Performance evaluation of magnetic plasma shield for protecting the cosmic radiation and obtaining the thrust

The 3rd Toyama International Symposium on "Physics at the Cosmic Frontier" (PCF2021)

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Outline

- Self Introduction

- Research on Magnetic Shielding for Protection against Charged Particles of Cosmic Ray

- Research on Magnetic Sails and Magnetic Plasma Sails, which are propelled by receiving solar wind plasma with a magnetic field

Self Introduction

- <u>**Doctoral course, University of Toyama (1996- 2000)**</u>
  - **Numerical Study of Collisions of electron and positron plasmas near pulsars and black holes using Full-PIC Code.**

    Y.kajimura, Generation of magnetic field and particle acceleration during collision of electron–positron plasmas. The Astrophysical Journal(letter), 498 183–186, 1998

  - **Simulation of electromagnetic waves observed near electron plasma frequencies in the polar regions of the Earth's magnetosphere**

    Electromagnetic fluctuations near the electron plasma frequency from an electron/electron instability Y Kajimura, JOURNAL OF GEOPHYSICAL RESEARCH–SPACE PHYSICS, 105(A5) 10537–10542, May, 2000

- <u>**Private company (2000-2004)**</u>
  - **Research and development using general-purpose thermo-fluid numerical analysis software (STAR-CD)**

- <u>**University→JAXA, (2004-2011), NIT(Akashi 2012-)**</u>
  - **Laser Fusion Rocket, Magneto Plasma Sail, Ion thruster**
  - **Magnetic shield**

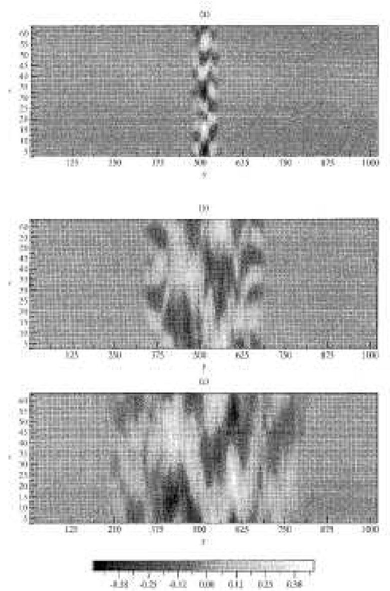
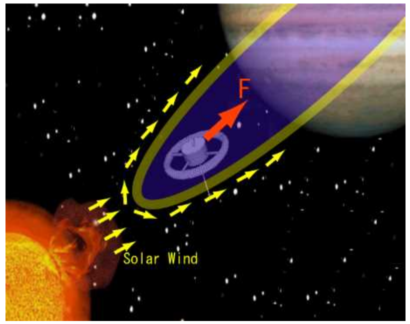


Fig. 2.—Time development of the magnetic field (B_z) structures in the x-y plane.



Magneto Plasma Sails

Outline

- Self Introduction
- Research on Magnetic Shielding for Protection against Charged Particles of Cosmic Ray
- Research on Magnetic Sails and Magnetic Plasma Sails, which are propelled by receiving solar wind plasma with a magnetic field

Outline :Magnetic Shield

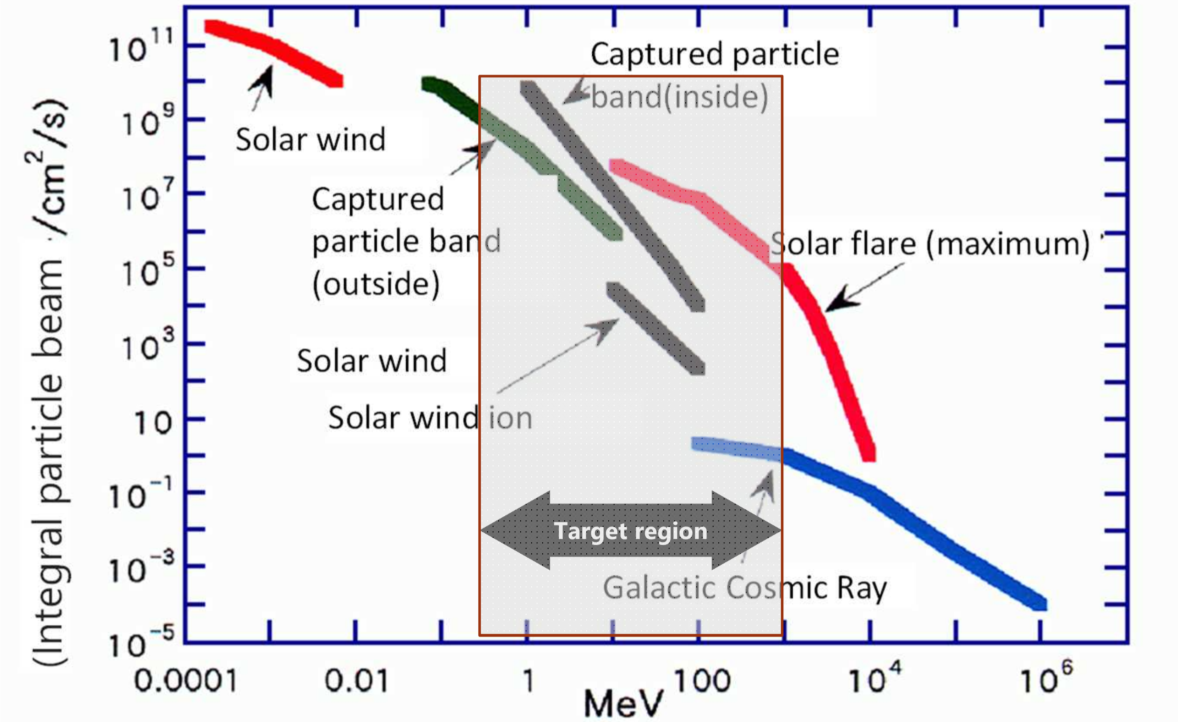
- **Background of the Present Research: Magnetic Shielding**

- **Numerical Simulation for the Evaluation of the magnetic shield performance**

- **Chamber experiment for the Evaluation of the magnetic shield performance**

Background

Cosmic Ray (alpha, beta, X, gamma, neutron rays, protons (solar flares), etc.)



Energy and Source of the space radiation

Ref. Kazunobu Fujitaka Radiation science, 40 (4), 124, 1997

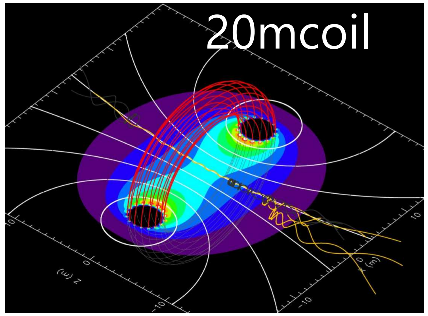
A method to prevent 0.5 MeV or more cosmic rays is proposed.

Past researches on magnetic shield

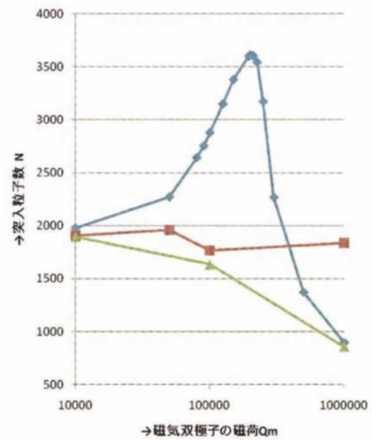
- Magnetic shield concept using superconducting coils （Levy,R.H.,1961）

- Behavior of charged particles in a dipole magnetic field （Stormer region） （Shepherd,S.G.,2007）
  For protecting the super relativistic cosmic ray → 10^8 [A] is needed

- Numerical Simulation: Test particle simulation for 0.5MeV （Nariyuki, et. al, Symposium on Space Environment 2010.）



Shepherd,S.G.,2007



Nariyuki ,2010

⇨ Present research: Research of the magnetic shield for protecting from the high energy radiation with 0.5-1000 [MeV].

