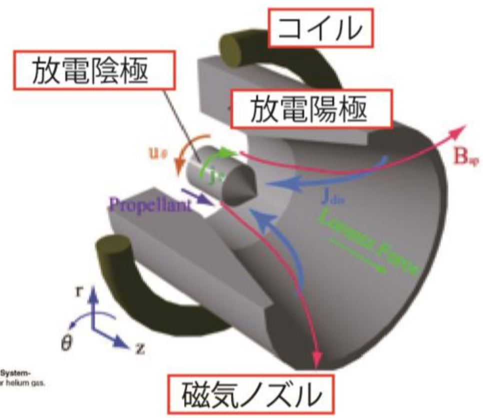
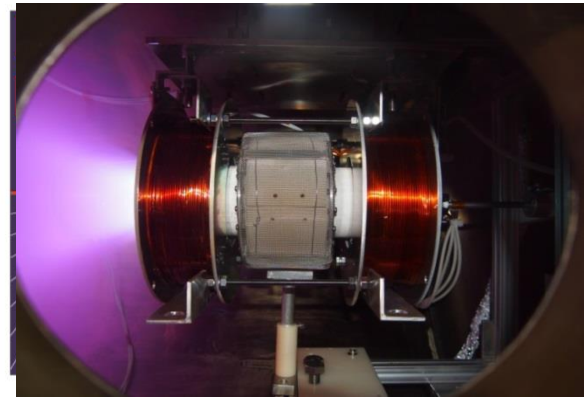
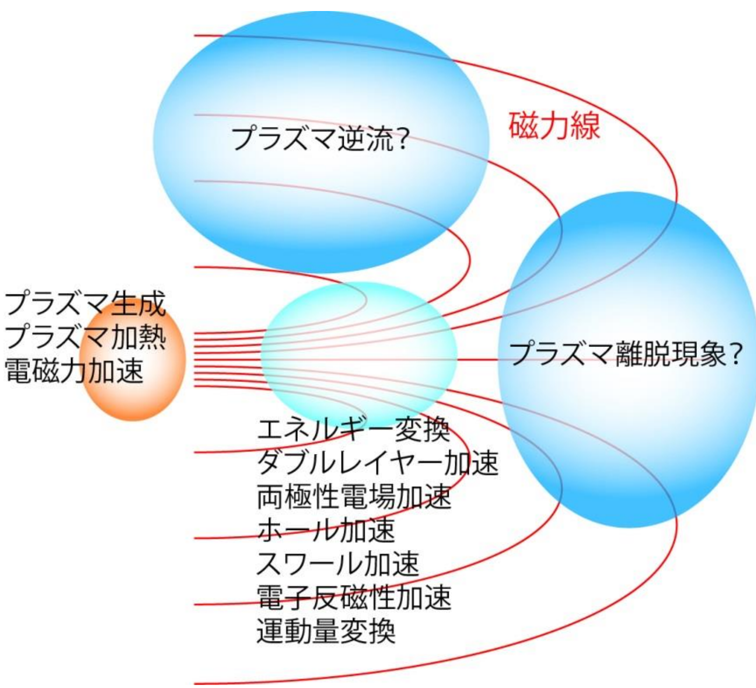


ＭＰＤスラスタ



ヘリコンスラスタ





The magnetic nozzle seems to arise various types of plasma acceleration and momentum conversion mechanisms.

This work is aimed to fully understand the magnetic nozzle physics in the wide range of the parameters and develop a high performance plasma thruster.

The biggest problem called PLASMA DETACHMENT still remains future issue (we might need a big big big tank or space test.)

Thruster facilities in Sendai

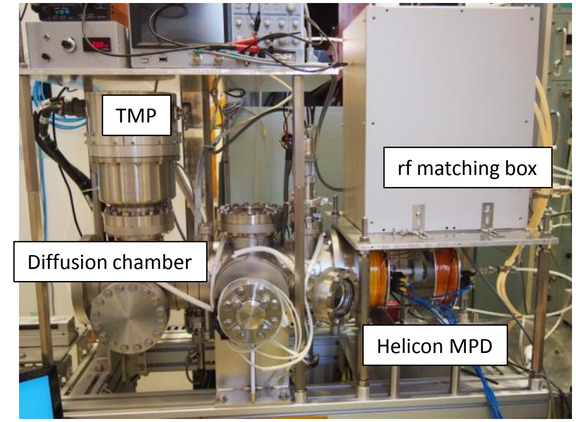
HPT-I

60-cm-diam and 140-cm-length tank
500 l/s pumping speed
Prf < 2 kW
Electrodeless helicon thruster
Individual measurement of thrust components

HITOP

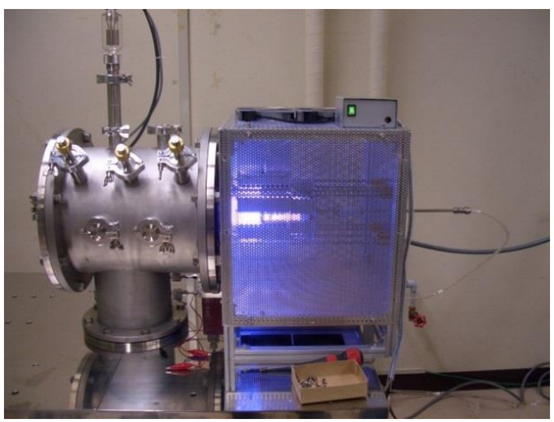
70-cm-diam and 400-cm-length tank
1500 l/s pumping speed
High power MPD power supply
Lab test of MPD thruster

HPT-XS

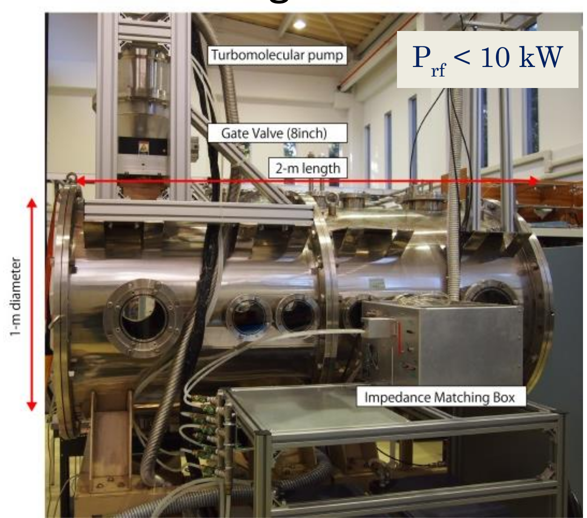


14-cm-diam and ~50-cm-length tank
300 l/s pumping speed
Prf < 2 kW
MPD power supply (~ 100 J)
Lab test of helicon MPD thruster

PMPI (In Iwate)

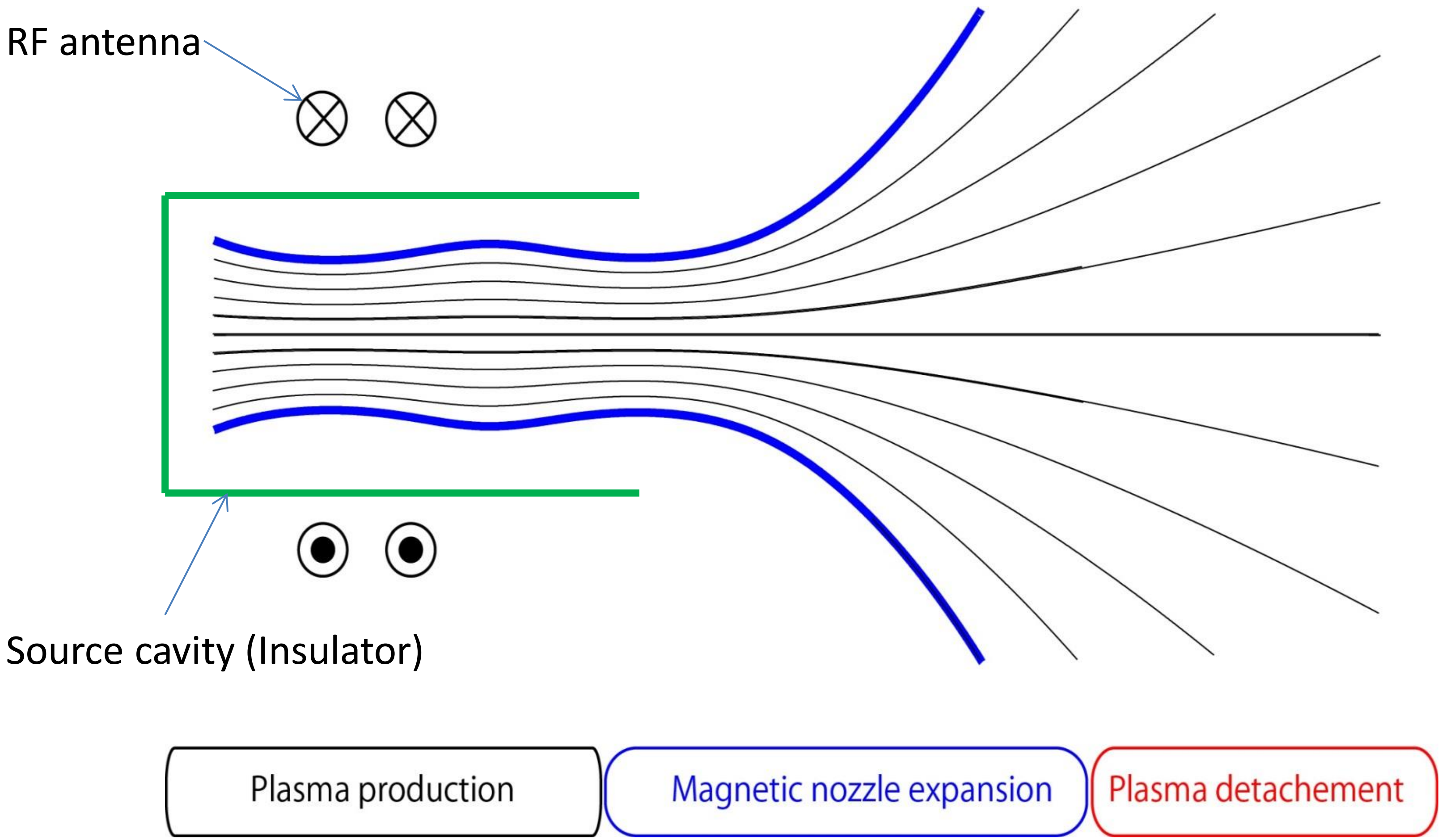


Mega-HPT

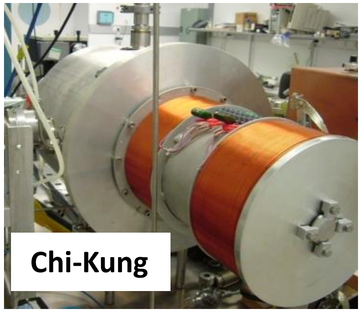


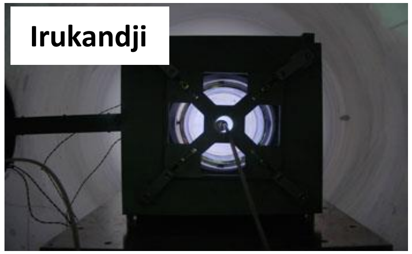
100-cm-diam and 200-cm-length tank
5000 l/s pumping speed.
Prf < 10 kW
Thruster test facility
Pendulum thrust balance (working well).
Target type force balance (working well now).
Langmuir probes if needed.
Pulsed solenoid power supply if needed.
MPD power supply (same as HPT-XS) if needed.

