Studies on Helicon Plasma Thruster and Measurement Methods

A162

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0. Abstract & conclusion

- Internal gas feeding (IFT)
  - Increase of electron density compared to conventional. (~1.5x)
  - Ion flow velocity was decreased in upstream area.
  - Observing neutral depletion is a next issue.
- Supersonic gas puffing (SSGP)
  - Narrow gas beam was obtained in small thought diameter and high pressure case.
  - Electron density, ion velocity and flux were increased in case of middle nozzle position (-370 mm)
  - Although the supply amount was excessive at present, SSGP has potential to improve thrust characteristics.
- Acceleration schemes
  - Rotating magnetic field acceleration and m=0 coil acceleration methods have been developed.
- Measurements
  - Compact Pirani gauge => local neutral pressure
  - Laser induced florescence => ion velocity (to obtain flux and thrust)
  - Intensity ratio method (CR model) => electron density and temp.

1. Introduction

Problem of conventional electric thrusters

Present electric thrusters (e.g., Ion thruster, Hall thruster)

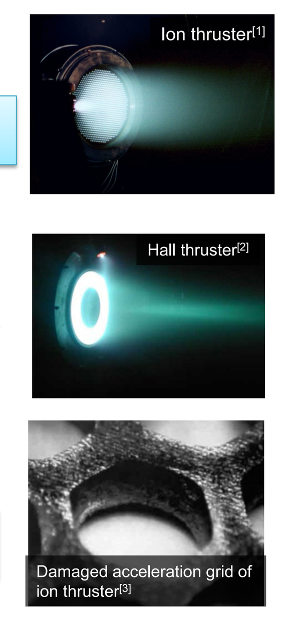
Direct contact between plasma and electrodes

- Problem of short lifetime due to the erosion of electrodes

Due to this problem, the following development is difficult.

- kW class long lifetime thrusters
- MW class thruster

Long lifetime, high thrust and high specific impulse thruster are needed for deep space exploration.



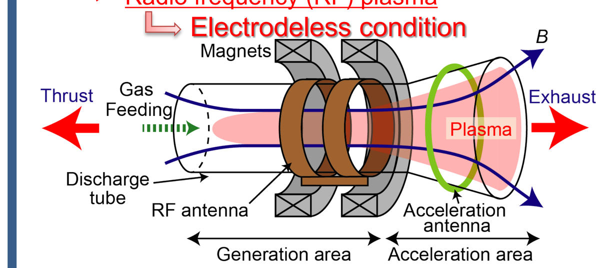
[1] http://www.jaxa.jp/article/special/hayabusa/kuninaka_j.html
[2] Y. Raitses et al., IEEE Trans. Plasma Sci. 36 (2008) 1202.
[3] http://www.isas.jaxa.jp/ISASnews/No.222/isas.html

2. Concept & objective

Helicon Electrodeless Advanced Thruster (HEAT)[4]

- Helicon plasma[5]
  - High-density (~10^{19} m^{-3})
  - Wide operation range (RF freq & Power., applied field, pressure)
  - Radio frequency (RF) plasma
  - Electrodeless condition

- High thrust
- High efficiency
- Easy throttling
- Long lifetime



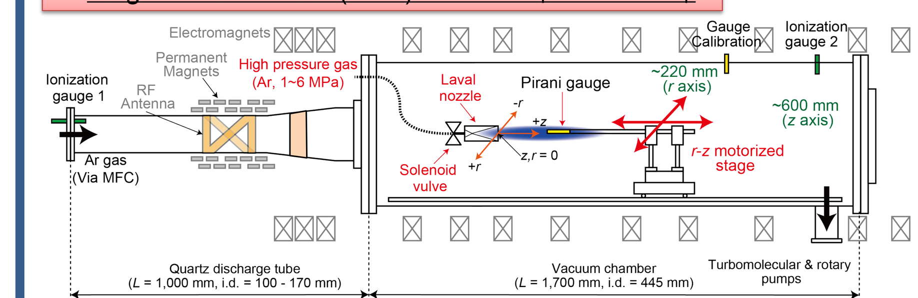
Objective: To develop high-performance helicon plasma thruster, We develop followings

- Plasma generation => Gas feeding method
- Plasma acceleration => RMF & m=0 coil method
- Measurement tools for above-mentioned studies

[4] S. Shinohara, et al., IEEE trans. Plasma Sci. 42 (2014) 1245.
[5] R. W. Boswell, Phys. Lett. 33A (1970) 457

3. Experimental device

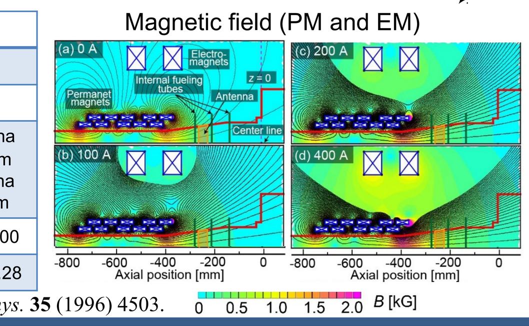
Large Mirror Device: (LMD)[6] *SSGP experimental setup



Operation parameters of LMD

RF power	$P_{RF} \le 3$ kW		
RF frequency	7 MHz		
RF antenna	Single loop antenna z = -255 ~-210 mm Half helical antenna z = -570~-385 mm		
Gas flow rate [sccm]	30	65	100
Pressure [Pa] (IG1)	0.09	0.18	0.28

Magnetic field (PM and EM)



[6] S. Shinohara et al., Jpn. J. Appl. Phys. 35 (1996) 4503.