Particle tracking Simulation

Particle tracking method

- Motion equation of cosmic ray charged particles (4th order Runge-Kutta method)

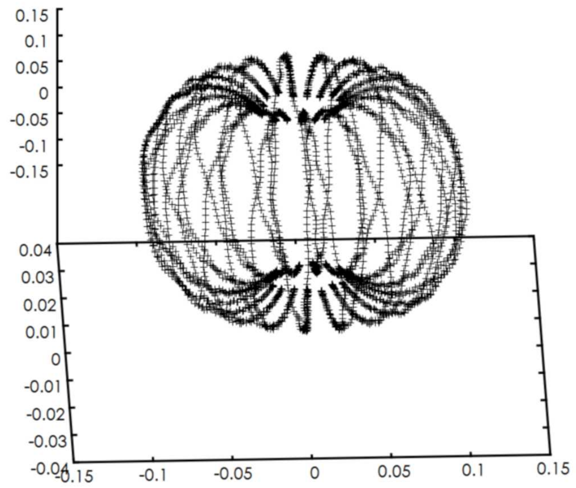
$$m\overline{v'} = q(\not{\bar{E}} + \bar{v} \times \bar{B})$$

- Dipole magnetic field

$$B = \frac{Q_m \overline{r_1}}{4\pi|\overline{r_1}|^3} - \frac{Q_m \overline{r_2}}{4\pi|\overline{r_2}|^3}$$

Q_m:Magnetic charge of a magnetic dipole

- Code Test: Mirror reflection

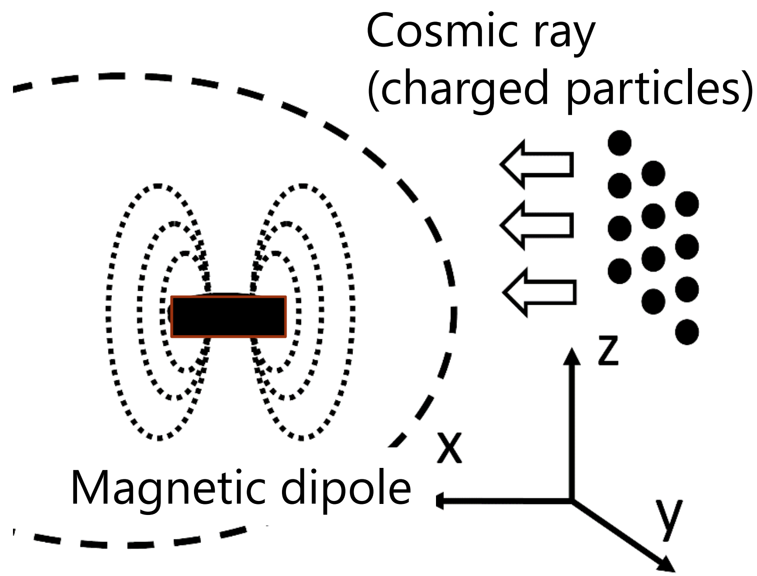


Code Test

Simulation Model

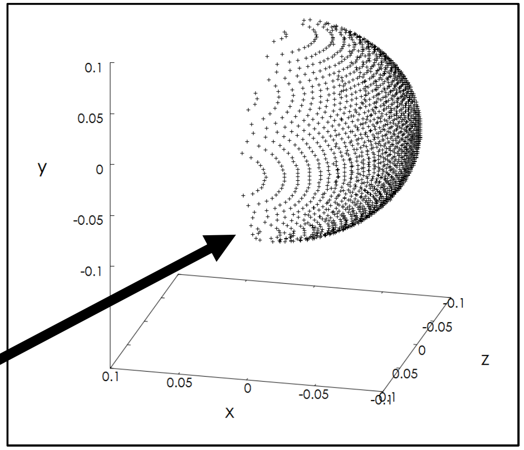
Coil radius [m]	Current[A]	Magnetic charge Qm
2	0～10^5	0～10^8

Initial velocity v_x [m/s]	Particle Energy [MeV]
10^7	0.525
10^8	57
2-2.6×10^8	320-1000



Distance from the spacecraft decided to have invaded

- Within 10 m radius
- invaded position is indicated by + marks

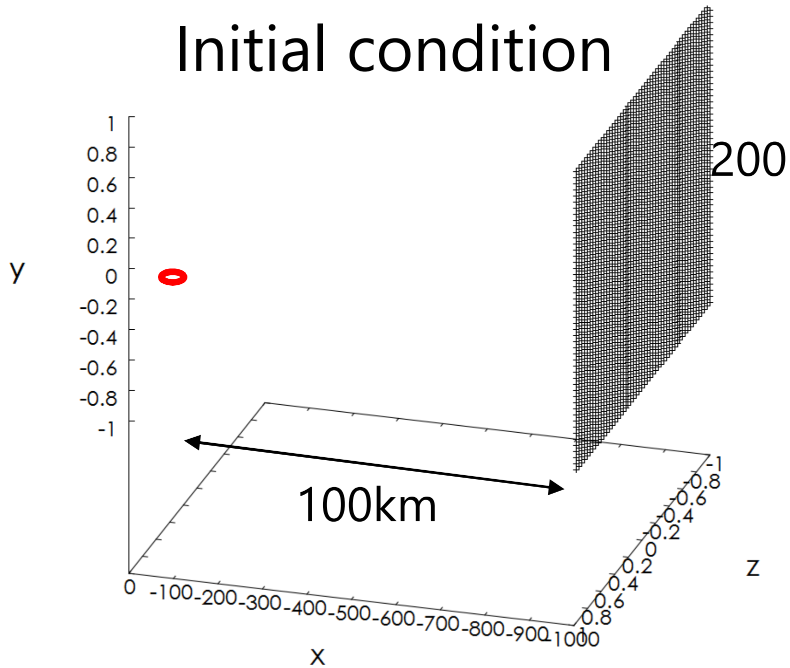


Simulation Results (0.5MeV)

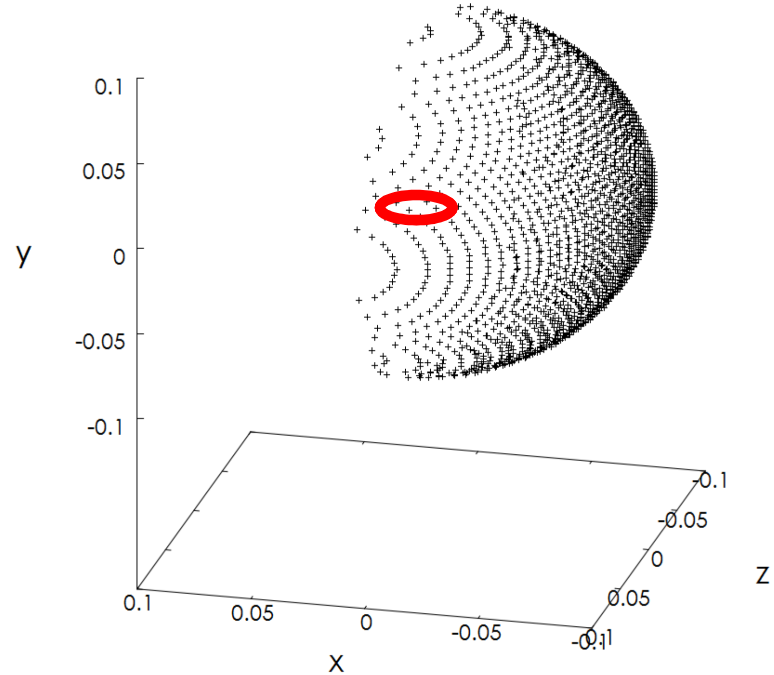
- Invaded position marker "+"

$Q_m = 1.0 \times 10^4$
$(r = 2[\mathrm{m}],$ *I*=1.27[A])

Initial condition



Initial number : 250000
→7850 (non-sheild)