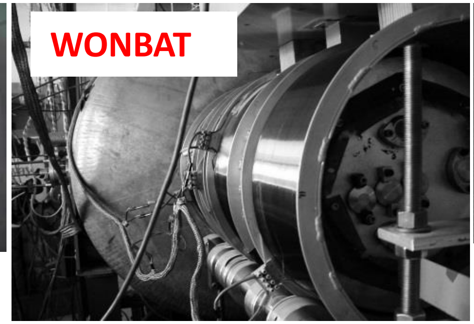
Helicon plasma thruster

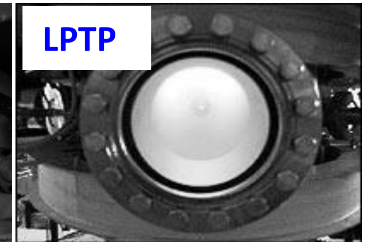


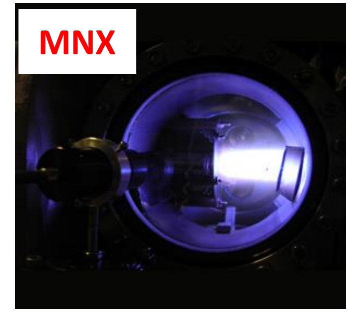
Basic laboratory experiments on helicon double layer and ambipolar fields

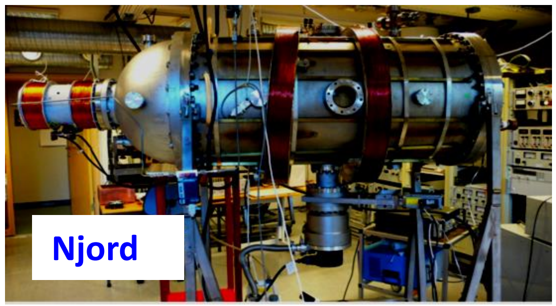


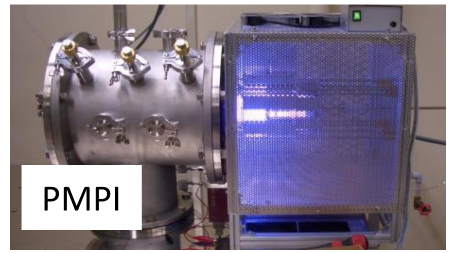


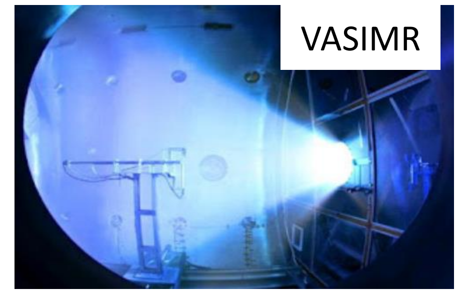




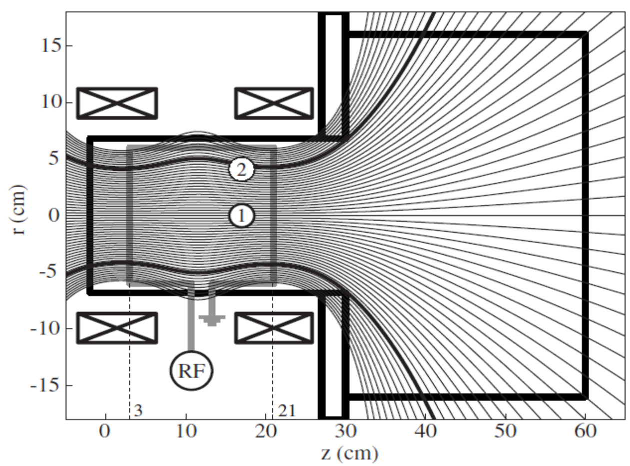


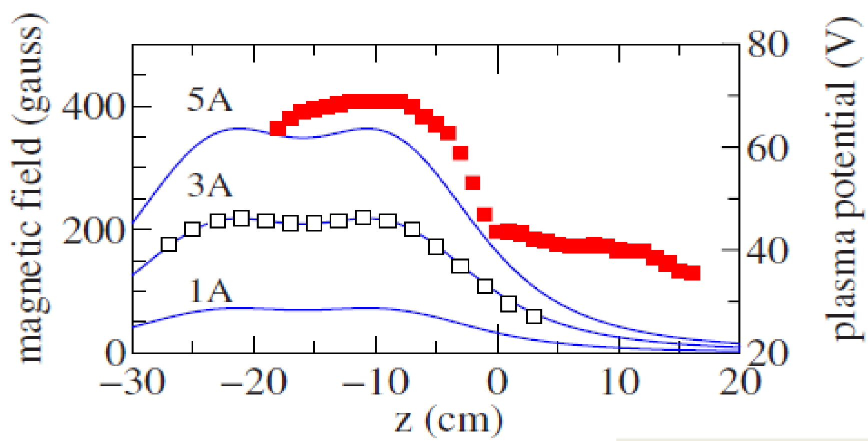






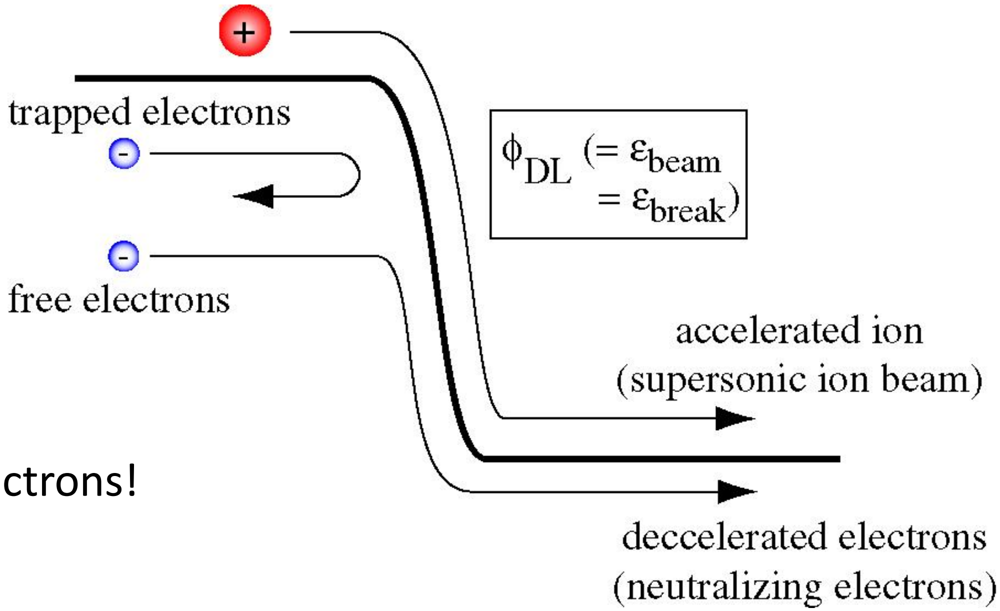
Current-free double layer / Ambipolar electric field



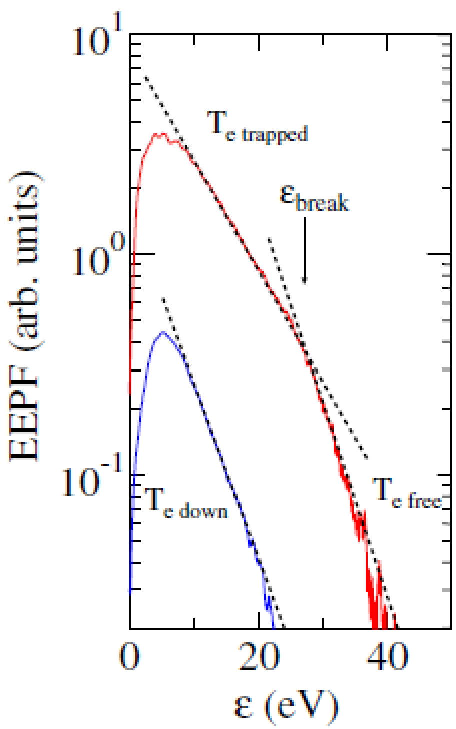


Charles and Boswell, APL2003
Takahashi et al, APL 2010

Particle Dynamics in spontaneous electric fields on axis

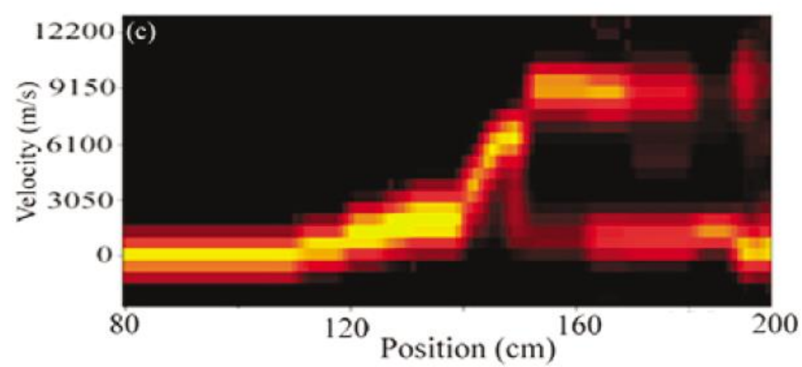


No counter-streaming electrons!

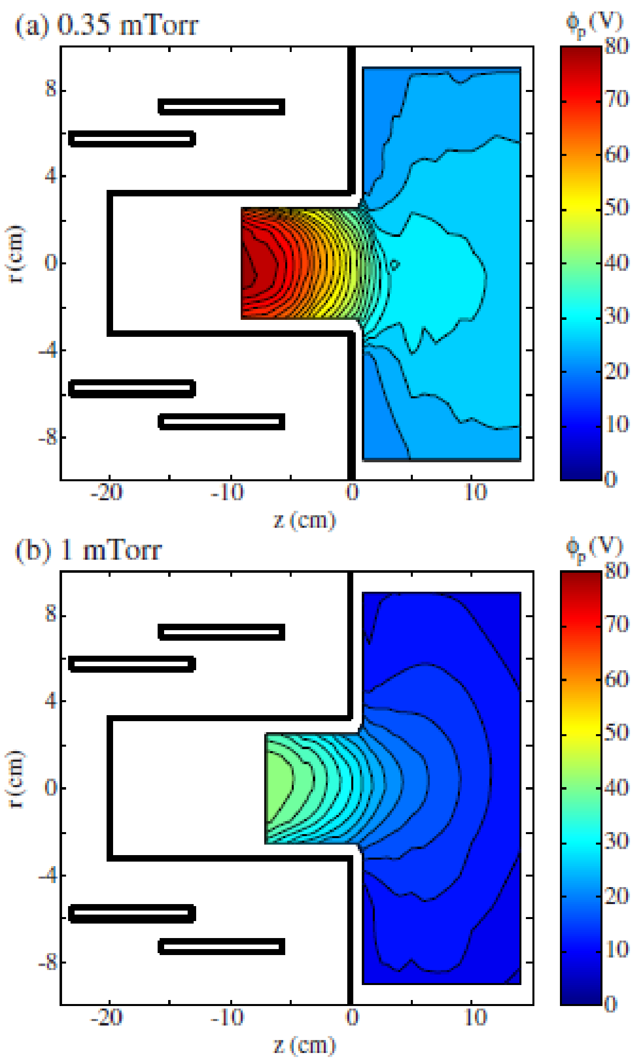


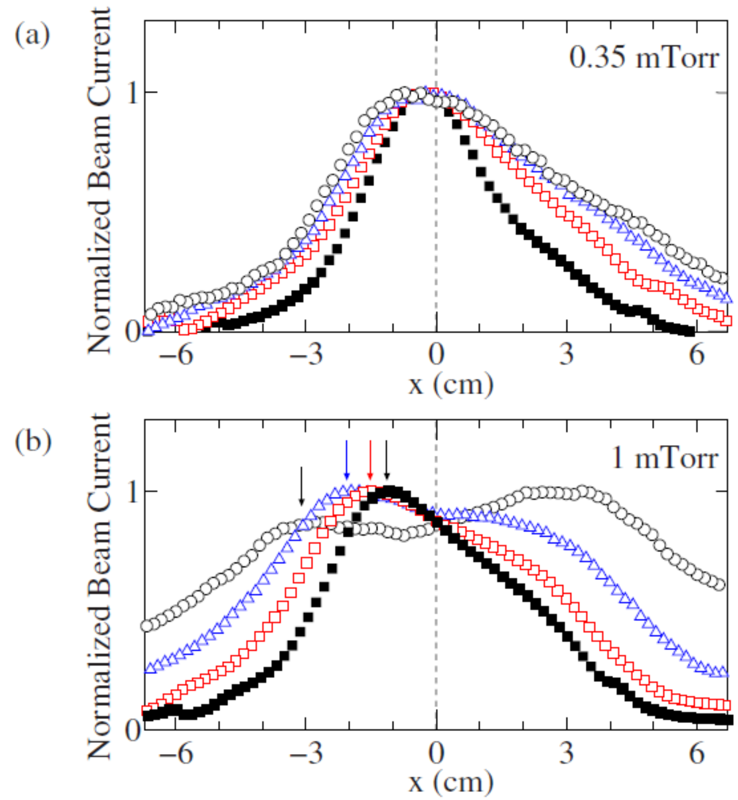
Takahashi et al, POP2007
Takahashi et al, JPD2010