4. Proposed Helicon thruster

Present status of development of our helicon plasma thruster [7]

Thrust:	20 mN @ 3 kW, 70 sccm, Ar 40 mN @ 3 kW, 90 sccm, Xe
Thrust to power ratio:	8 mN / kW @ 2 kW, 70 sccm, Xe 15 mN / kW @ 2 kW, 90 sccm, Xe
Specific Impulse:	2,000 s @ 3 kW, 30 sccm, Ar 1,500 s @ 3 kW, 10 sccm, Xe
Thrust Efficiency:	6 % @ 3 kW, 70 sccm, Ar 4 % @ 3 kW, 90 sccm, Xe

In order to improve plasma performance, we have proposed to develop new schemes in plasma generation and acceleration

- Plasma generation
  - Local fueling (this poster)
- Electrodeless Plasma acceleration
  - m = 0 coil acceleration
  - Rotating Magnetic Field (RMF) acceleration

[7] D. Kuwahara et. al., J. Propul. Power 33 (2017) 420.

5. Gas feeding schemes

Problems

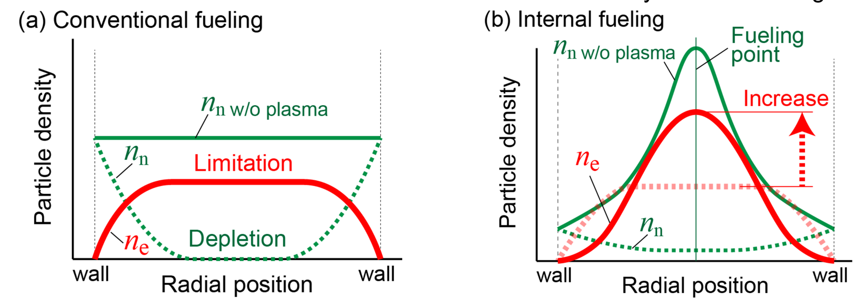
① Depletion of neutral particle[8]
Ionization area is changed in bad B-field area
Limitation of electron density (thrust)

② Wall loss
Decreasing of thrust to power ratio

③ Damage of discharge tube wall (contamination of plasma)
Limitation of thruster lifetime

Internal feeding method can solve these problems.

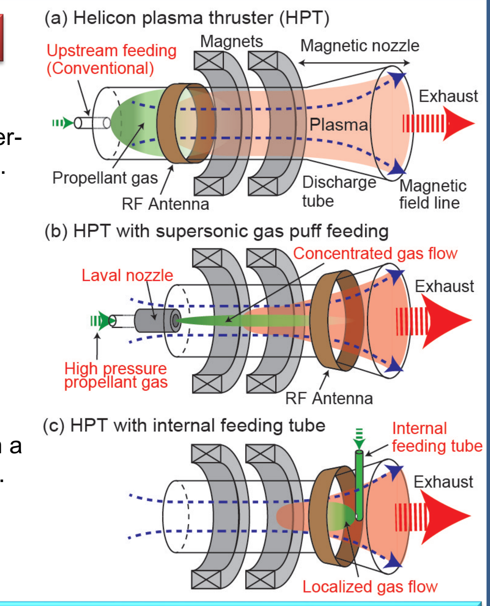
※Depletion of neutral particles in a certain axial region [8,9] can be also solved by internal feeding.



[8] A. Fruchtman, Plasma Sources Sci. Technol. 17 (2008) 024016.
[9] K. Takahashi, et al., Appl. Phys. Lett. 108 (2016) 074103
[10] A. Murakami, et al., Plasma Fusion Res. 5 (2010) S1032

local fuel gas injection methods

- Internal Feeding Tube (IFT)
  - Test method to check about center-localized particle feeding scheme.
  - Gas feeding tube (ceramic) is inserted plasma directly.
  - Damage of IFT may occur.
- Supersonic Gas Puffing (SSGP) [10]
  - Developed as a fueling method in a magnetically confined fusion field.
  - Generating concentrated neutral gas beam using Laval nozzle.

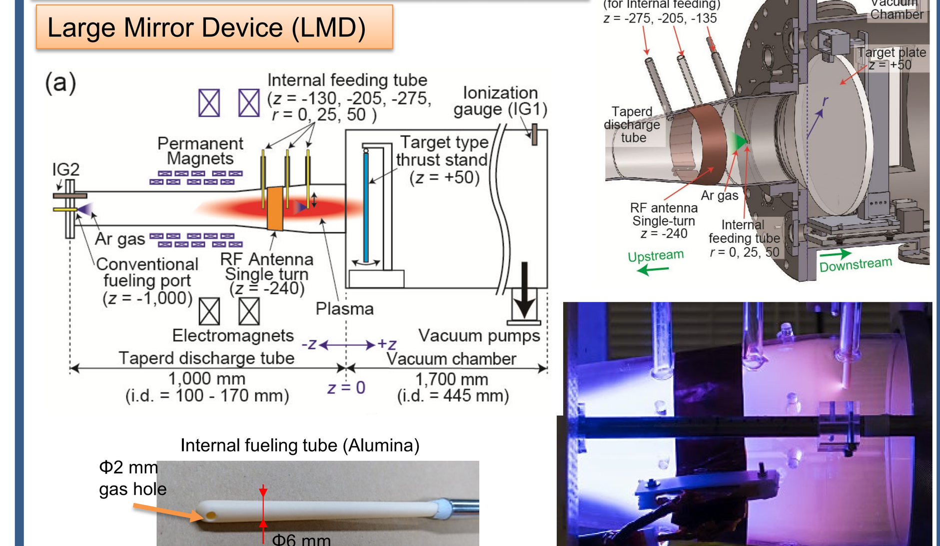


Control of neutral gas distribution can be a solution for above-mentioned problems.