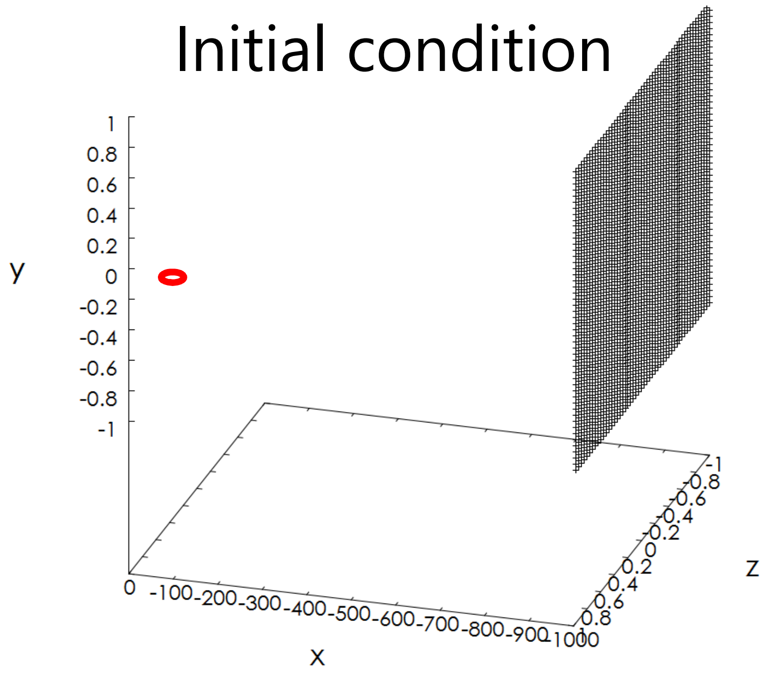
Number of invading particles : 1978

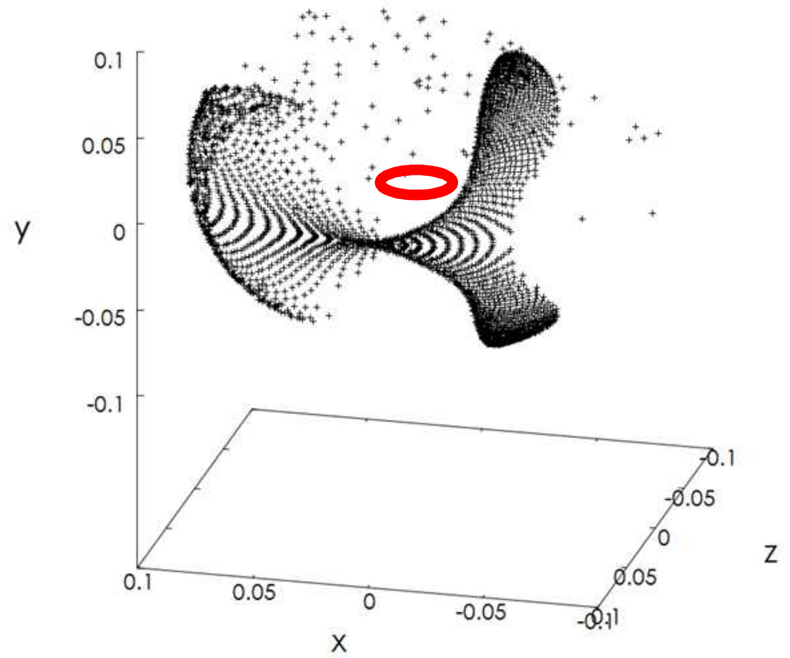
Simulation Results (0.5MeV)

- Invading position marker "+"

$Q_m = 1.0 \times 10^5$
($r = 2$[m], I=25.4[A])

Initial condition





Total particle numbers : 250000

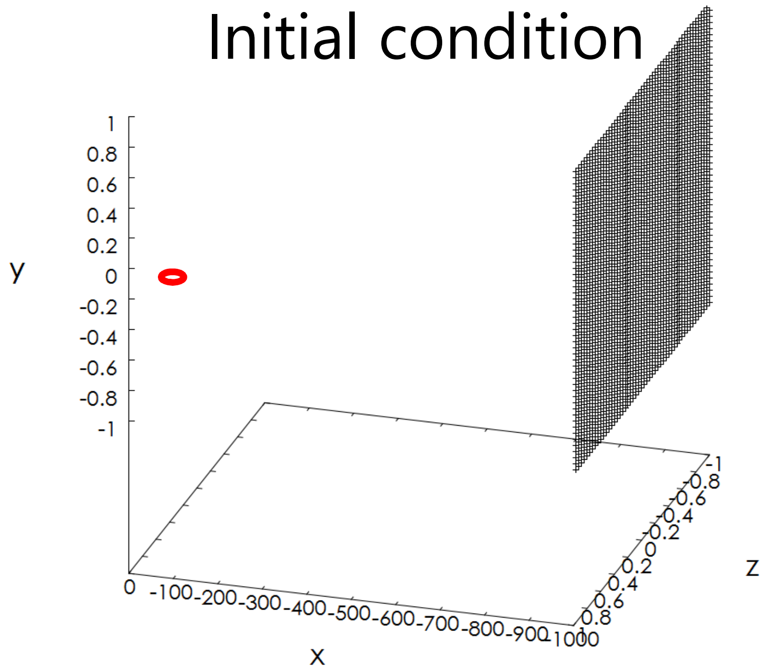
Number of invading particles : 3607

Simulation Results (0.5MeV)

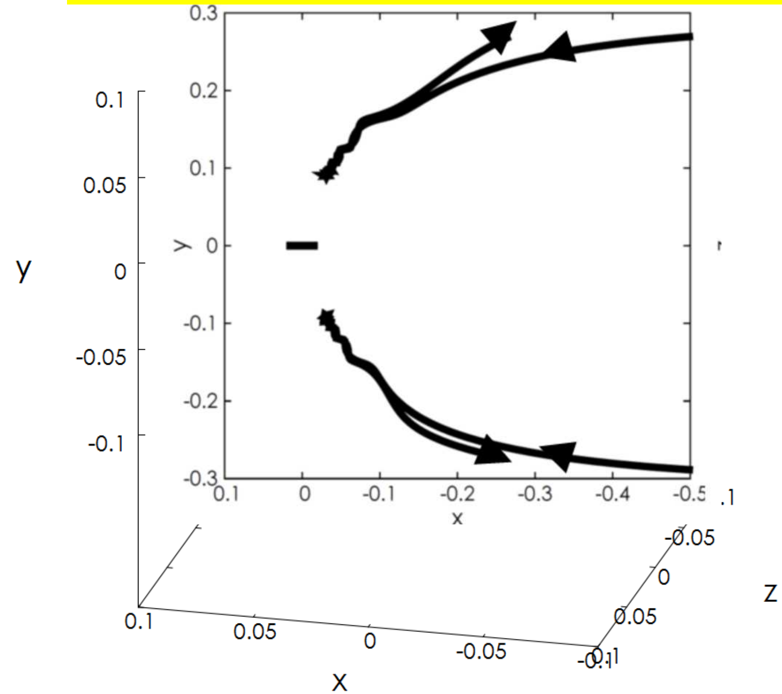
- Invading position marker "+"