Charles and Boswell, APL2003
Sun et al., PRL2005



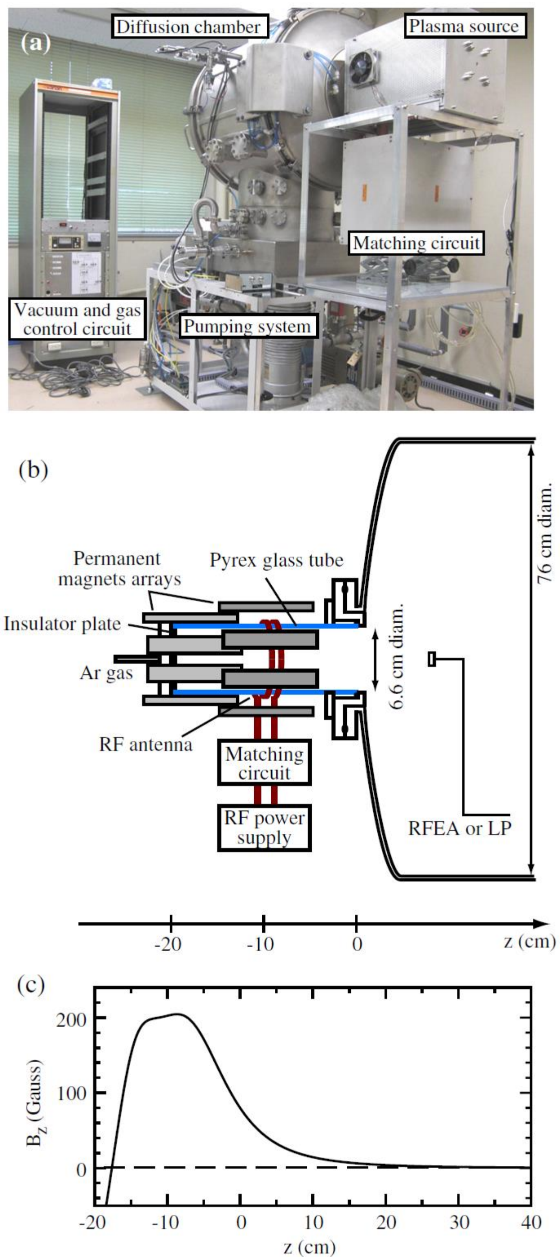
Ion beam profiles : *plane double layer generates the collimated ion beam*

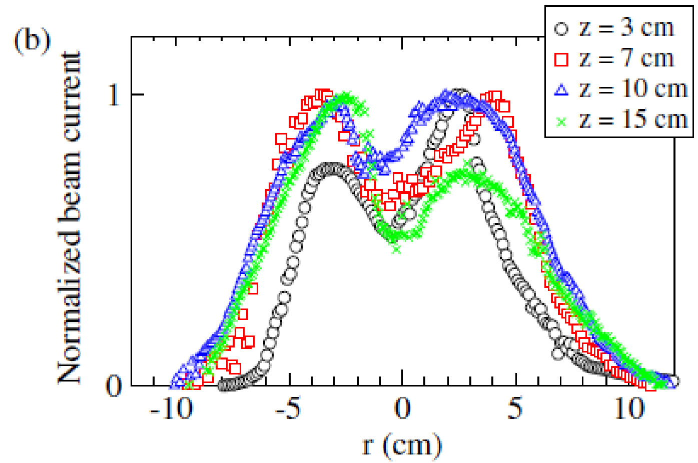


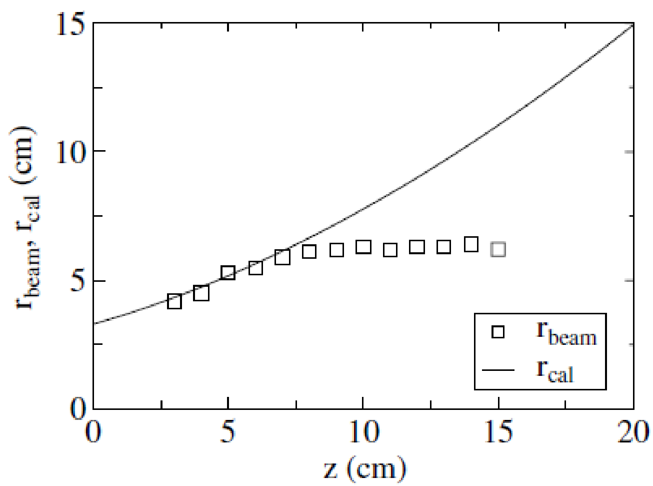


Takahashi and Fujiwara, APL2009
Takahashi, Igarashi, and Fujiwara, APL2010

Ion beam is detached from the magnetic nozzle







Takahashi et al. JPD2011

Modeling of eepfs, being responsible for the ion acceleration energy

PRL **107**, 035002 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

Electron Energy Distribution of a Current-Free Double Layer: Druyvesteyn Theory and Experiments

Kazunori Takahashi,[1,2,*] Christine Charles,[1] Rod W. Boswell,[1] and Tamiya Fujiwara[2]
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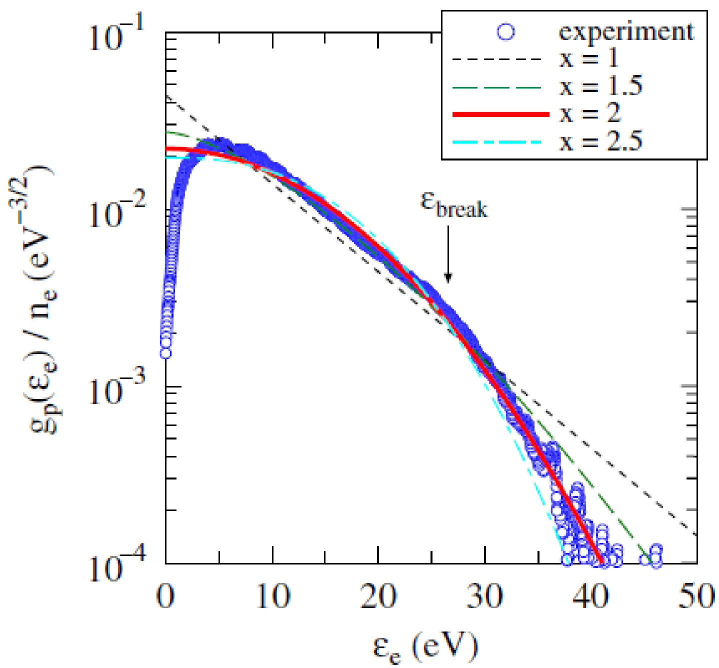
(Received 7 April 2011; published 11 July 2011)



$$g_p(\varepsilon_e) = g_x \frac{n_e}{T_{\mathrm{eff}}^{3/2}} \exp\left[-C_x\left(\frac{\varepsilon_e}{T_{\mathrm{eff}}}\right)^x\right],$$

$$g_e(\varepsilon_e) = \varepsilon_e^{1/2} g_p(\varepsilon_e),$$

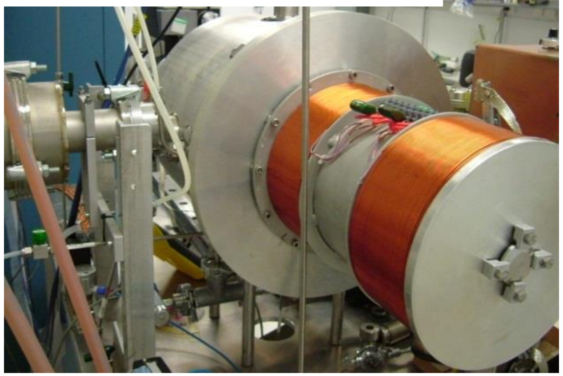
$$K_{iz} n_g \pi R^2 l = u_B(2\pi R^2 h_l + 2\pi R l h_R),$$

Ionization Particle loss to the wall

Takahashi, Charles, Boswell, and Fujiwara, Phys Rev Lett 2011

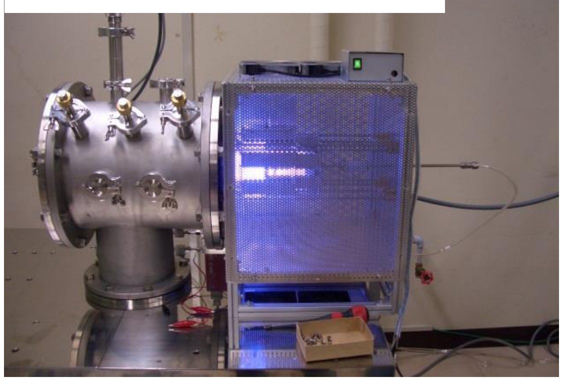
Theoretical and experimental effective electron temperature

I.D. = 13.7 cm, L = 25 cm

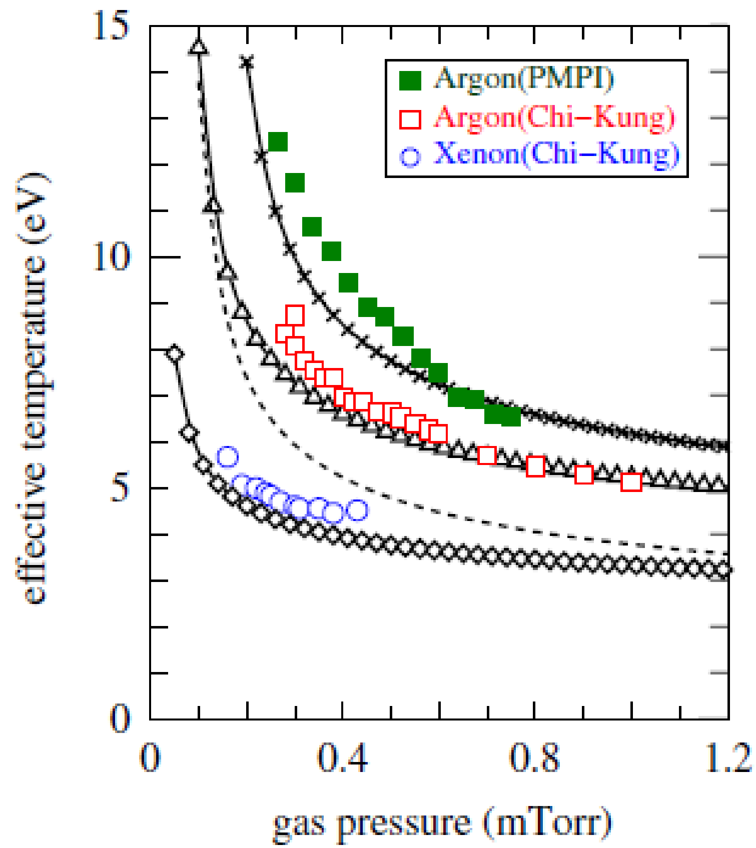


Chi-Kung @ ANU

I.D. = 6.6 cm, L = 17 cm



PMPI @ Iwate



Takahashi, Charles, Boswell, and Fujiwara, Phys Rev Lett 2011

1st direct measurement of the thrust imparted by the PM-HDLT

APPLIED PHYSICS LETTERS **98**, 141503 (2011)

Direct thrust measurement of a permanent magnet helicon double layer thruster

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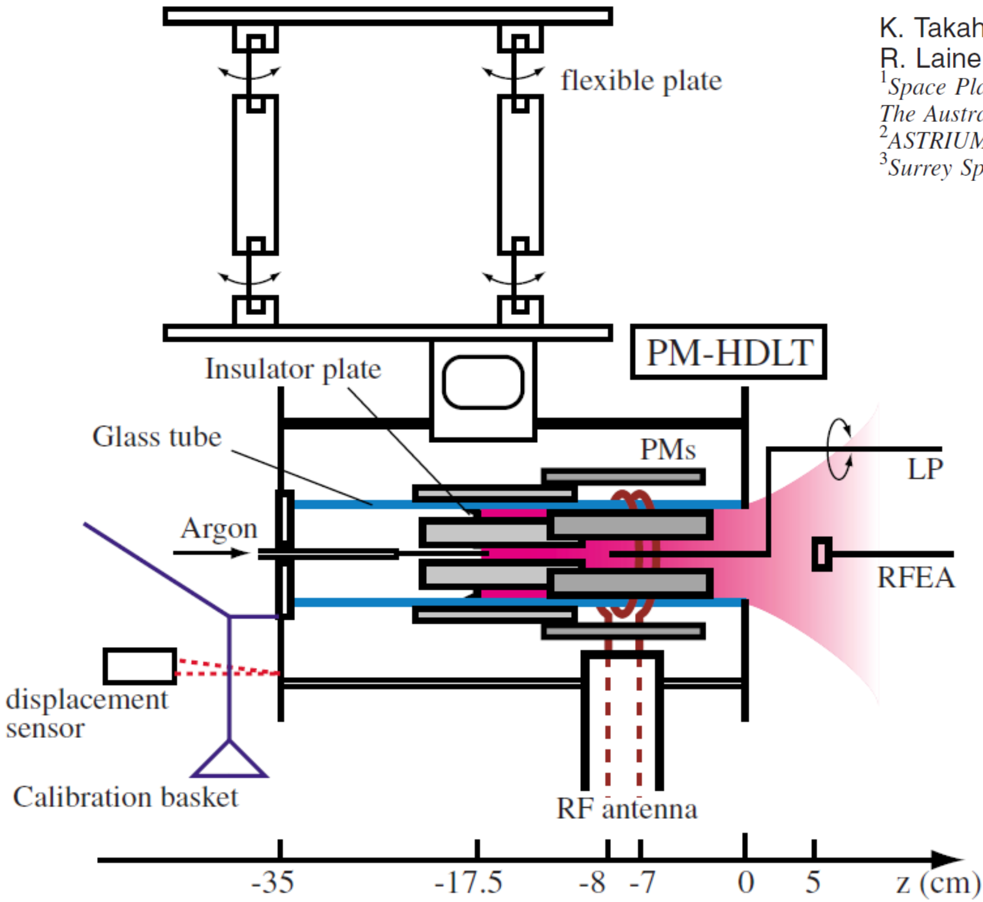