6. Internal gas feeding (IFT)

Experimental setup of internal fueling tube

Large Mirror Device (LMD)

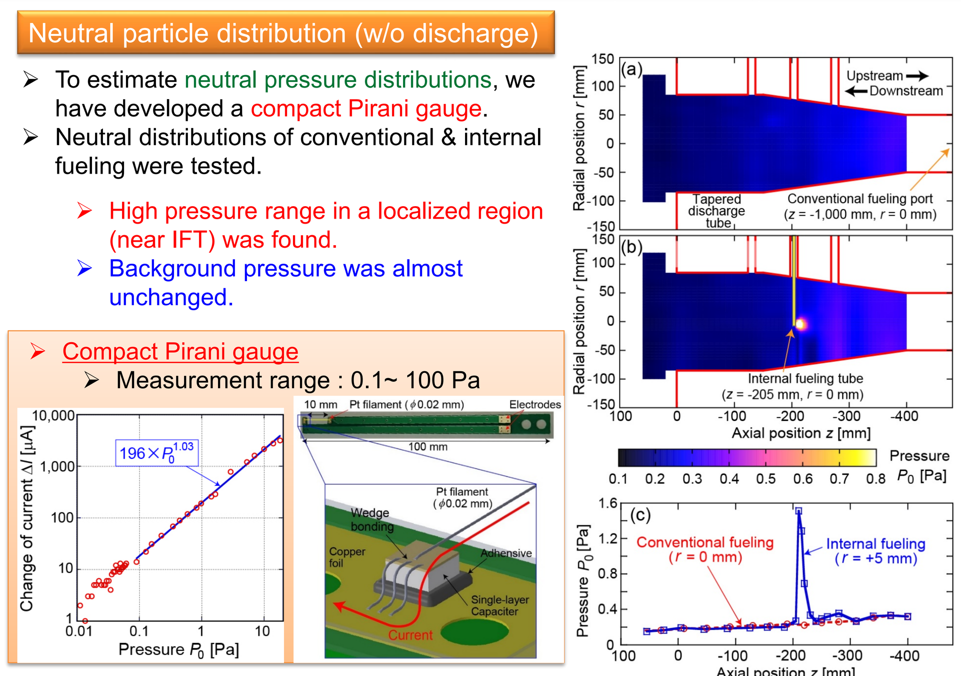


6. Internal gas feeding (IFT) (continued)

Neutral particle distribution (w/o discharge)

- To estimate neutral pressure distributions, we have developed a compact Pirani gauge.
- Neutral distributions of conventional & internal fueling were tested.
  - High pressure range in a localized region (near IFT) was found.
  - Background pressure was almost unchanged.

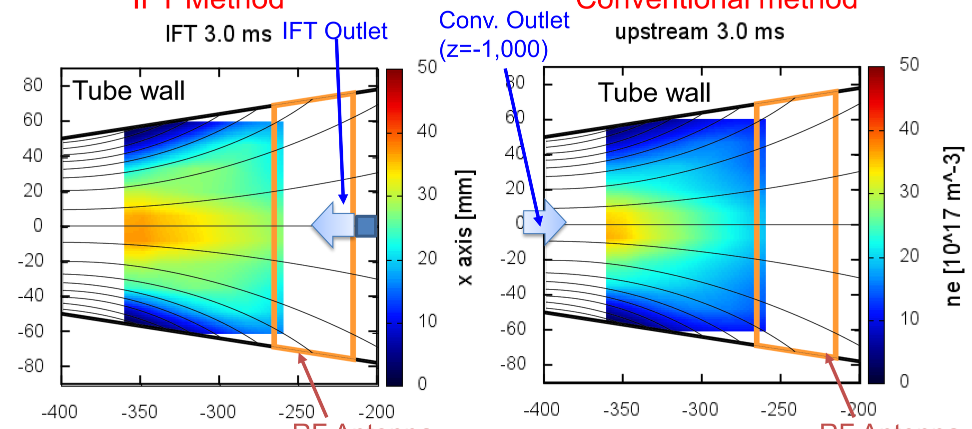
Compact Pirani gauge
- Measurement range : 0.1~ 100 Pa