$$Q_m = 1.0 \times 10^6$$
$(r = 2[\mathrm{m}], I = 127[\mathrm{A}])$

Initial condition

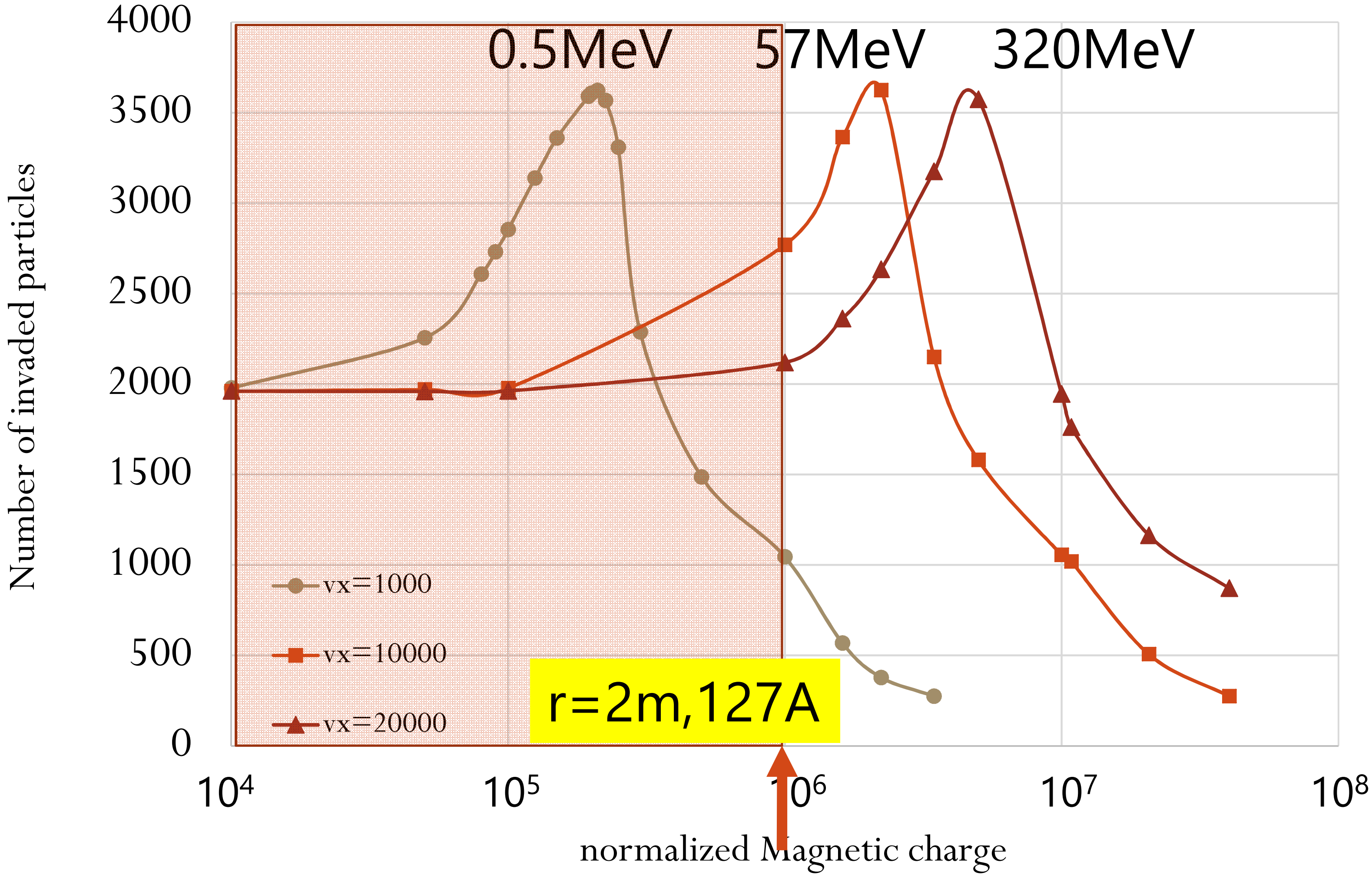


number of particles: 250000

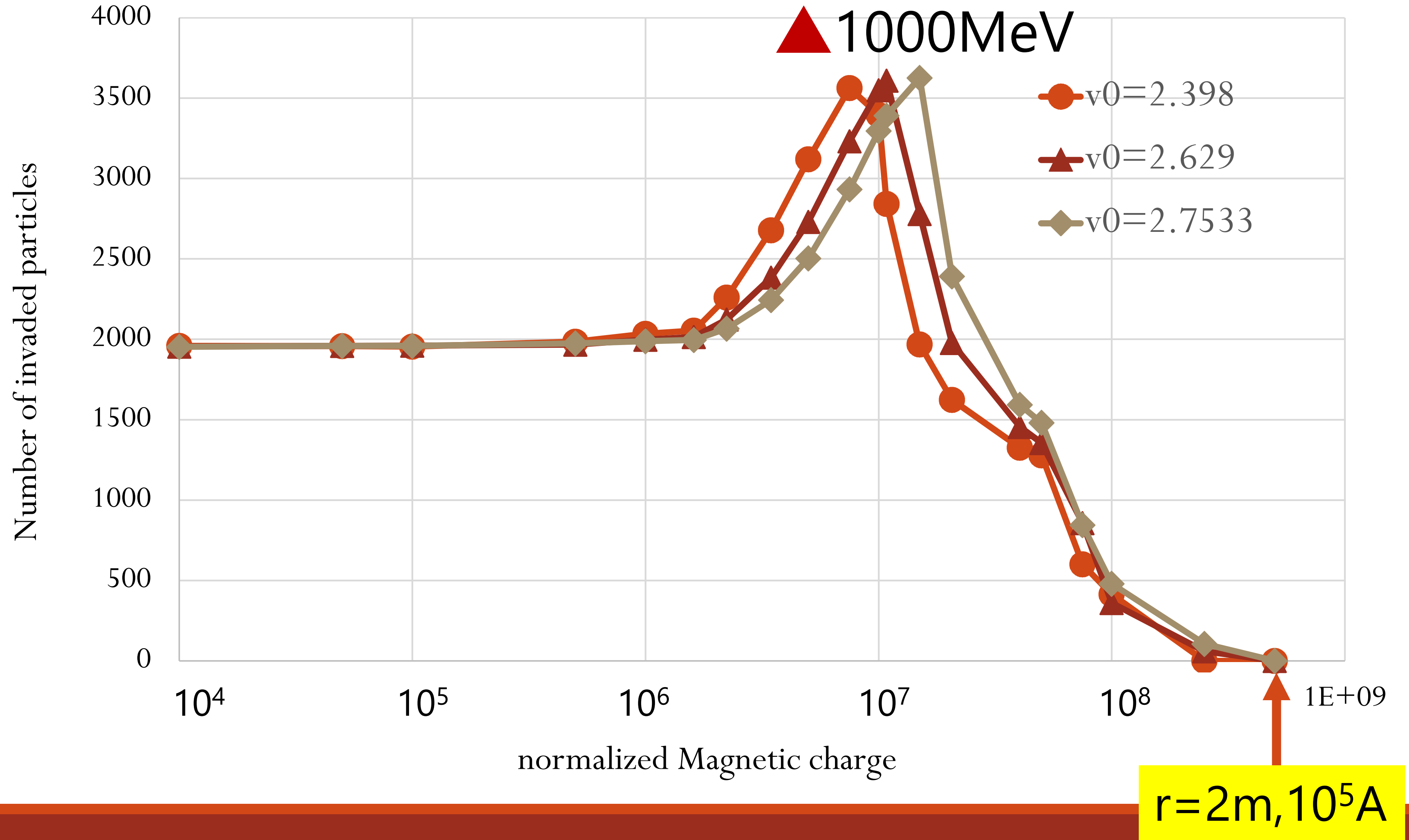


Number of invading particles : 1045

Number of invading cosmic rays (0.5,57,320[MeV])



Number of invading cosmic rays (0.5,57,320[MeV])



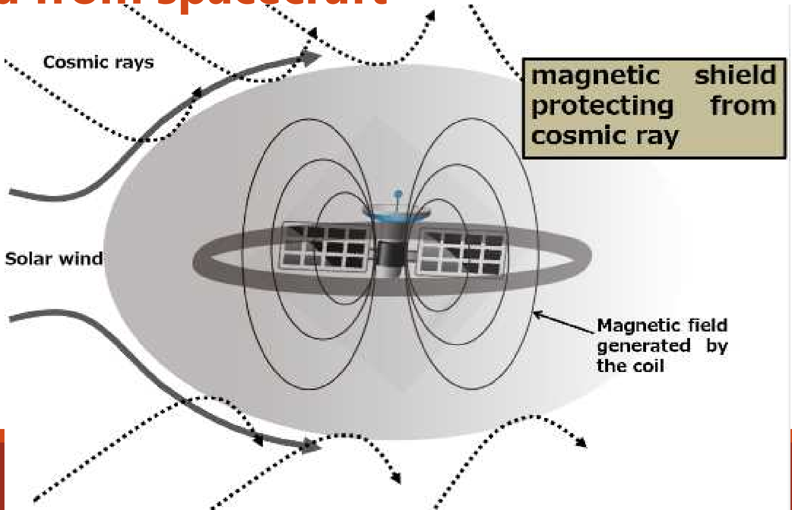
How do we strengthen the shield?

- Performance of the Magnetic shield

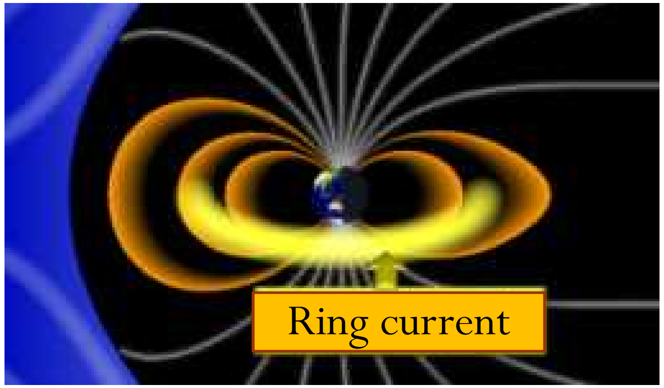
➡ Depending on the coil radius and current

How strengthen?

Use of the ring current generated by the injecting plasma from spacecraft



Ring current inside earth magnetosphere



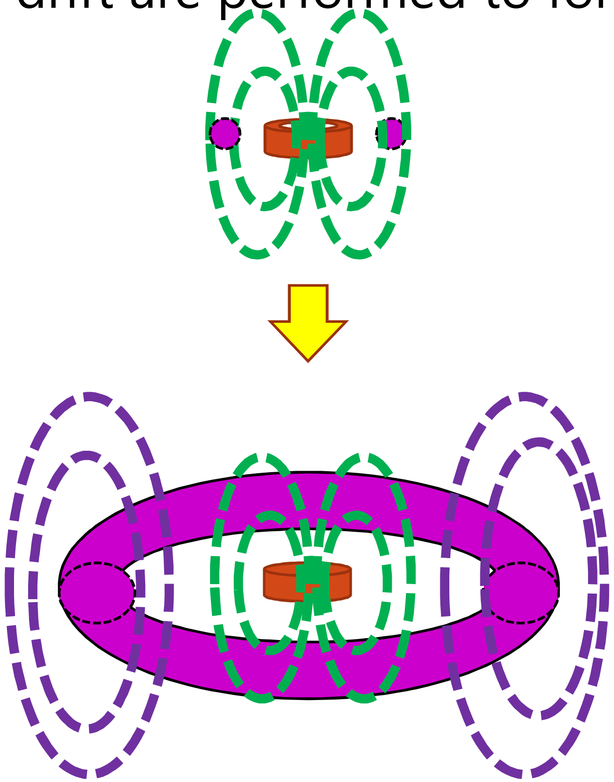
Magnetic storm occurrence by ring current
(Ebihara, Kyoto University)

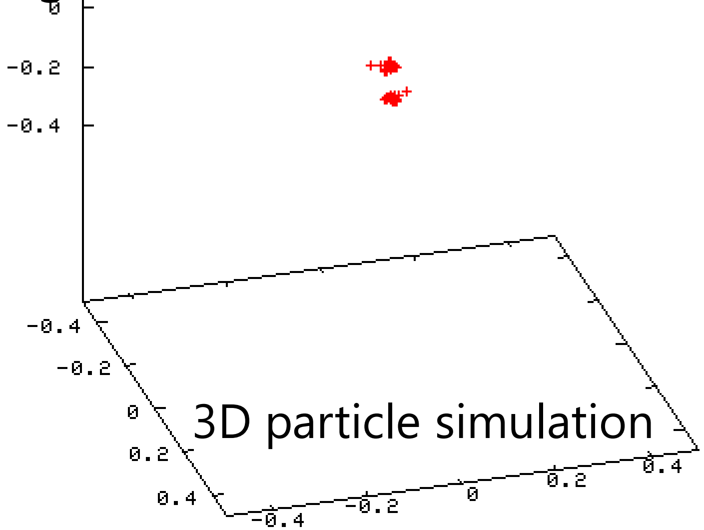
RT-1: Magnetic Confinement Fusion Device

Magnetospheric plasma confined in RT-1
(Yoshida, Tokyo Univ.)