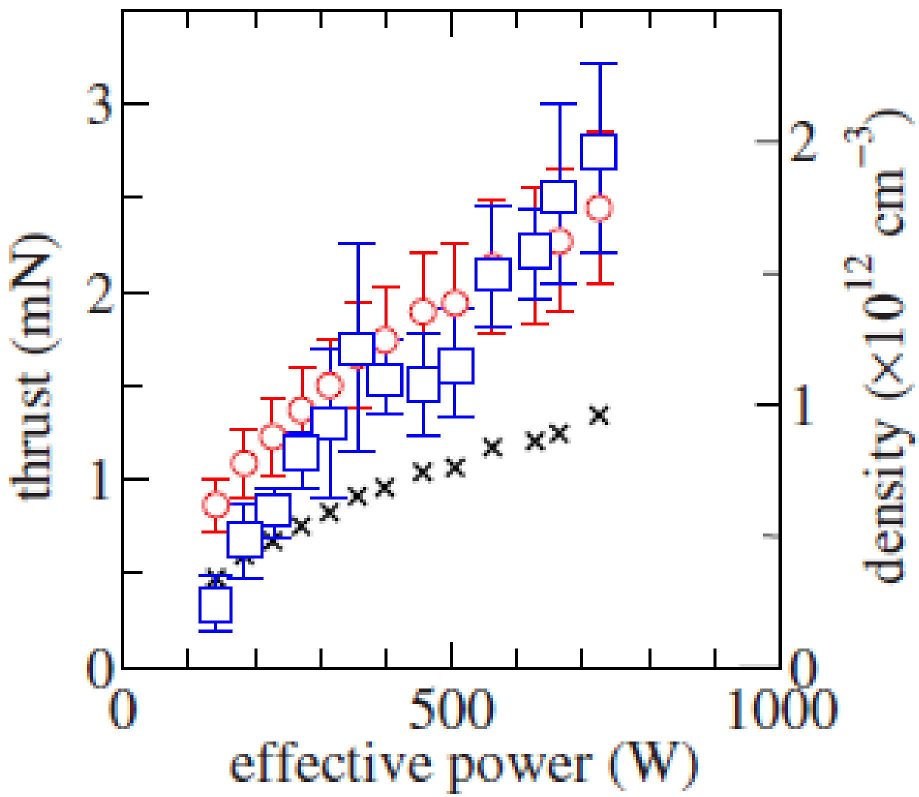
Pendulum thrust balance
(developed in Surry)

Laser displacement sensor
(Commercial product)

Permanent magnets-Helicon double layer thruster
(developed in Iwate and tested in Canberra)

Takahashi et al, Appl. Phys. Lett. 2011

1st results of the thrust measurement: Bloody poor performance!!!!



Disappointed Poor performance
2.7 mN @ 900 W rf generator output
350 sec specific impulse

Research Subject
Thrust generation mechanisms.
Source cavity.
Magnetic nozzle.
RF antenna.
Gas species.
Source efficient.
Etc…

Takahashi et al, APL 2011

‘Spontaneous’ electrostatic acceleration does not impart a momentum

Fruchtman, PRL2006

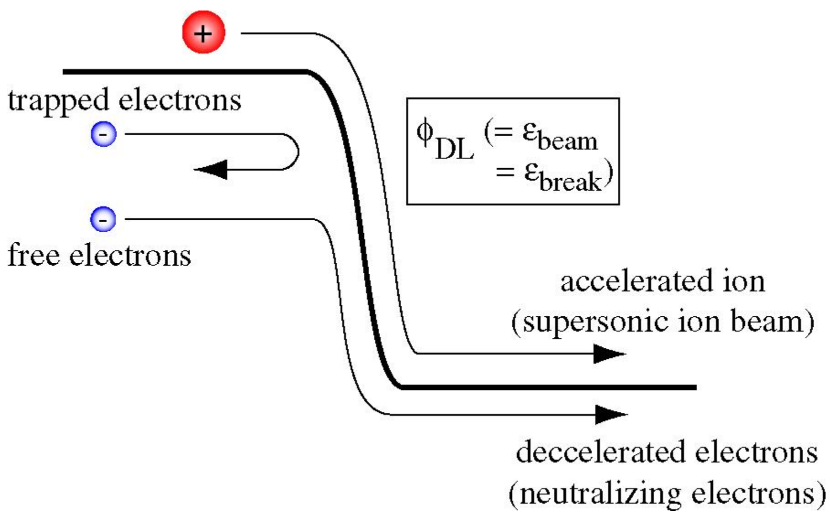
$$m_j \nabla \cdot (n_j \mathbf{v}_j \mathbf{v}_j) = q_j n_j (\mathbf{E} + \cancel{\mathbf{v}_j \times \mathbf{B}}) - \nabla \cdot \mathbf{P}_j$$

Electron: $-eE_z = \frac{d}{dz}(p_e)$

Ion: $eE_z = \frac{d}{dz}(mnu_z^2)$

$$\Rightarrow \quad \frac{d}{dz}(p_e + mnu_z^2) = 0$$

Thrust corresponds to the plasma momentum, which can be given by $(p_e + mnu_z^2)*A$



The plasma momentum is conserved along the axis.
When the free electrons overcome the potential drop, they give their energy/momentum to the potential drop.
The potential drop can give their potential energy to the ions.

Hence, the role of the double layer is the momentum conversion from the electron pressure to the ion dynamic momentum.

Thrust arising from the magnetic nozzle

electron:

$$-en(E_r + v_\theta B_z - v_z B_\theta) = \frac{\partial p_e}{\partial r}, \tag{12}$$

$$-en(E_z - v_\theta B_r) = \frac{\partial p_e}{\partial r}, \tag{13}$$

ion:

$$\cancel{\frac{1}{r}\frac{\partial}{\partial r}(rmnu_r^2) + \frac{\partial}{\partial z}(mnu_z u_r) - \frac{mnu_\theta^2}{r}} = en(E_r + u_\theta B_z), \tag{14}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rmnu_r u_z) + \frac{\partial}{\partial z}(mnu_z^2) = en(E_z - u_\theta B_r), \tag{15}$$

$$\frac{\partial}{\partial z}(p_e + mnu_z^2) = \underbrace{en(-u_\theta B_r + v_\theta B_r)}_{\text{Lorentz force } (j_\theta \times B_r)} - \underbrace{\frac{1}{r}\frac{\partial}{\partial r}(rmnu_r u_z)}_{\text{Axial momentum lost to the radial direction from the fluid cell}}.$$

The local plasma momentum can be given by

$$T(z) = \iint (p_e + mnu_z^2)\,d\theta\,dr$$

Thrust expression

Total momentum (Thrust)

Takahashi et al, PRL2011 (HPT), POP2012

$$T_{total}(z) = \boxed{2\pi \int_0^{r_s} r p_e(r, z_0) dr \quad T_S}$$

* Initial total axial momentum having the source plasma
* Electron pressure onto the source tube (back wall)

$$\boxed{-2\pi \int_{z_0}^{z} \int_0^{r_p(z)} r \frac{B_r}{B_z} \frac{\partial p_e}{\partial r} dr dz \quad T_B}$$

* Momentum gain by the JxB force in the magnetic nozzle
* Lorentz force pushing the magnetic field lines

$$\boxed{-2\pi \int_{z_0}^{z} \int_0^{r_p(z)} \frac{\partial}{\partial r} (r m n u_r u_z) \, dr dz, \quad T_w}$$

Momentum loss escaping radially onto the source wall.
This term vanishes for no radial boundary

Assumption
Magnetized ions and electrons (no net ExB current)
Neglecting the radial ion inertia term

PRL 107, 235001 (2011) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2011

Electron Diamagnetic Effect on Axial Force in an Expanding Plasma: Experiments and Theory

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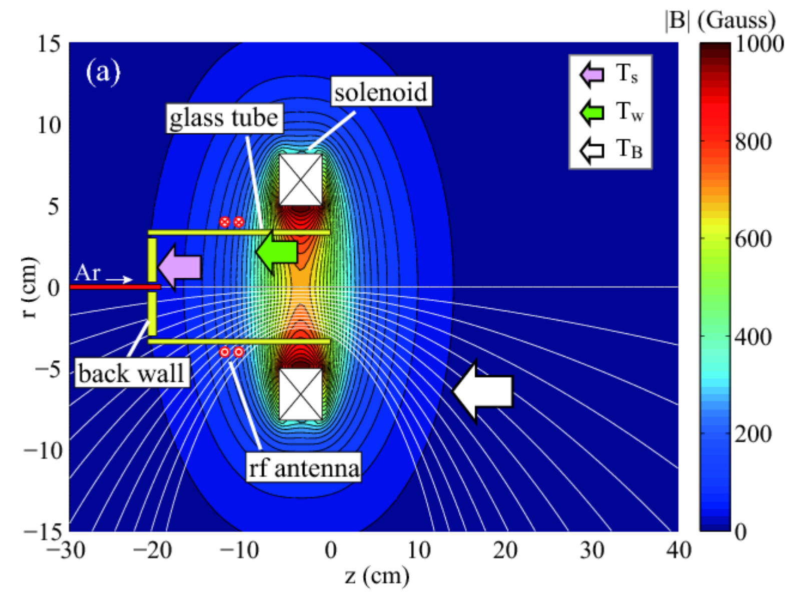

Cross-field diffusion effect on the magnetic nozzle term

PRL **110,** 195003 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Approaching the Theoretical Limit of Diamagnetic-Induced Momentum in a Rapidly Diverging Magnetic Nozzle

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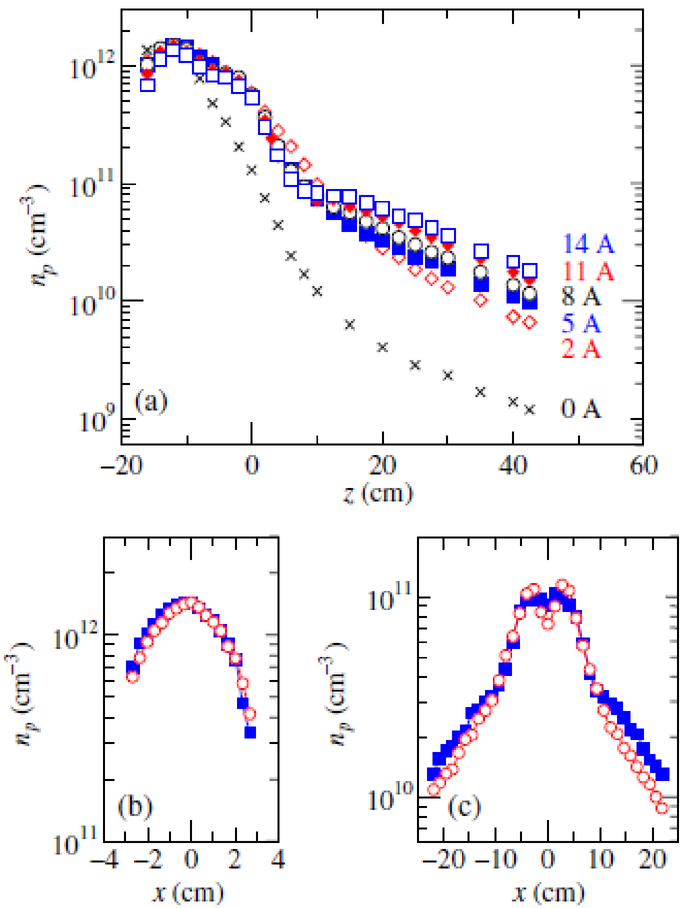