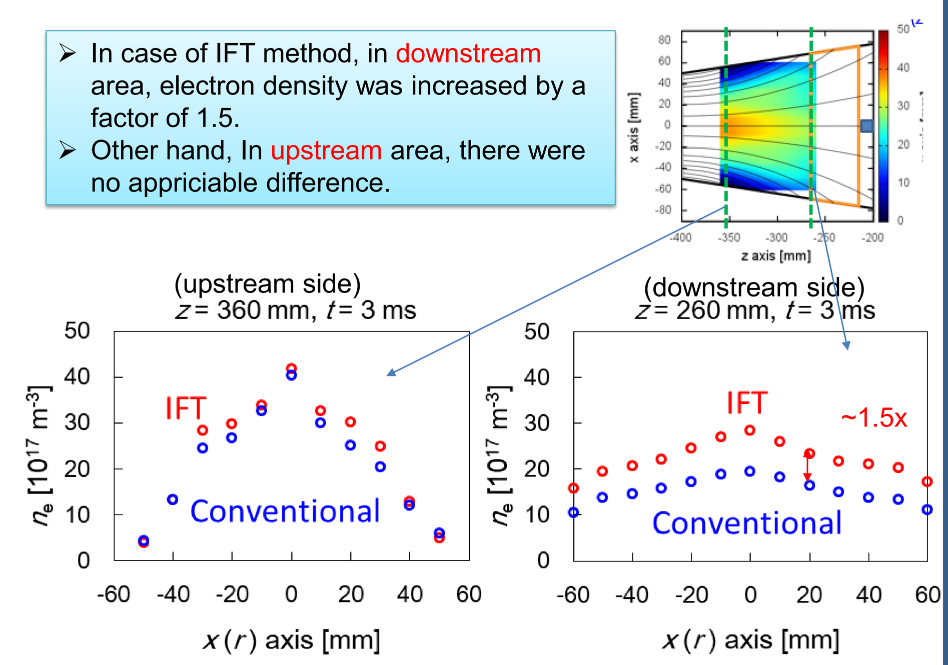
Electron density distribution (with discharge)

- IFT case, the electron density profile is distributed along magnetic field (near the wall).
- Electron density using IFT was higher than conventional one.

RF power: 3 kW (75 ms)
RF Freq.: 7 MHz
Gas flow late: 80 sccm (Ar)
Measure timing: Discharge started after 3 ms



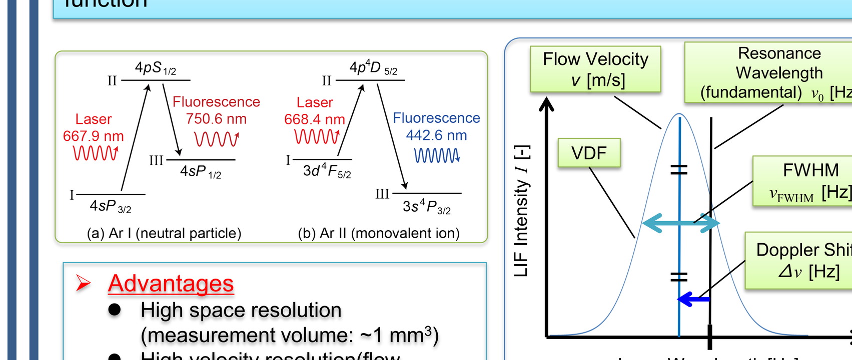
- In case of IFT method, in downstream area, electron density was increased by a factor of 1.5.
- Other hand, In upstream area, there were no appriciable difference.



7. LIF measurement

Particle flow velocity measurement (LIF)[11-13]

Using excitation, emission and Doppler shift phenomena, Laser induced fluorescence (LIF) measurement can measure particle velocity distribution function



- Advantages
  - High space resolution (measurement volume: ~1 mm^3)
  - High velocity resolution(flow velocity: ~50 m/s)
  - Absolute measurement

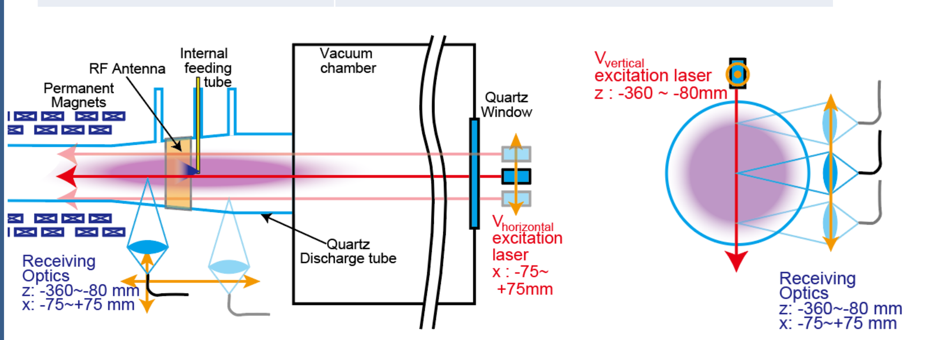
Flow Velocity: v [m/s]
$v = c\Delta\nu/\nu_0$
Temperature: T [K]
$\nu_{FWHM} = 7.7\times10^{-7}\nu_0\sqrt{T_i/A}$

[11] R. F. Boivin et al., Plasma Sources Sci.Technol. 16 (2007) 742.
[12] R. F. Boivin et al., Rev. Sci. Instrum. 19 (2003) 4352.
[13] N. Teshigahara, Plasma Fusion Res. 9 (2014) 3406055.