Ring current production process

- Thermal plasma injection gradually into dipole magnetic field (thermal cathode plasma source)
- Particles are trapped in the magnetic field and the gyro motion + ∇B drift are performed to form a ring current.





3D particle simulation

- ◆ Available for protecting against high energy, time-varying solar flares and radiation
- ◆ Reduce the influence of the magnetic field on the spacecraft because it is created outside the spacecraft

Required ring current (Radius, Current)

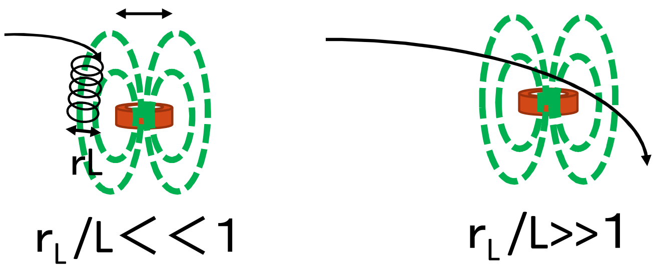
Energy[MeV]	Coil Current [A] r=2m	Coil Current +Ring Current [A]
0.5	127	
57	127×100	250A + <u>10m, 200A</u>
1000	127×1000	2500A + <u>10m, 200A</u>

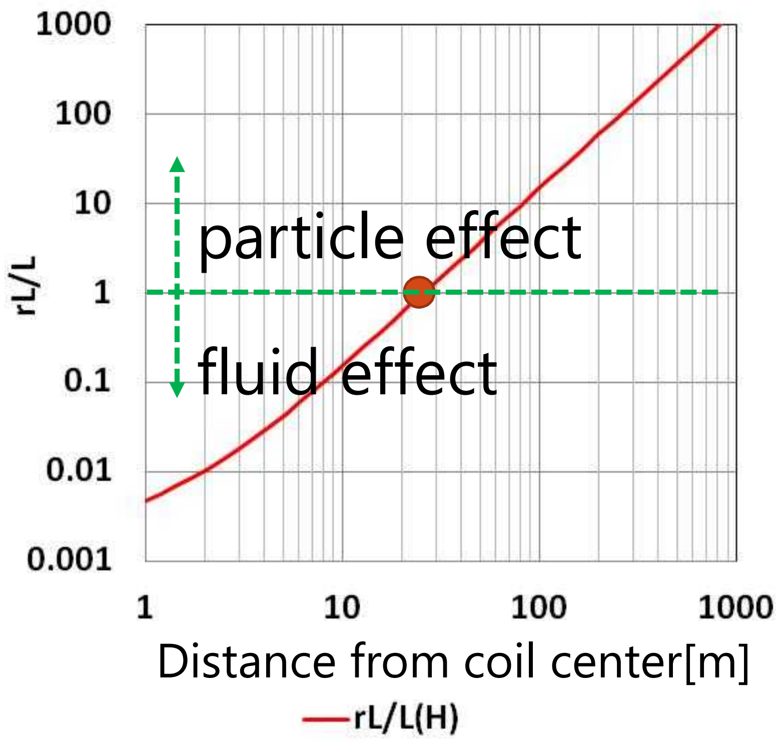
Requires 50 times increase in magnetic moment

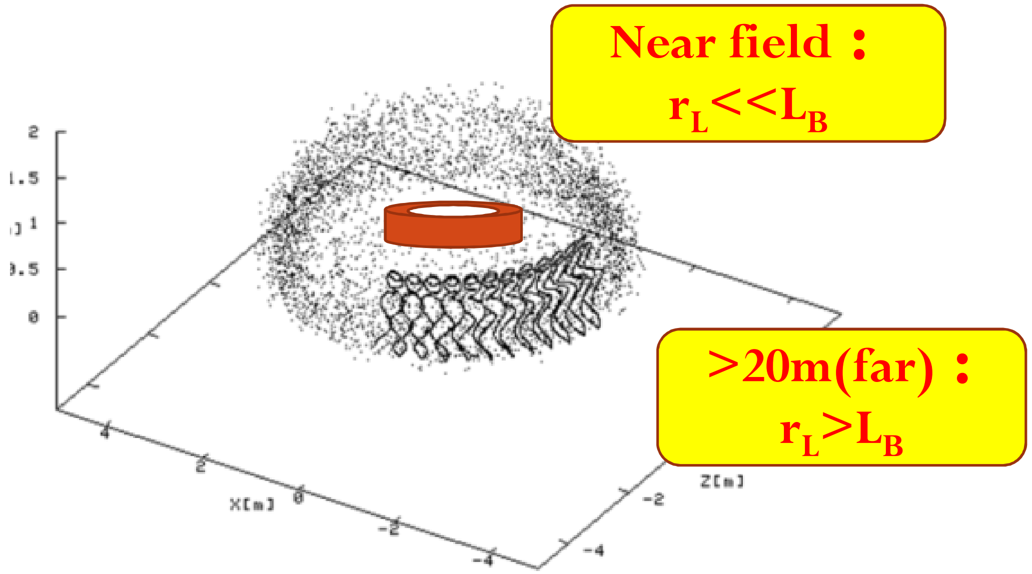
What is the upper limit of the ring-current current formed by plasma injection from the vicinity of the coil?

Numerical Simulation for Ring Currents

- Assumed design parameters
- Coil: r=2m 10^5 AT
- Thermal Plasma Injection 1eV~, 10^{20} m^{-3}~







Trajectory of plasma particles near the coil

One-Component Plasma Model

Assume electrical quasi-neutrality, electric field = 0 (no consideration of wave motion)

- Equation of motion of ions

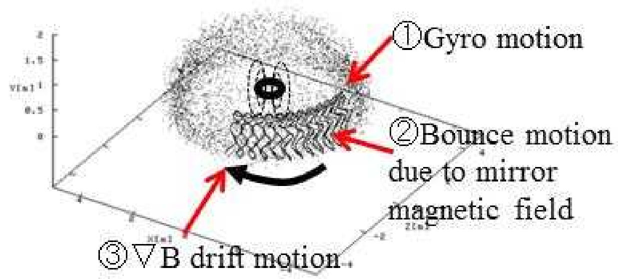
$$\begin{cases} m_i \dfrac{d\mathbf{V}_i}{dt} = q_i\left(\cancel{\mathbf{E}} + \mathbf{V}_i \times \mathbf{B}\right) \\ \dfrac{d\mathbf{X}_i}{dt} = \mathbf{V}_i \end{cases}$$

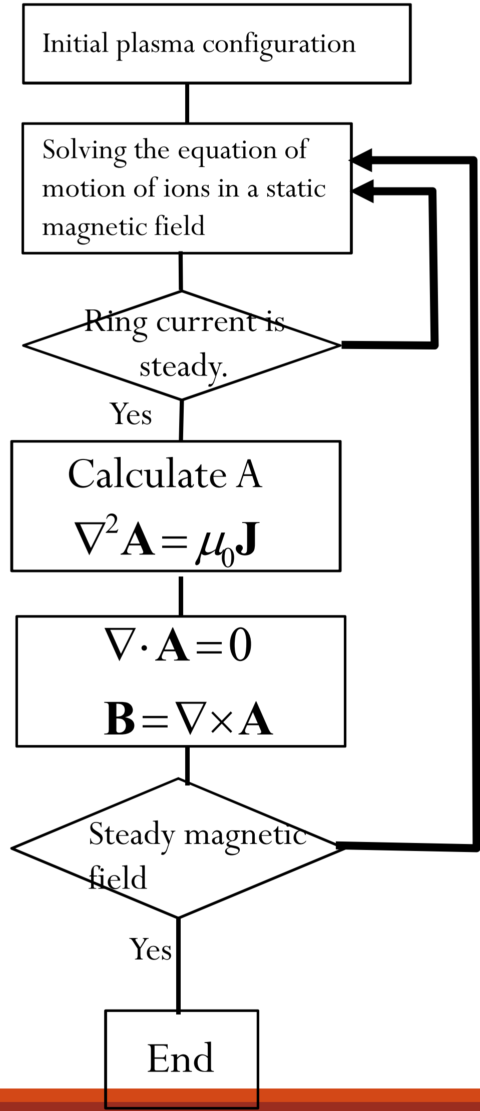
⟹ PIC method

Steady state → displacement current 0
Debye length < < scale length

- Maxwell's equation (vector potential A)