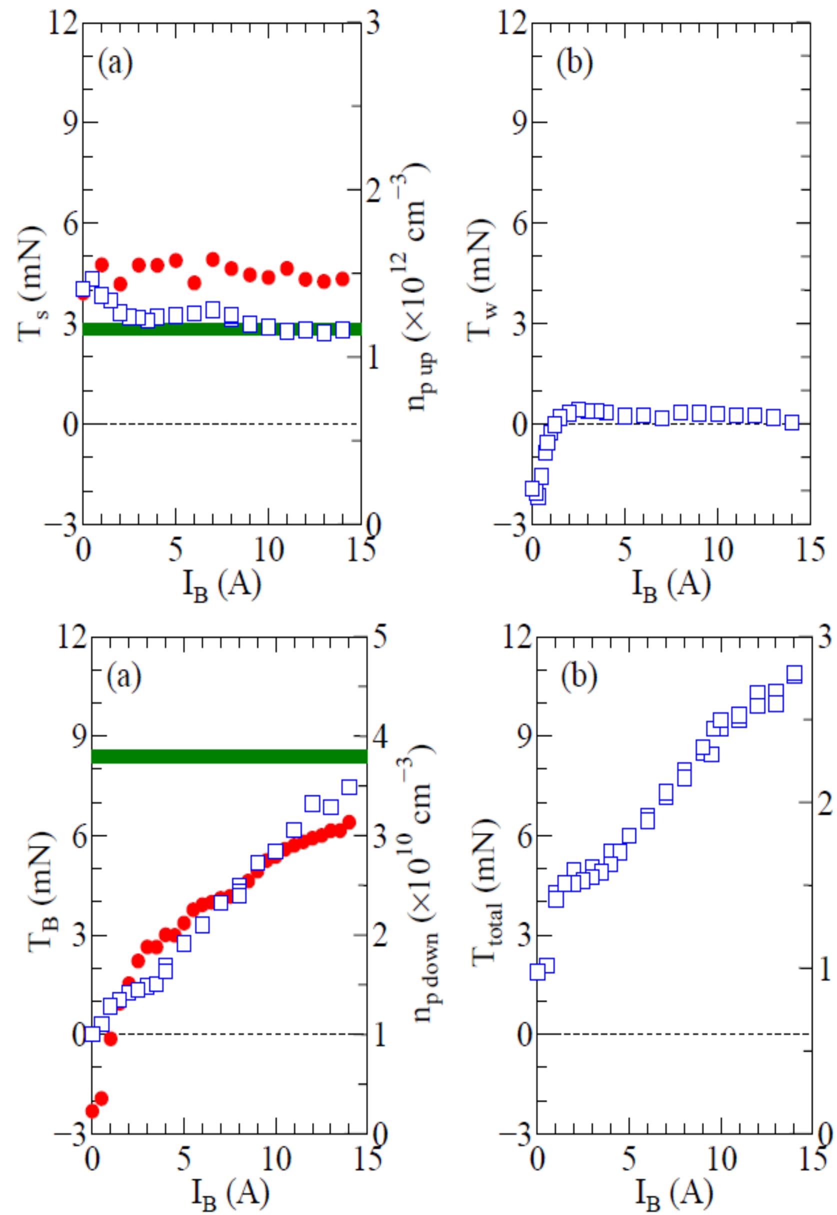

PHYSICS OF PLASMAS **19**, 033507 (2012)

A magnetic nozzle calculation of the force on a plasma

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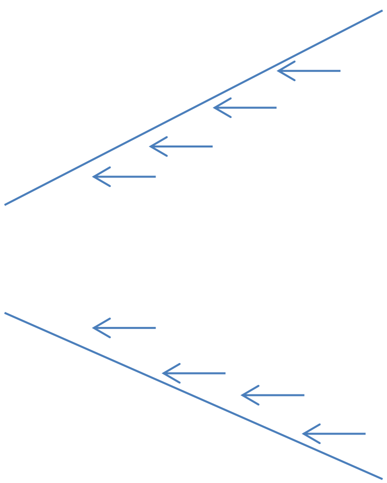
The magnetic nozzle is 'mathematically' equivalent to the physical nozzle.

The thrust arising from the magnetic nozzle is again given as

$$T_B = -2\pi \int_{z_0}^{z} \int_{0}^{r_p} r \frac{B_r}{B_z} \frac{\partial p_e}{\partial r} dr dz \tag{1}$$

When assuming the plasma flows in the magnetic flux tube Φ with radius $A(z)$ and the local field of B_z, i.e., $\Phi = B_z A(z) = const.$, and approximate the profile as $B_z(r,z) \simeq B_z(0,z)$, the T_B term can be written in one-dimensional model as



$$T_B \simeq -\int < p_e > A(z) \frac{1}{B_z} \frac{\partial B_z}{\partial z} dz, \tag{2}$$

$$= \int < p_e > dA \tag{3}$$

Equivalent to the physical nozzle thrust

The plasma velocity and density from the 1-D momentum equation

The equation drived from the plasma momentum equation,

$$\begin{aligned}\frac{\partial T_B}{\partial z} &= \frac{\partial}{\partial z}\int_0^{r_p} 2\pi r(mnu_z^2 + p_e)dr \\ &\simeq -\int < p_e > A(z)\frac{1}{B_z}\frac{\partial B_z}{\partial z}dz, \\ &= \int < p_e > dA, \end{aligned} \tag{4}$$

and the flux conservation and uniform axial velocity given by

$$\begin{aligned}\frac{\partial}{\partial z}(< n > u_z A) &= 0, \\ u_z(r,z) &\simeq u_z(0,z)\end{aligned}$$

gives the relation between the Mach number and the magnetic field strength as

$$\frac{M^2 - M_i^2}{2} - \ln\left(\frac{M}{M_i}\right) = \ln\left(\frac{A}{A_i}\right) = \ln\left(\frac{B_{zi}}{B_z}\right) \tag{5}$$

This is equivalent to the isentropic flow model in fluid dynamics.

Hence, the role of the electromagnetic force in the magnetic nozzle is equivalent to the physical wall

Inhibition of cross field diffusion in small laboratory device

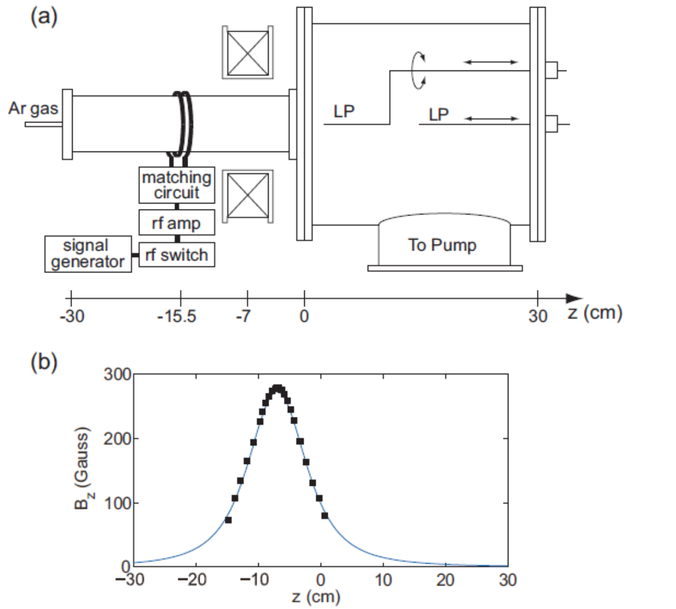


Figure 1. (a) Schematic diagram of the experimental setup. (b) Calculated axial profile of the magnetic field B_z on axis for 5 A solenoid current (solid line), together with the measured one (filled squares) for 5 A dc solenoid current.

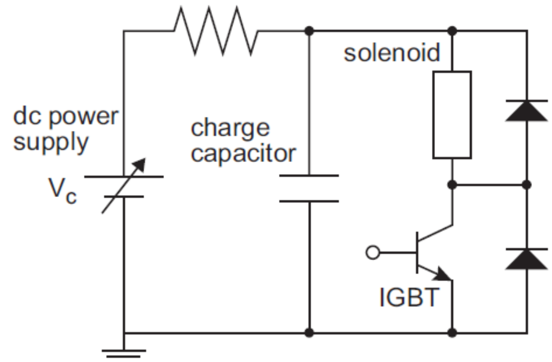
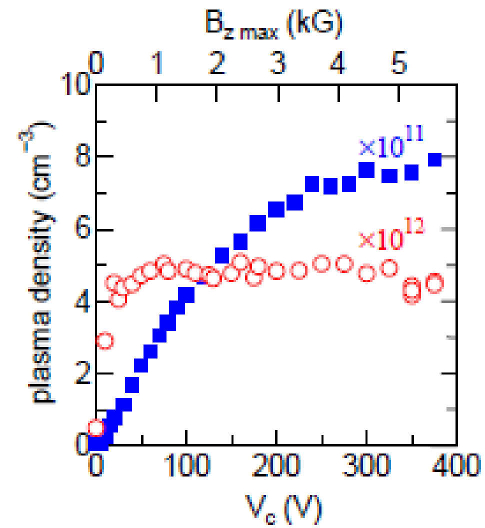
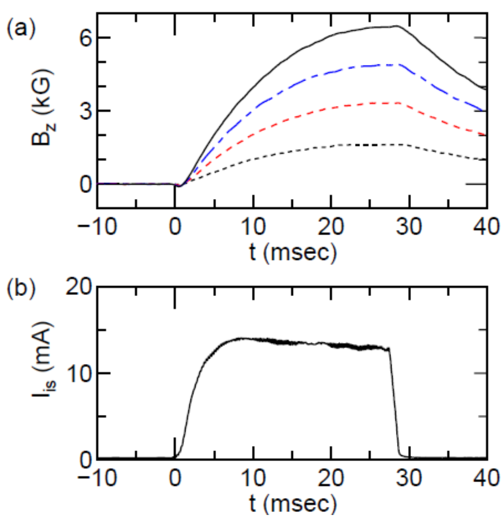


Figure 2. Schematic diagram of the switching circuit of the solenoid current.





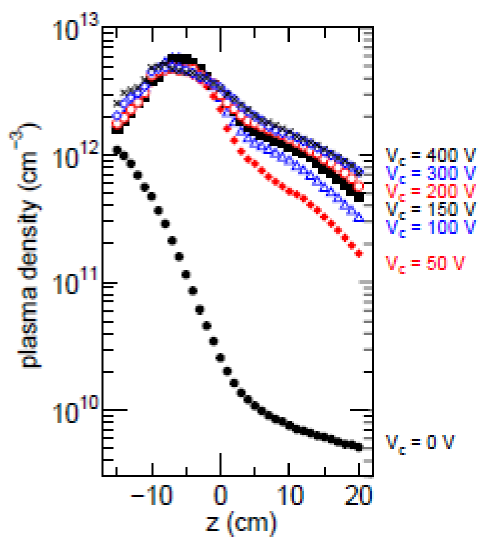


Figure 4. Axial profiles of the plasma density for $V_c = 0$ V (filled circles), 50 V (filled diamonds), 100 V (open triangles), 150 V (filled squares), 200 V (open circles), 300 V (open diamonds), and 400 V (crosses).

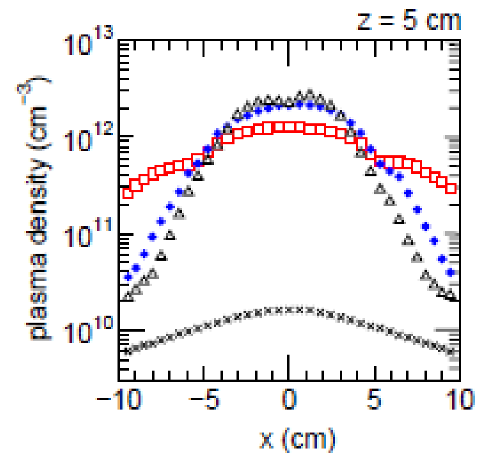


Figure 7. Radial profiles of the plasma density at $z = 5$ cm for $V_c = 0$ V (crosses), 100 V (open squares), 250 V (filled diamonds), and 400 V (open triangles).