7. LIF measurement (for IFT discharge)

Setup of LIF system in IFT discharge

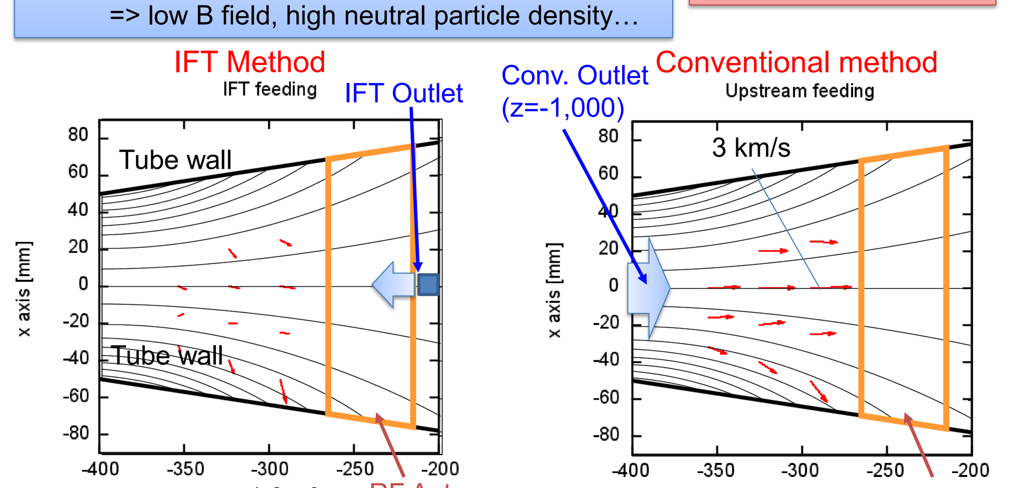
Excitation laser	~ 40 mW, (685~688 nm)
Detection method	Chopping laser (455 kHz) and FFT detection
Photon detector	Multi-pixel photon counter (MPPC)
Velocity direction	Horizontal (axial) and vertical (radial)
Measurement area	z: -360 ~ - 80 mm, r: -75 ~ +75 mm



(a) Horizontal velocity measurement (b) Vertical velocity measurement

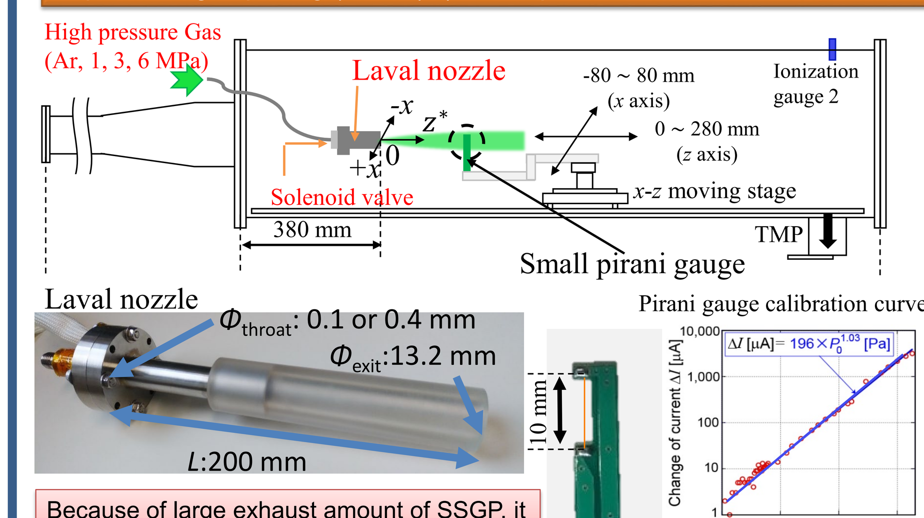
- In IFT case, ion velocities were slower than conventional one.
- Both IFT and conventional method, direction of ion velocities showed mismatch from field line.
  => low B field, high neutral particle density...

RF power: 3 kW (75 ms)
RF Freq.: 7 MHz
Gas flow late: 80 sccm (Ar)
LIF meas. time: 10~60 ms (quasi-steady)



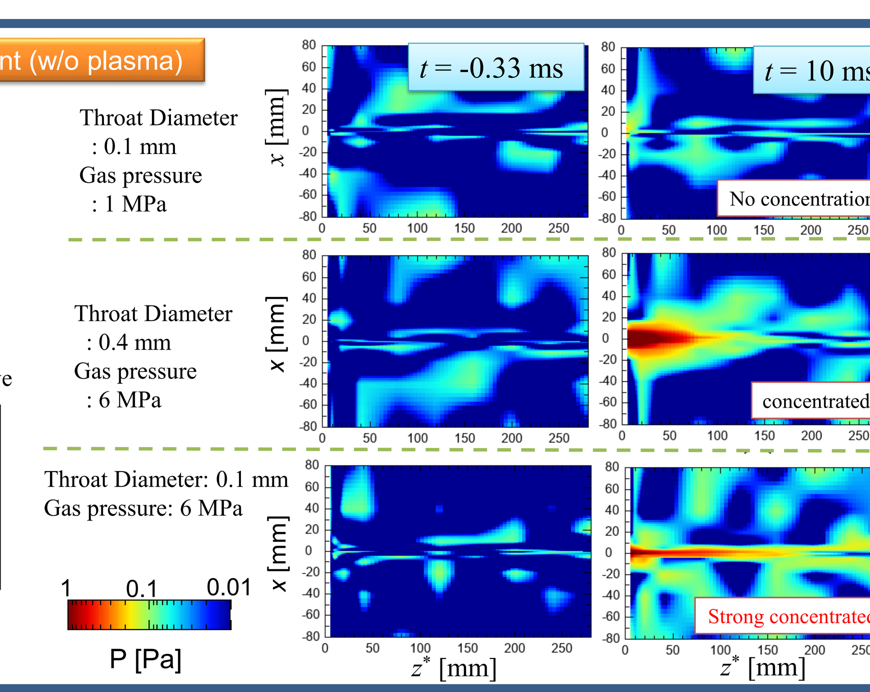
8. Supersonic gas puffing (SSGP)

Supersonic gas puffing (SSGP), (neutral particle distribution measurement (w/o plasma)



Because of large exhaust amount of SSGP, it drives as short pulse by solenoid valve.