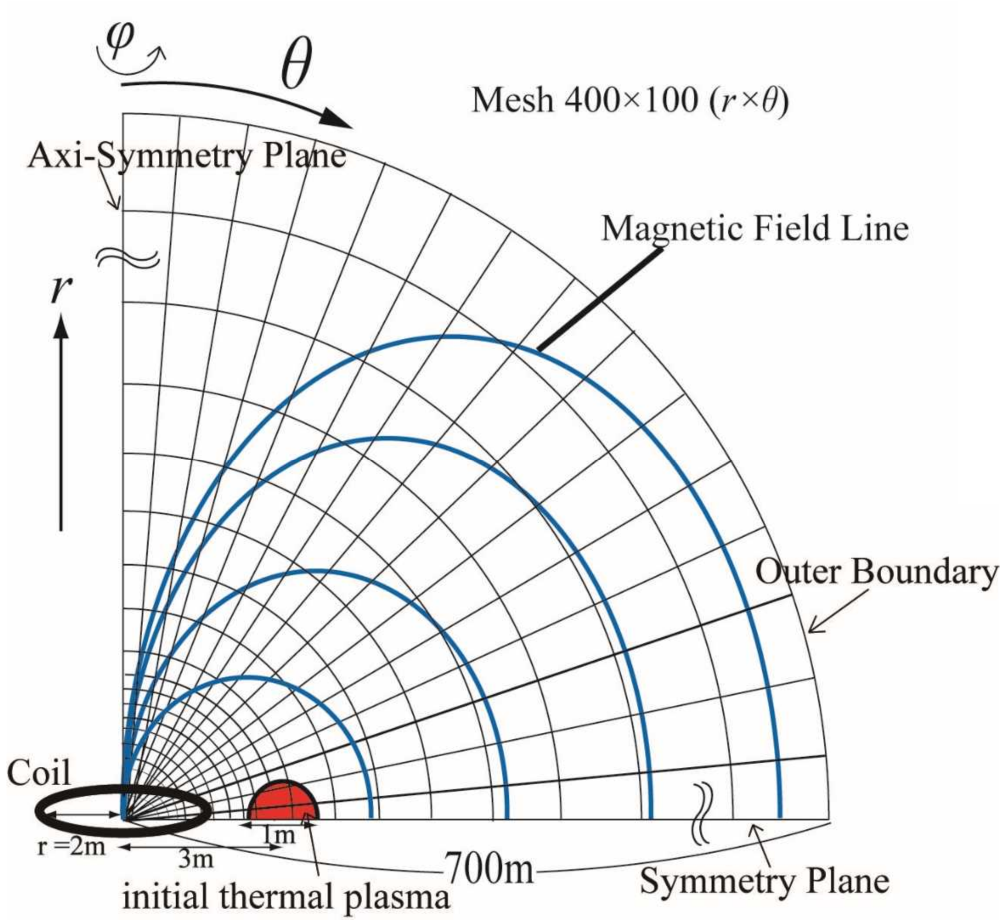
$$\begin{cases} \nabla^2 \mathbf{A} = -\mu_0 \mathbf{J} \\ \mathbf{B} = \nabla \times \mathbf{A} \\ \nabla \cdot \mathbf{A} = 0 \\ \mathbf{E} = 0 \end{cases}$$

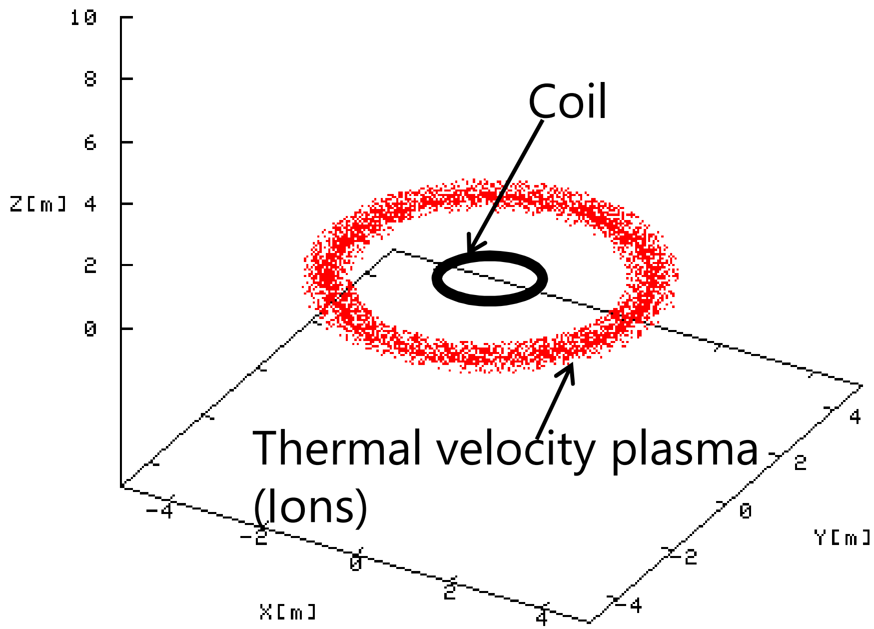




Simulation model (2-D axisymmetric)

- Simulation Models





Initial plasma distribution

- Open system with no outer walls
- Particles that leave the simulation area are replenished

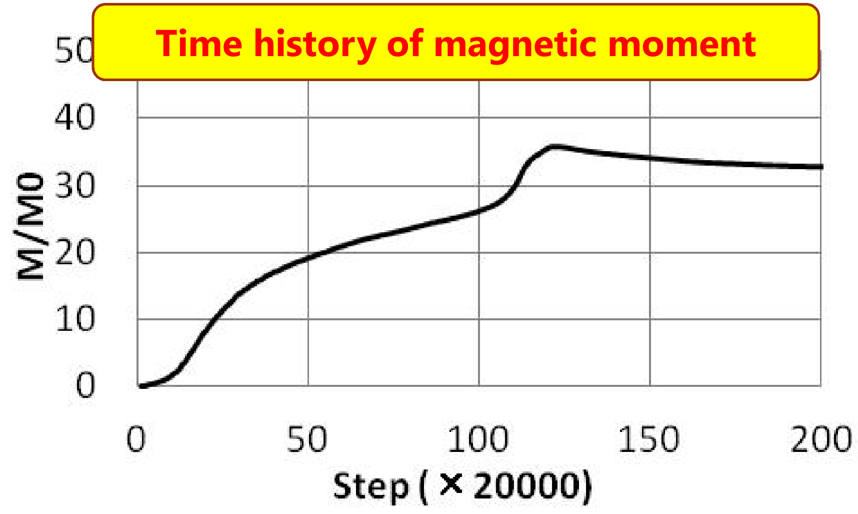
Simulation Parameters

parameters	Values
$\beta_{thermal}$	0.1～100
r_L/L	0.01～1.0
Evaluation	Magnetic moment ratio

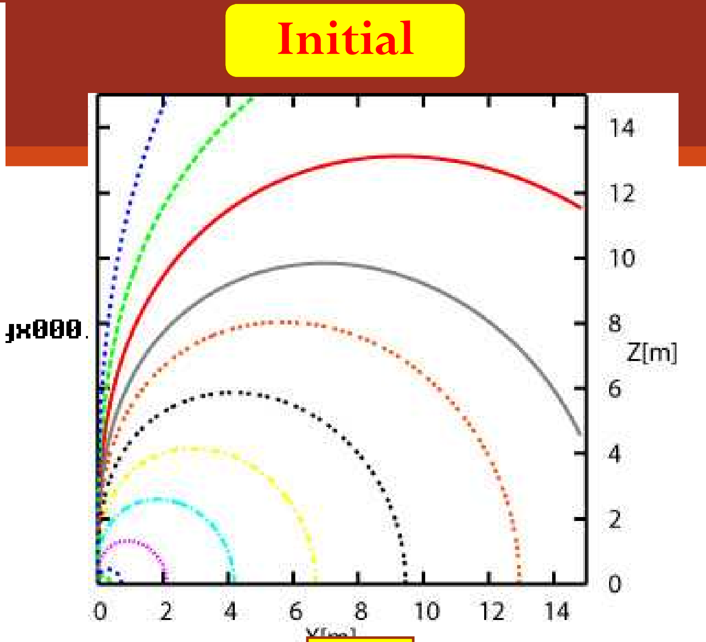
Magnetic moment ratio (definition)
= magnetic moment generated by plasma current / magnetic moment of coil