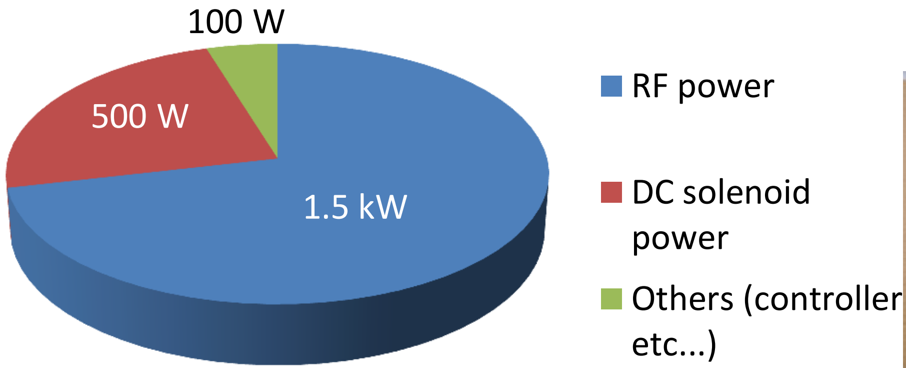
Takahashi, Sato, Takaki, Ando, PSST 2013

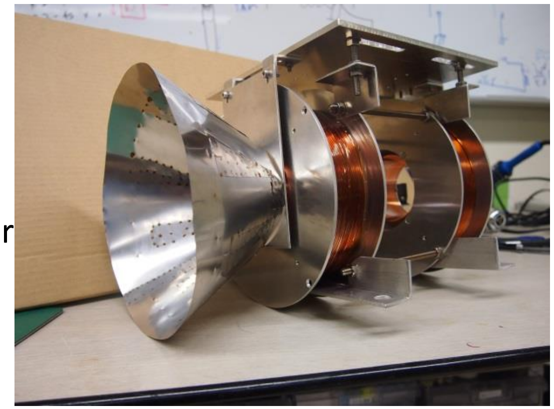
How big are the solenoid coils for magnetic nozzle and helicon discharge?

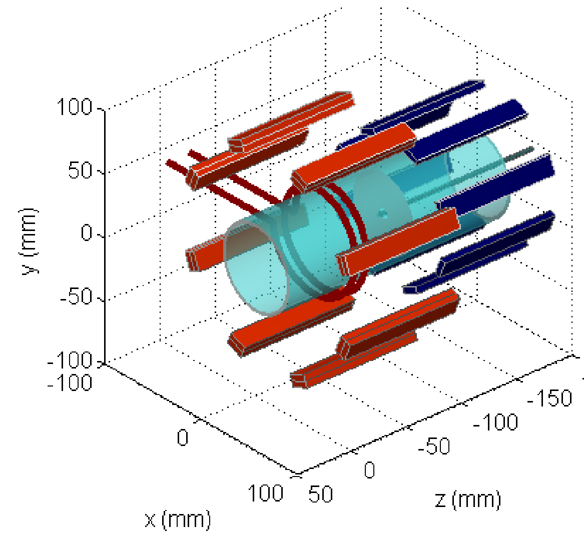
Typical laboratory model of 1 kW helicon thruster

~20-30% electricity and ~40 % weight are for the magnetic nozzle solenoids

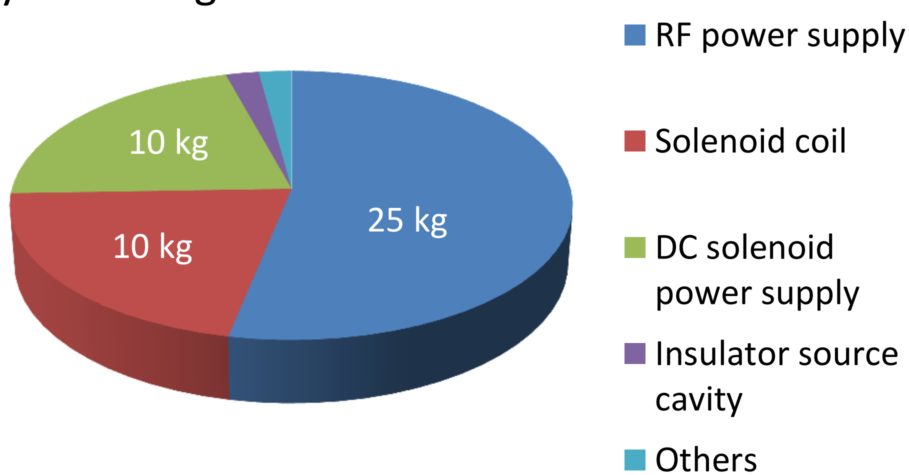
Consumed electric power

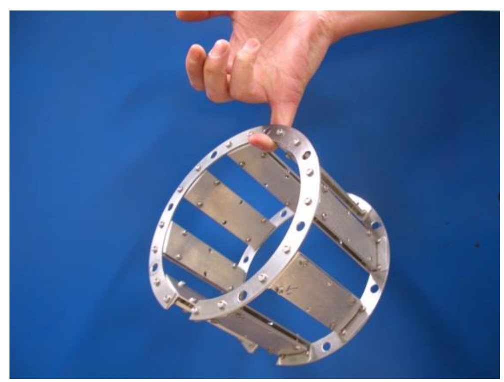






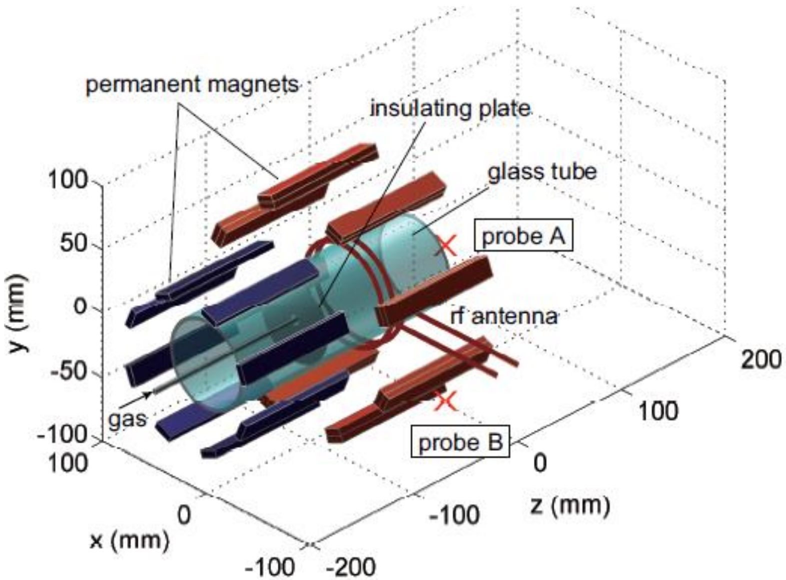
System weight

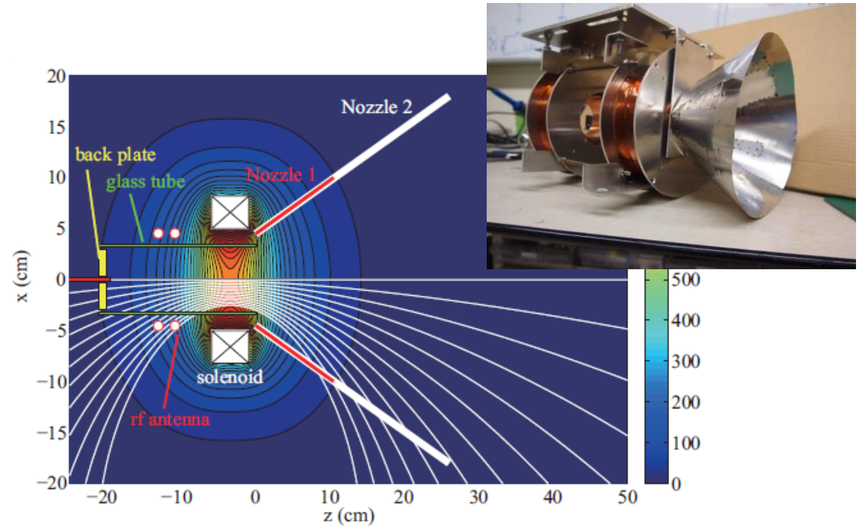


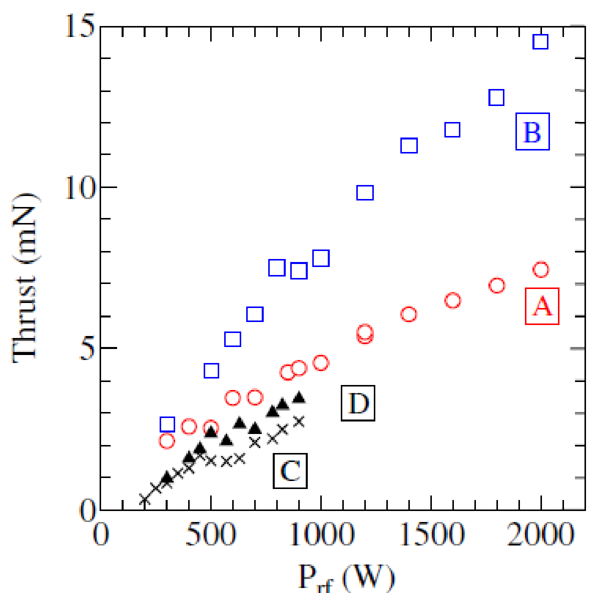


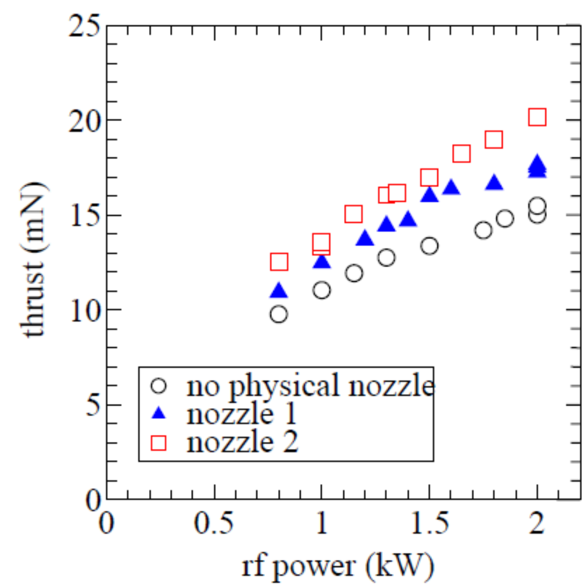
Light and no electricity

Performance of the helicon plasma thruster operated at Prf < 2 kW





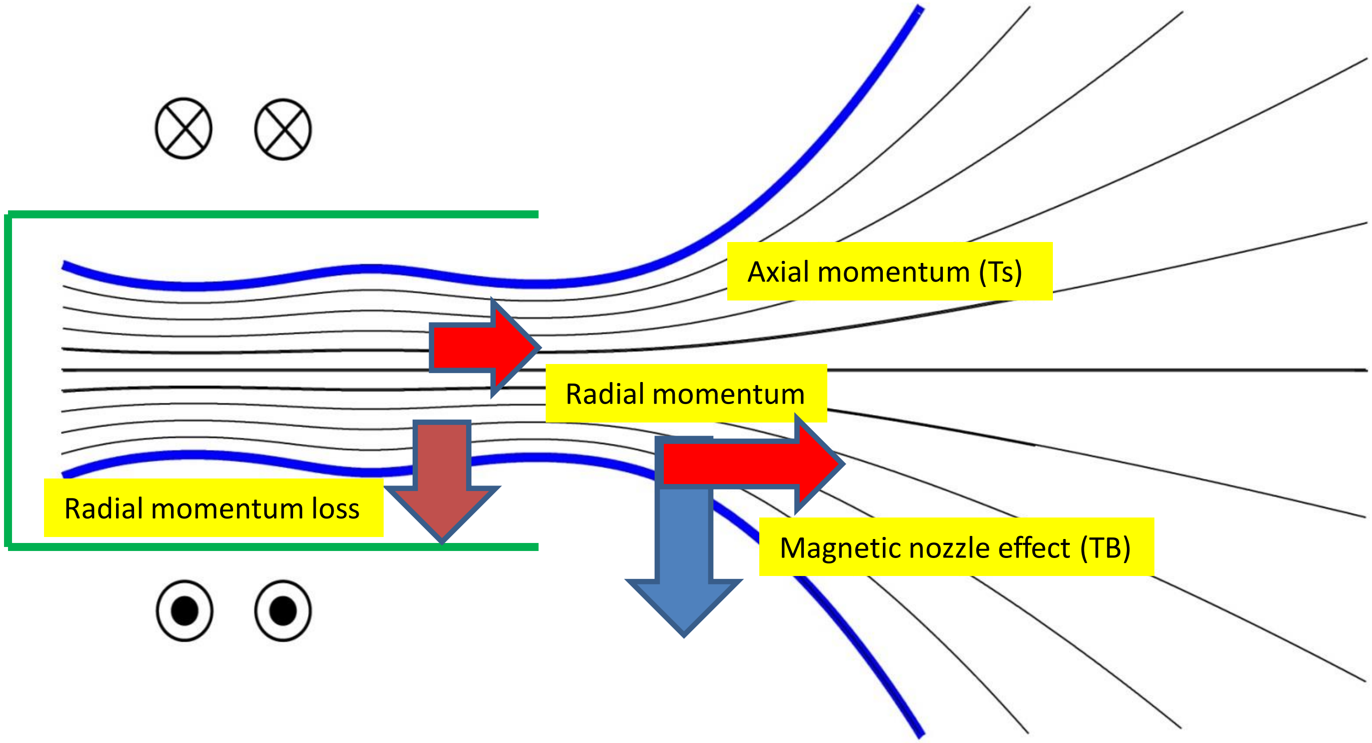




Takahashi et al., JPD 2013

Takahashi et al., PSST 2014

How can we improve the helicon thruster performance?