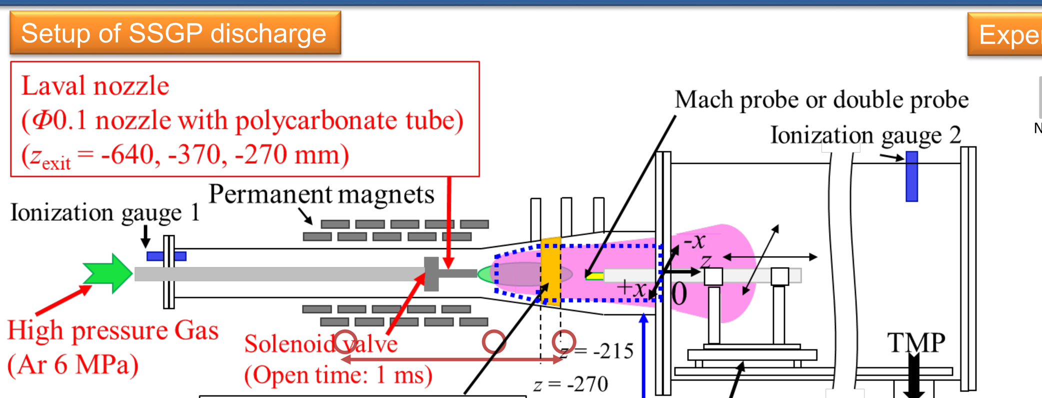
Filament: Φ 0.01 mm, Platinum
Sensitivity: ~0.1 Pa



8. Supersonic gas puffing (SSGP) (continued)

Setup of SSGP discharge

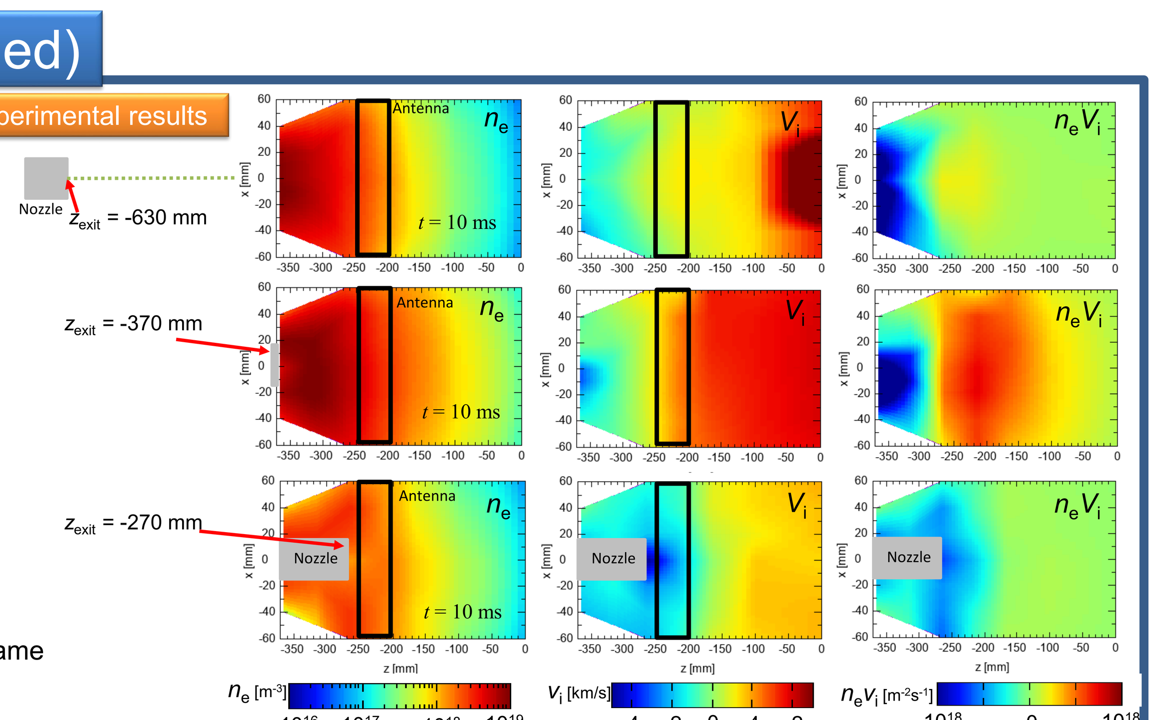
Laval nozzle
(Φ0.1 nozzle with polycarbonate tube)
(z_{exit} = -640, -370, -270 mm)



RF antenna (Single turn)
RF power: 3 kW
Frequency: 7 MHz
Discharge length: 75 ms

Measuring area
(z = -365 ~ 0 mm, Δz = 50 ~ 100 mm)
(x = -60 ~ 60 mm, Δx = 20 mm)

Experimental results



- z_{exit} = -630 mm case is considered as conventional feeding (no-concentrated) & same feeding amount about concentrated case (z_{exit} = -370 and -270 mm)
- In case of z_{exit} = -370 mm, ne, vi and n_eV_i (flux) were significantly increase.