Si

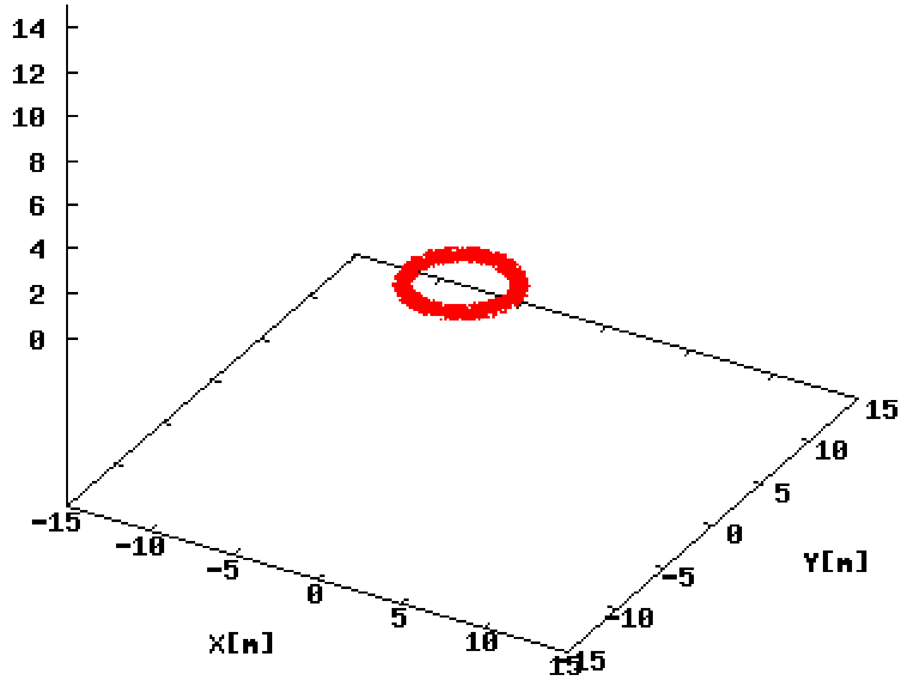
- Ic



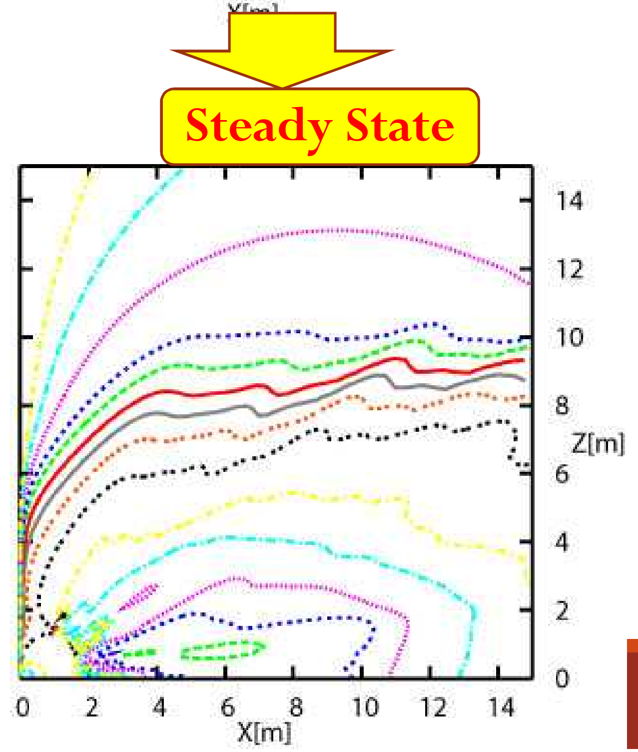
Time history of magnetic moment
M/M0
0
10
20
30
40
50
0
50
100
150
200
Step (× 20000)



Initial
14
12
10
8
Z[m]
6
4
2
0
0
2
4
6
8
10
12
14



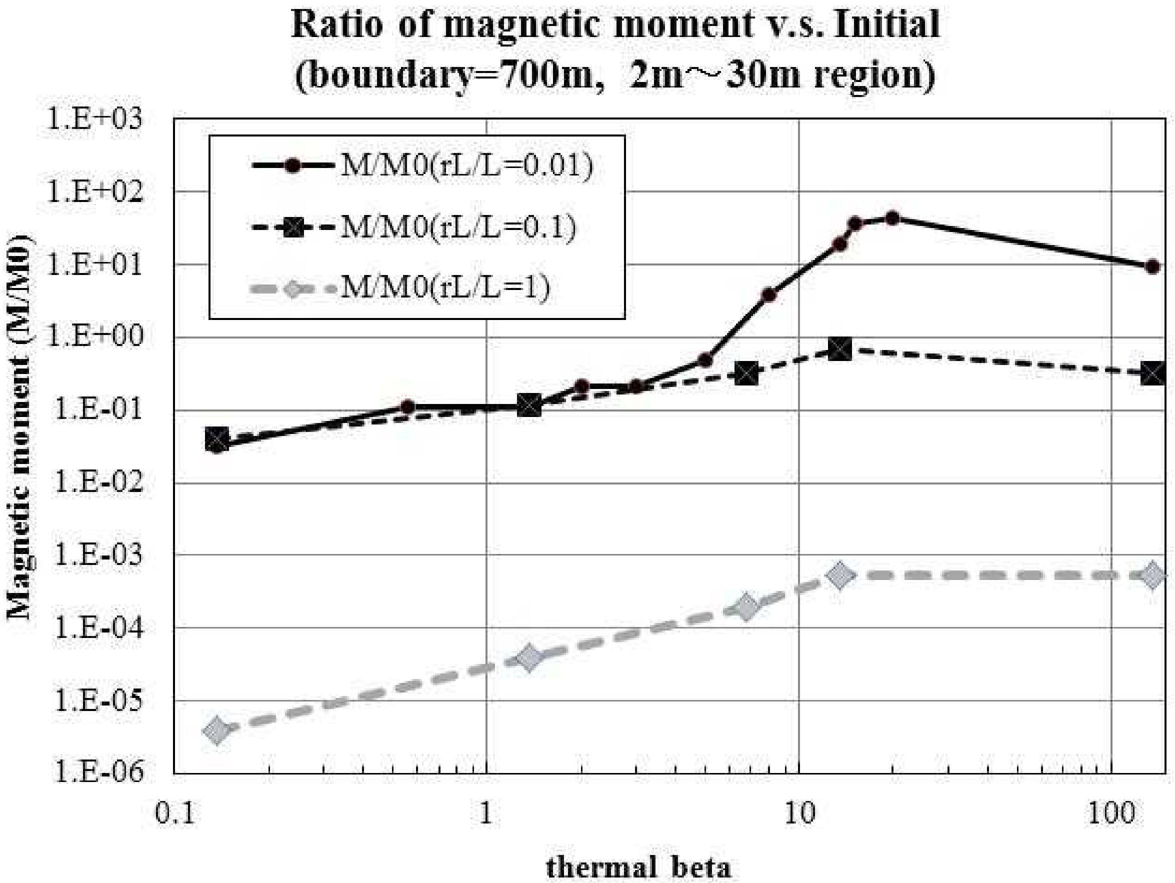
14
12
10
8
6
4
2
0
-15
-10
-5
0
5
10
15
X[m]
15
10
5
0
-5
-10
-15
Y[m]



Steady State
14
12
10
8
Z[m]
6
4
2
0
0
2
4
6
8
10
12
14
X[m]

Simulation Results

- Maximum value: 45 times (β=20, r_L/L =0.01)



Using a coil with r=2 m and current of 10^5 A turn, the magnetic moment is expected to increase by a factor of 45 with a steady-state plasma injection (35 mg/s) of N = 4.4 × 10^{21} [m^{-3}] and T = 1 eV.

Summary of Simulation for Magnetic Shield

- Magnetic shielding and ring currents are used to protect against 1000 MeV cosmic radiation.
  - Coil (radius: 2m, current: 2500[A])
  - Ring current (radius: 10[m], current: 200[A]): magnetic moment 45 times

- Using this value, it is predicted that a cosmic ray of 1000 MeV almost can be reduced.

- On the other hand,
  - the ring-current magnetic field needs to be taken into account.
  - it is necessary to consider the solar wind magnetic field.
  - Chamber experiments for magnetic shield and ring current formation.