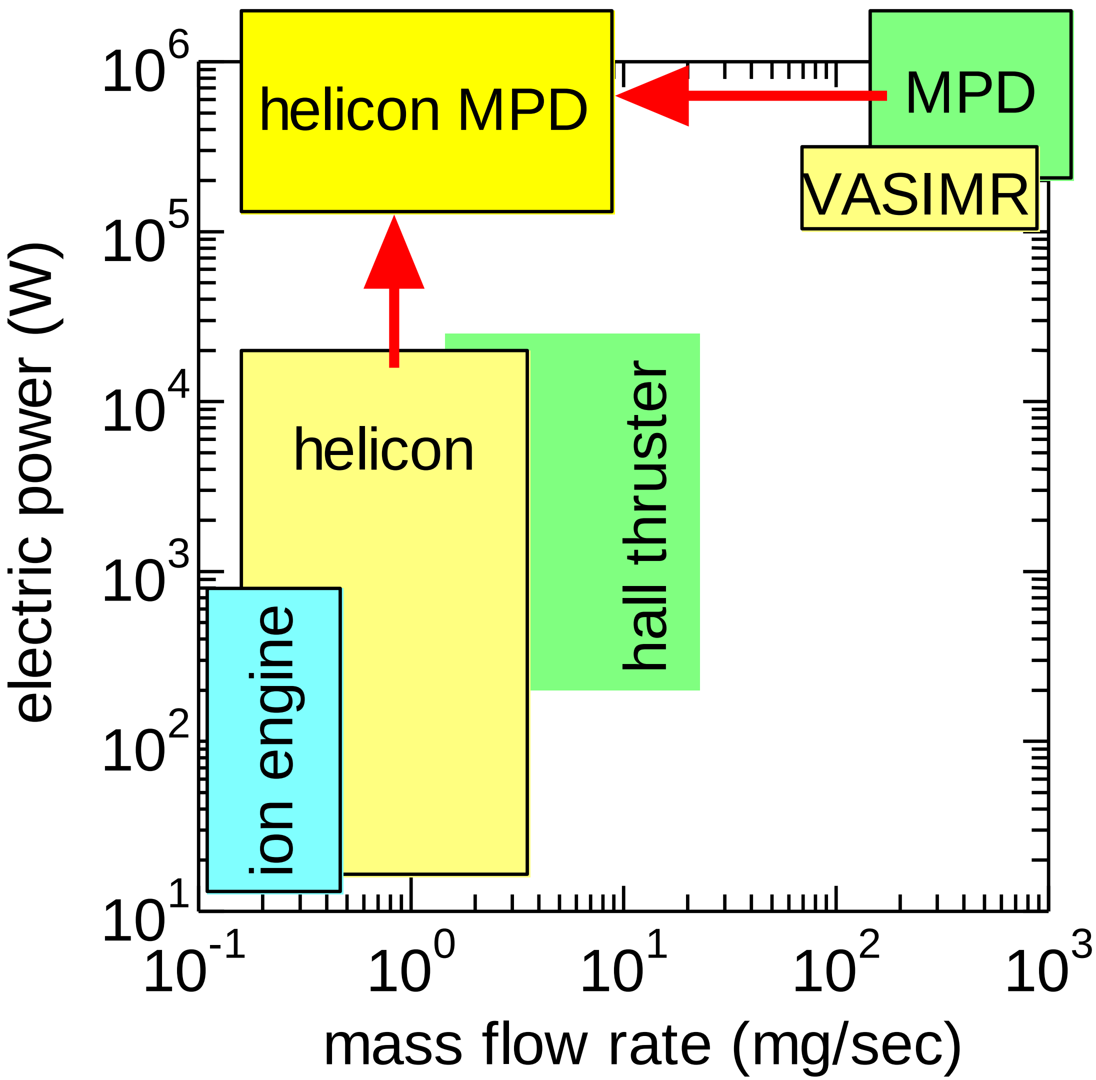


Inhibition of the plasma loss onto the radial source boundary might be key technology.

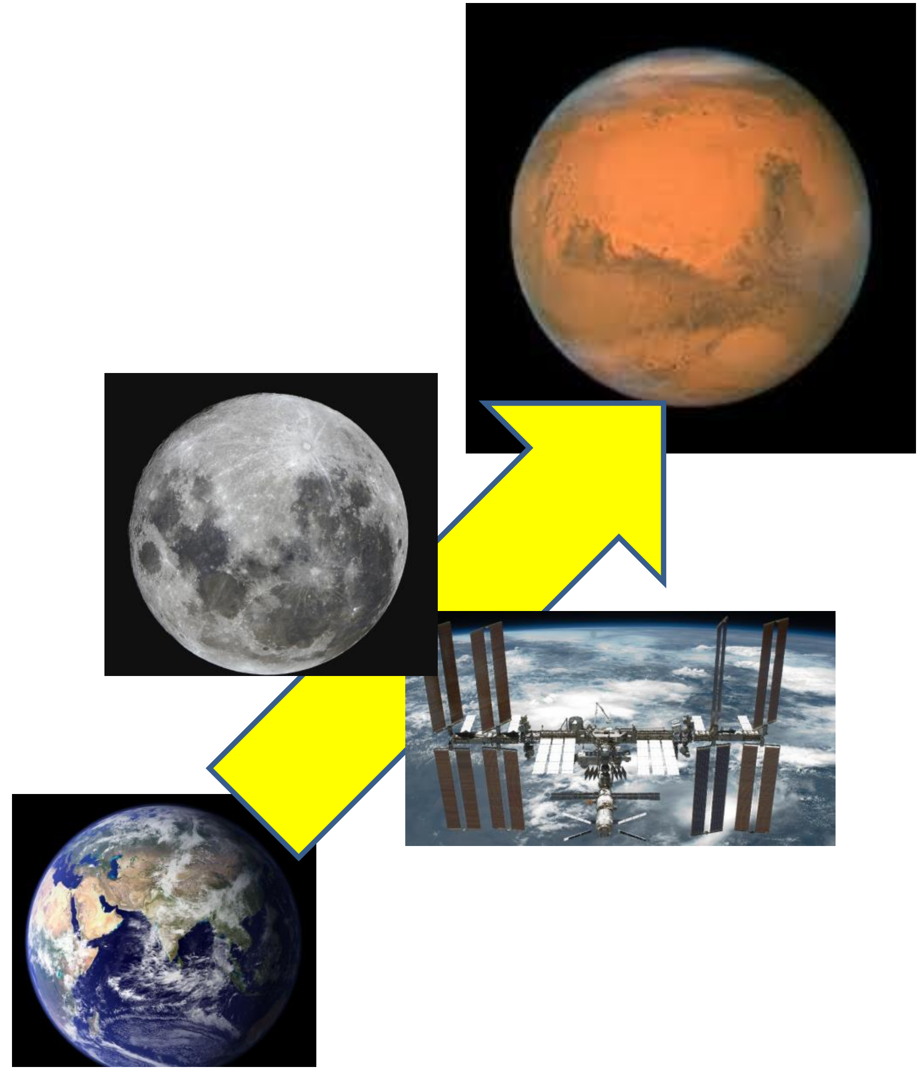
↓

Permanent magnet confinement,
Modification of the physical boundary,
Magnetic nozzle strength etc…

Target of operational range in power versus mass flow rate



High power and high specific impulse thruster for manned exploration to MARS and massive material transport in space



Helicon MPD thruster

AF-MPD thruster

Gas flow rate	~0.1-0.5 g/sec for argon
	<0.1 g/sec for helium
Discharge power	a few 100kW (1msec pulse)
Magnetic field	~ a few kGauss
Thrust	several Newtons

Power is divided into production and acceleration.
Electrode damage is serious issue.

Helicon thruster

Gas flow rate	< 0.003 g/sec for argon
Discharge power	several kW (CW)
Magnetic field	< a few kGauss
Thrust	several tens of mN

All of the power is coupled with plasma electrons. The electron pressure is converted into the ion dynamic momentum via a electrostatic and nozzle acceleration.

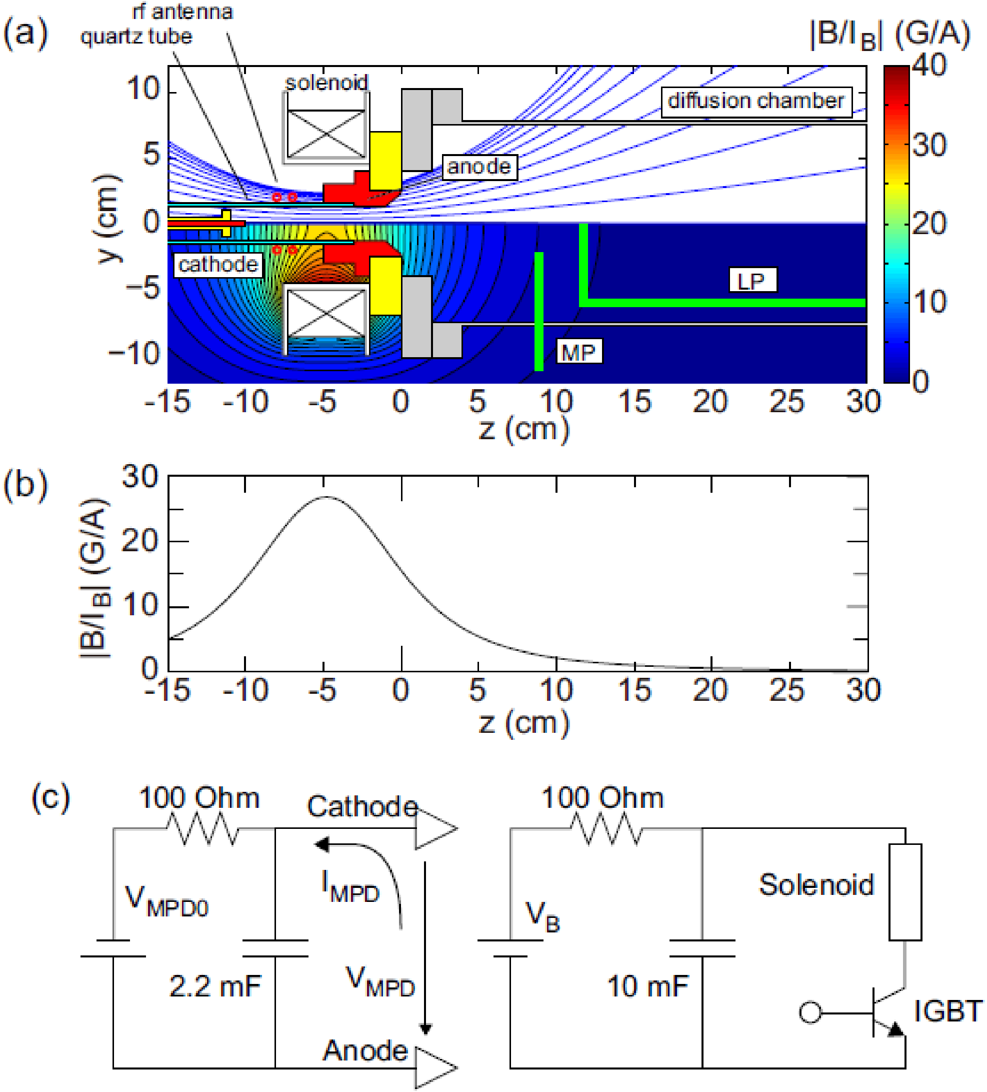
Helicon MagnetoPlasmaDynamic (MPD) thruster