9. Rotating magnetic field acceleration[14-16] (see T. Furukawa's presentation A198)

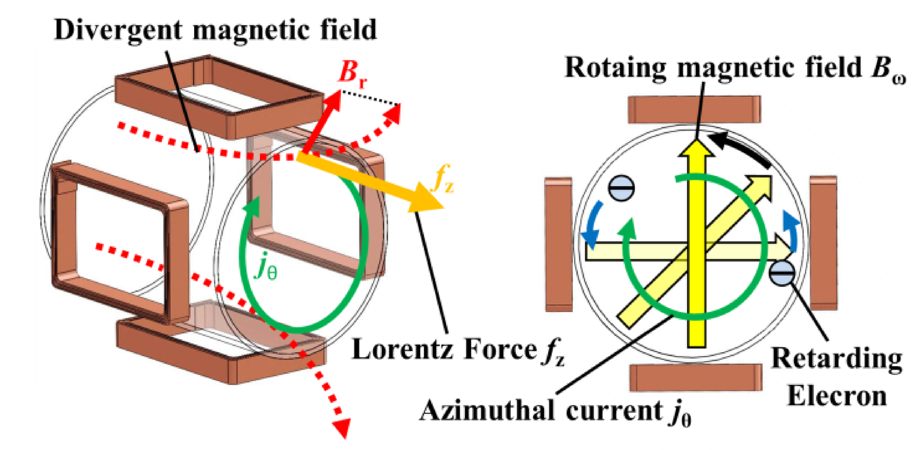
・Using two pairs of opposing coils with RMF current frequency f_{RMF} in the range $f_{ci} << f_{RMF} << f_{ce}$ (f_{ci} and f_{ce} are ion and electron frequencies, respectively).

I. RMF makes axial oscillating component of the electrostatic field $\tilde{E}_z$ by Faraday's law

II. $\tilde{j}_z$ is induced by $\tilde{E}_z$, and then electron rotates in the azimuthal direction by $\tilde{E}_\theta$ (by a non-linear effect of $j_z \times B_r$)

III. Azimuthal current j_θ is induced by Ohm's law (at most $j_\theta = n_e e r 2\pi f_{RMF}$)

IV. In the presence of the external radial magnetic field B_r, axial Lorentz force f_z is generated



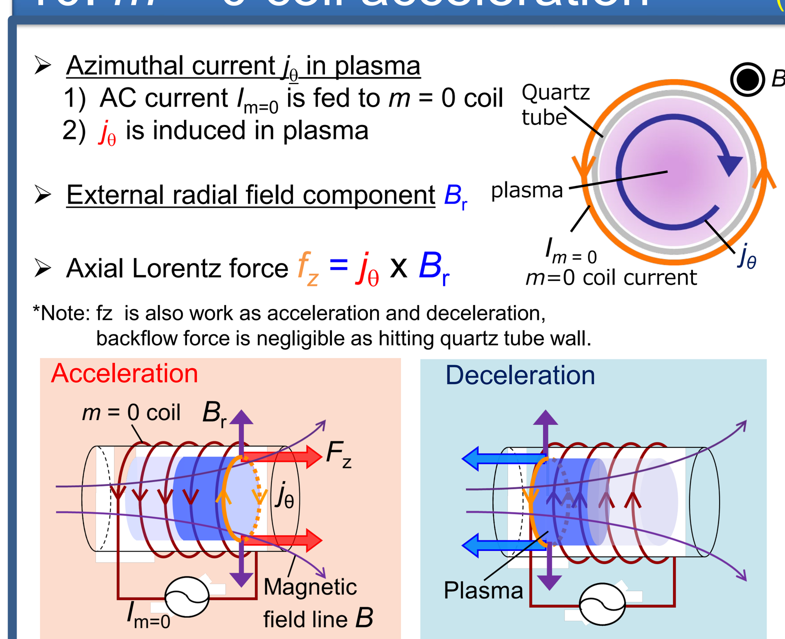
Schematic view of RMF acceleration.

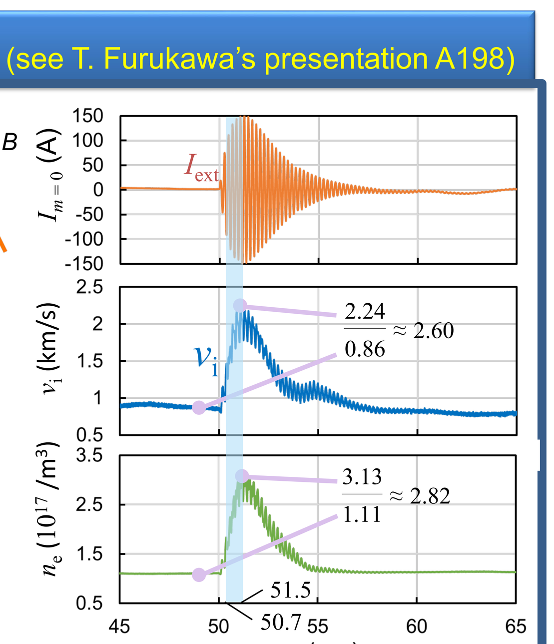
[14] T. Furukawa et al., Rev. Sci. Instrum. 89 (2018) 043505.
[15] T. Furukawa et al., AIP. Adv. 7 (2017) 115204.
[16] T. Furukawa et al., Phys. Plasmas 24 (2017) 043505.

10. m = 0 coil acceleration[17,18] (see T. Furukawa's presentation A198)

- Azimuthal current j_θ in plasma
  1) AC current $I_{m=0}$ is fed to m = 0 coil
  2) j_θ is induced in plasma
- External radial field component B_r
- Axial Lorentz force $f_z = j_\theta \times B_r$

*Note: fz is also work as acceleration and deceleration, backflow force is negligible as hitting quartz tube wall.





[17] S. Shinohara et. al., IEEE TPS. 42 (2014) 1245.
[18] D. Kuwahara et al., Trans JSASS ATJ. 14 (2016) 117

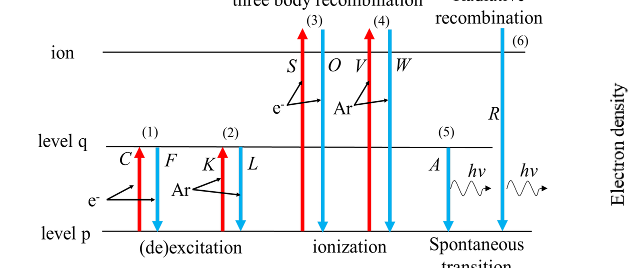
11. Spectral measurement

- Quite small diameter plasma
- High density & high temperature plasma

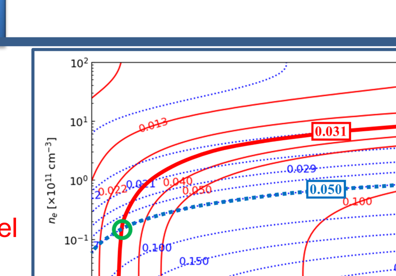
Difficult to probe electron density & temperature

Spectral measurement using collisional radiation model (CR model) [19-22]

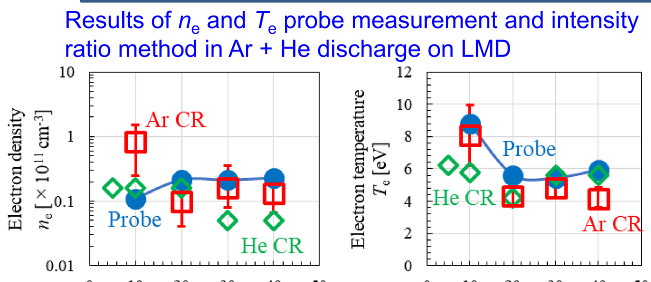
- small aperture, non-invasive
- inexpensive spectrometer



Scheme of CR model



Results of n_e and T_e probe measurement and intensity ratio method in Ar + He discharge on LMD

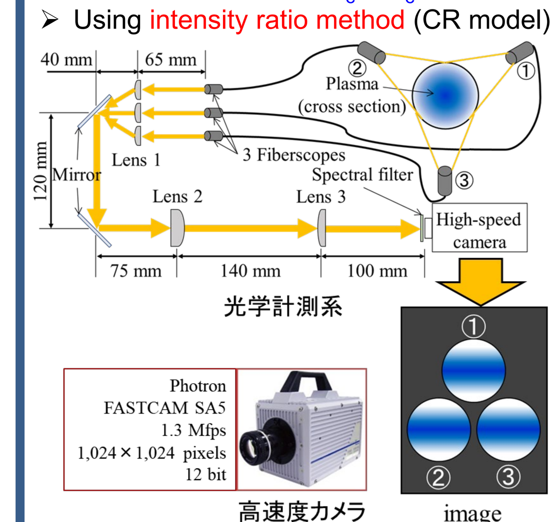


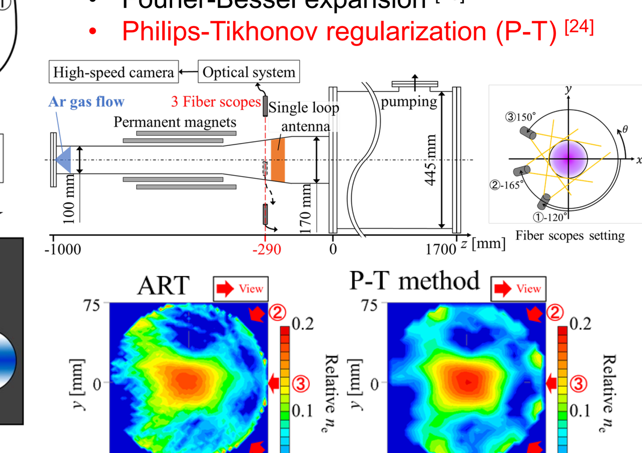
[19] Vlček, J., J. Phys. D: Appl. Phys., Vol. 22, No. 5 (1989), pp. 623-631.
[20] J. Mizouchi, Jpn. J. Appl. Phys. 49 (2010) 036001.
[21] Amy M. Keesee, et al., Rev. Sci. Instrum 77 (2006) 10F304
[22] K. Sawada et al., Plasma Fusion Res. 5 (2010) 001.

12. Spectral image reconstruction using high-speed camera

- Non-invasive
- cross-section view of n_e & T_e
- Using intensity ratio method (CR model)

Reconstruction method
- Abel inversion
- ART (Algebraic Reconstruction Technique
- Fourier-Bessel expansion [23]
- Philips-Tikhonov regularization (P-T) [24]





[23] Y. Nagayama, J. Appl. Phys., 62, 7 (1987), pp. 2702-2706.
[24] N. Iwama, Appl. Phys. Lett. 54, 6 (1989) pp. 502.

13 Acknowledgement

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