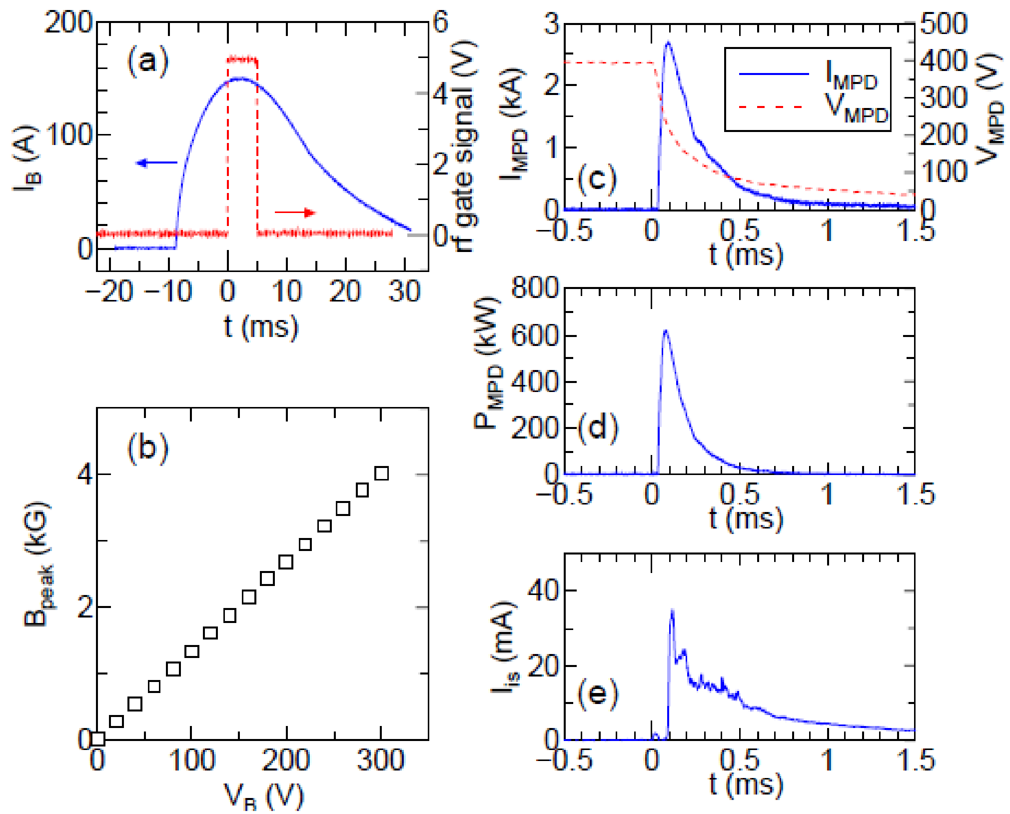
Gas flow rate	< 0.01 g/sec for argon
Discharge power	less than kW (rf) + a few 100kW (dc pulse)
Magnetic field	< a few kGauss
Thrust	not investigated yet

RF power is coupled with electrons to produce the plasma.
The MPD energy is divided into production and acceleration.
The source can be operated with very low gas flow rate because the helicon plasma can trigger the MPD discharge even for the low pressure less than a few mTorr.

Configuration of helicon MPD thruster

Takahashi et al., APL 2014





Operational parameter range

Takahashi et al., APL 2014

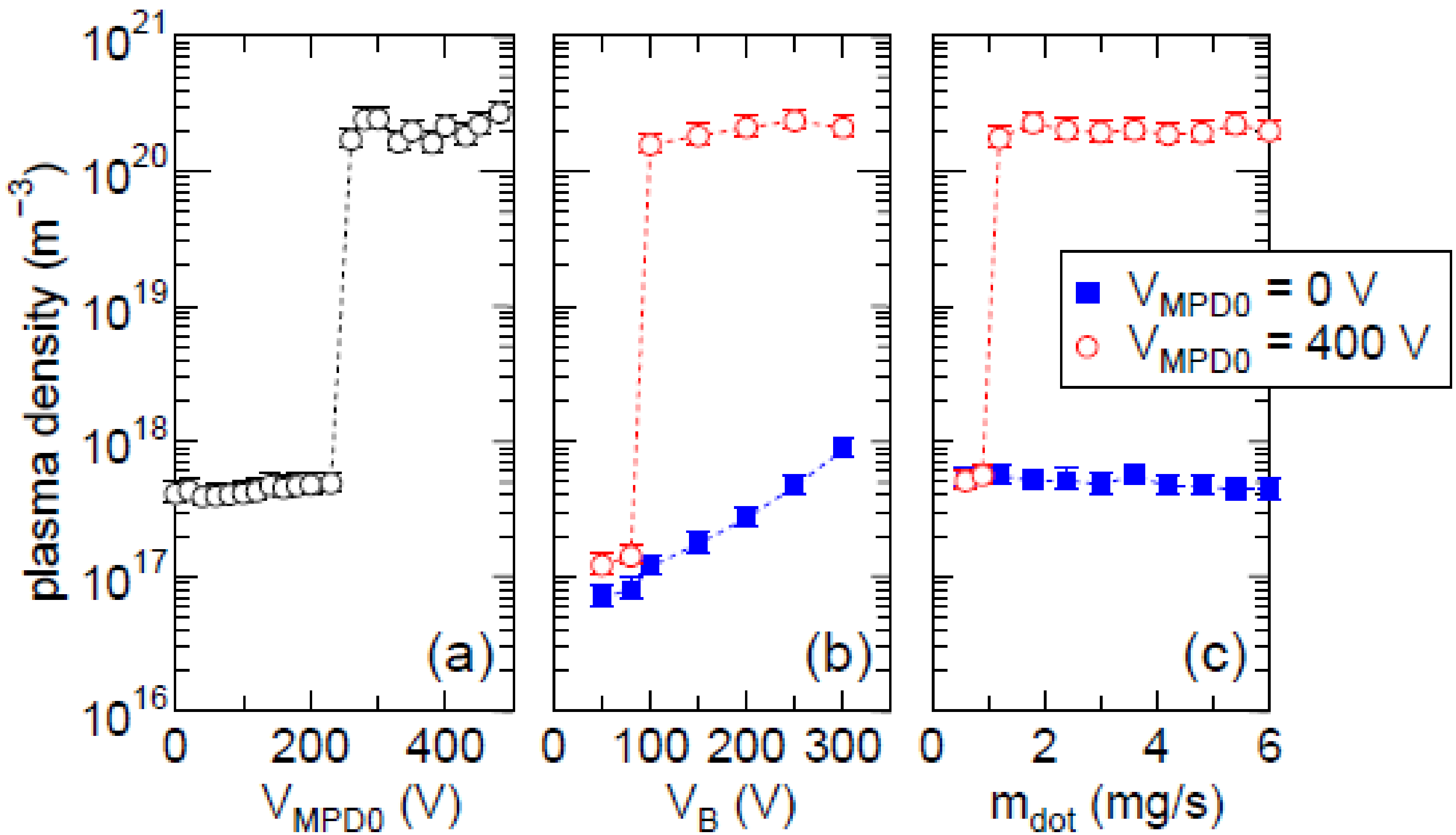
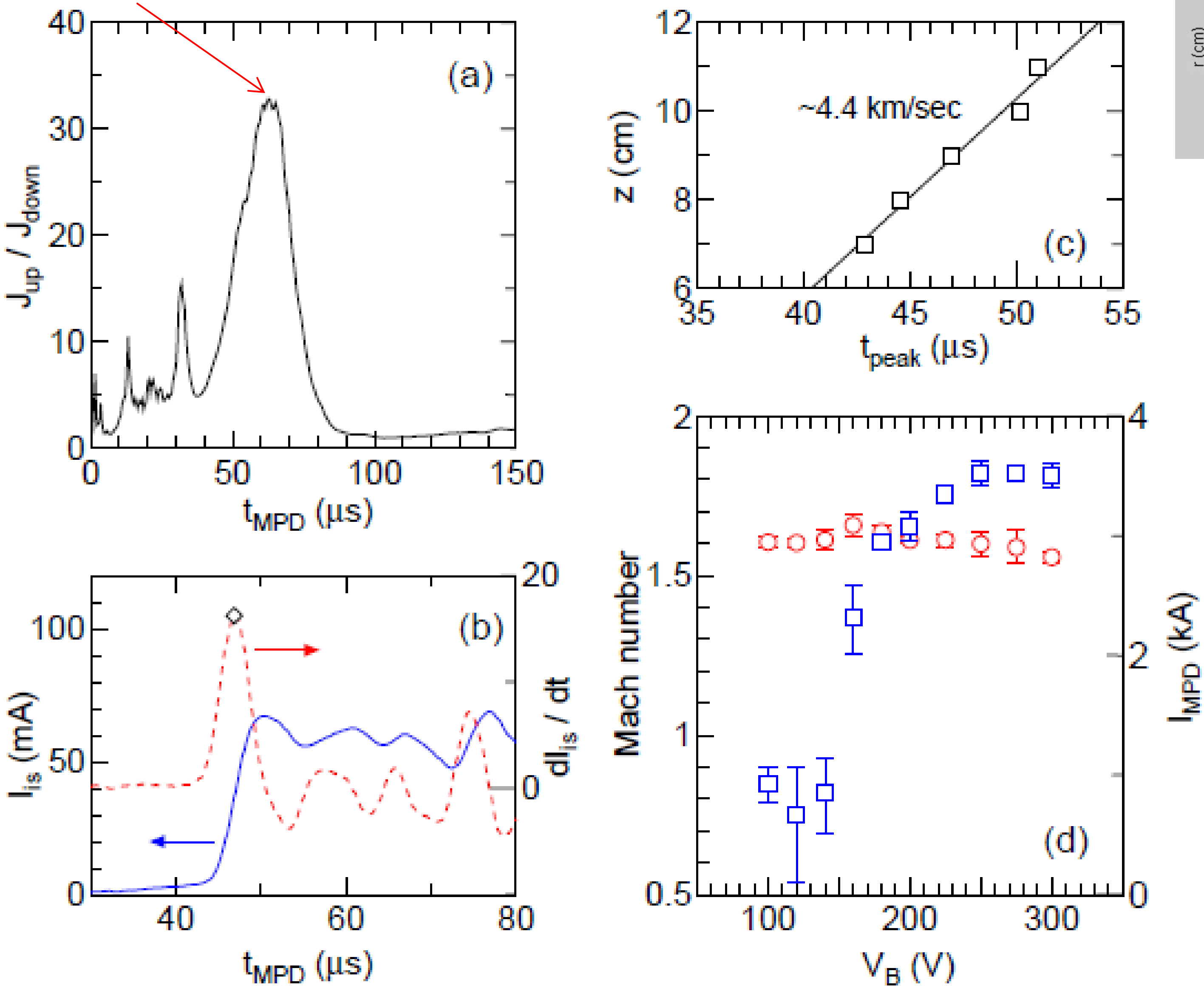
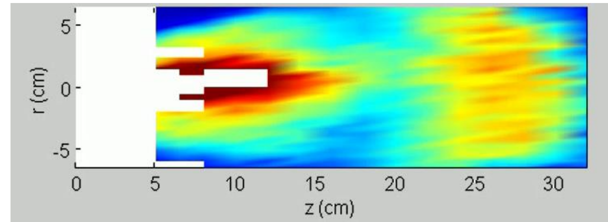


FIG. 3: Plasma density at $z = 15$ cm as functions of (a) V_{MPD0} for $V_B = 250$ V and $m_{dot} = 6$ mg/s, (b) V_B for $m_{dot} = 6$ mg/s, and (c) m_{dot} for $V_B = 250$ V, where the two cases of $V_{MPD0} = 0$ V and 400 V are tested in Figs. 3(b) and 3(c). The dotted lines are added as vidual guides.

Flow velocity measurements by Mach probe and Time of Flight

Mach 1.8 = 4.8 km/s





Takahashi et al., APL 2014

Conclusion

The magnetic nozzle plasma thruster, which has been investigated in Iwate University, The Australian National University, and Tohoku University, is briefly reviewed.

Electrodeless Helicon Plasma Thruster, being a new type of electric propulsion device, is now just started being investigated vigorously.

- ✓ The direct thrust measurement is firstly performed.
- ✓ The thrust imparted from the helicon thruster is arising from the electron pressure force onto the source and the Lorentz force due to the electron diamagnetic drift current and the radial magnetic field.
- ✓ The performance of the helicon thruster is gradually increased in the last two years.

Helicon MPD thruster, being a new concept of the thruster, is now preliminarily tested by the small laboratory experiment.

- ✓ The similar performance to the applied field MPD thruster seems to be obtained with much lower gas flow rate as the high density helicon can trigger the MPD discharge in the low pressure argon.
- ✓ The plasma density above 10^{20} m^{-3} can be obtained at 10cm downstream of the thruster exit.