Outline :Magnetic Shield

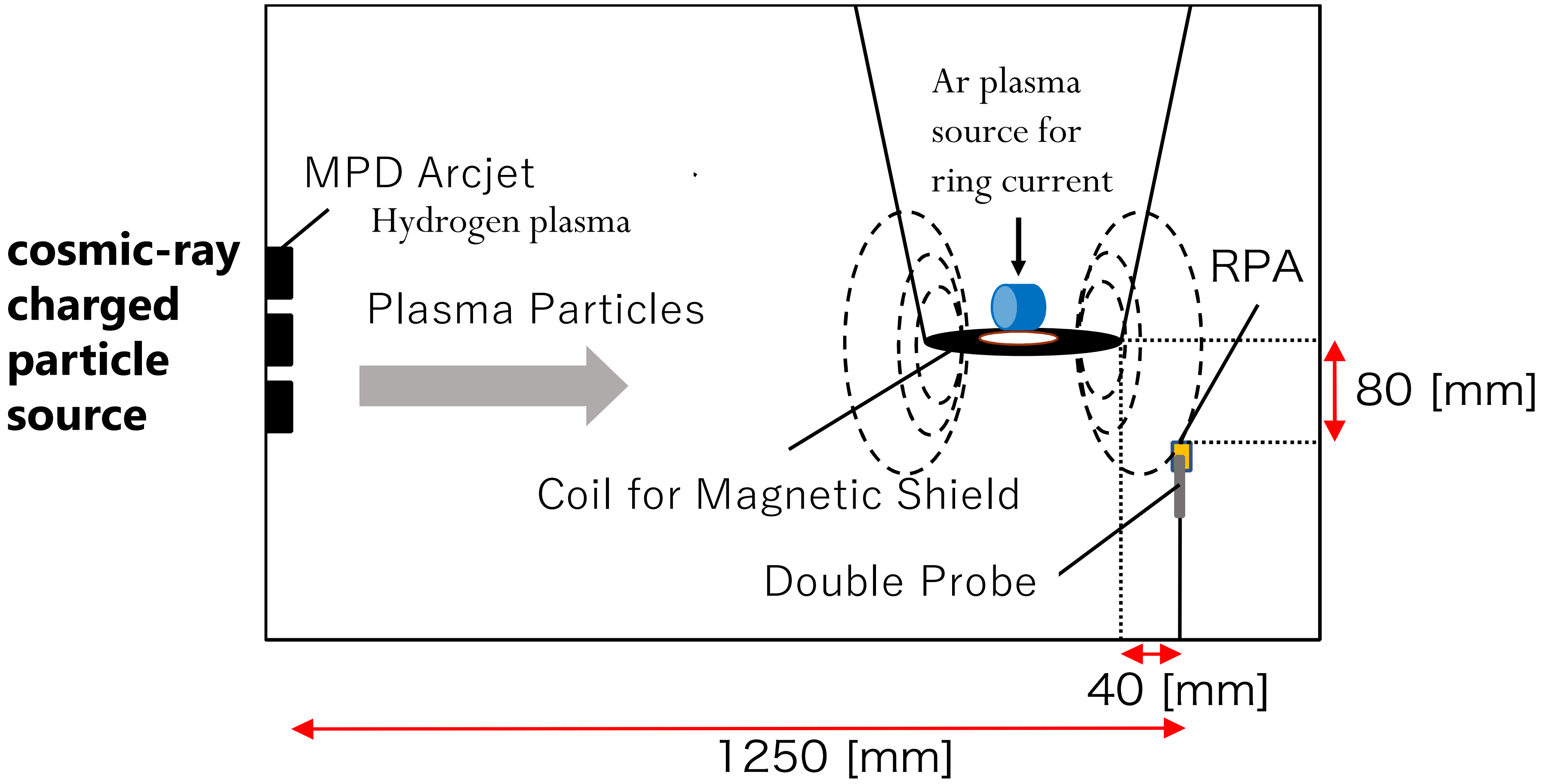
- **Background of the Present Research: Magnetic Shielding**

- **Numerical Simulation for the Evaluation of the magnetic shield performance**

- **Chamber experiment for the Evaluation of the magnetic shield performance**

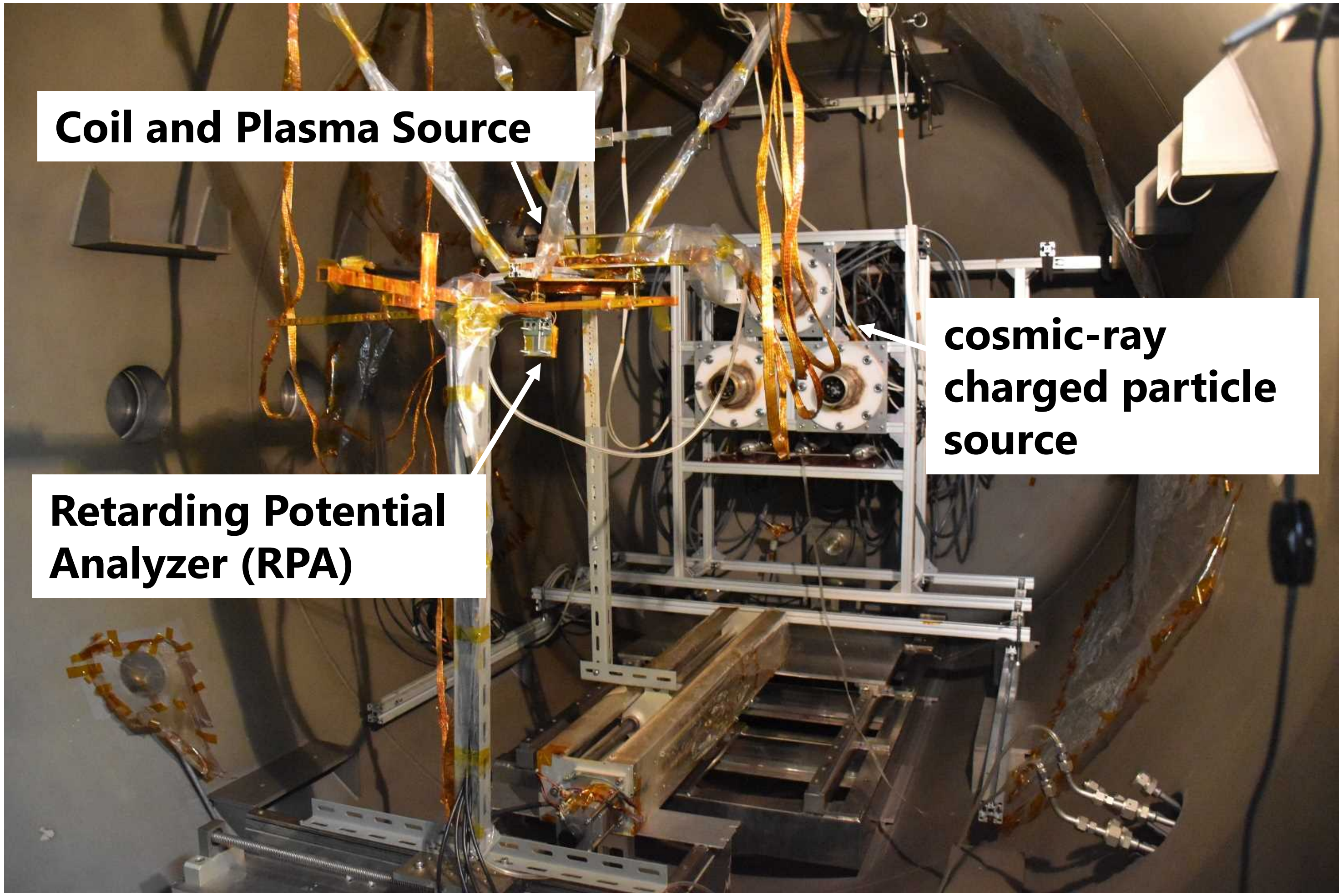
Chamber Experiments

- Schematic diagram of experimental equipment



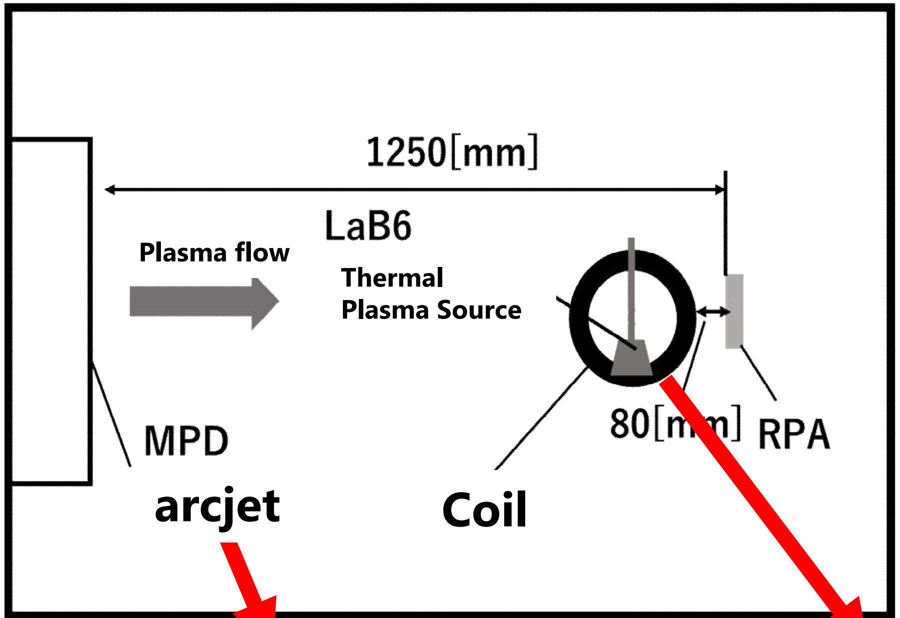
Chamber Experiments

Photograph of experimental equipment

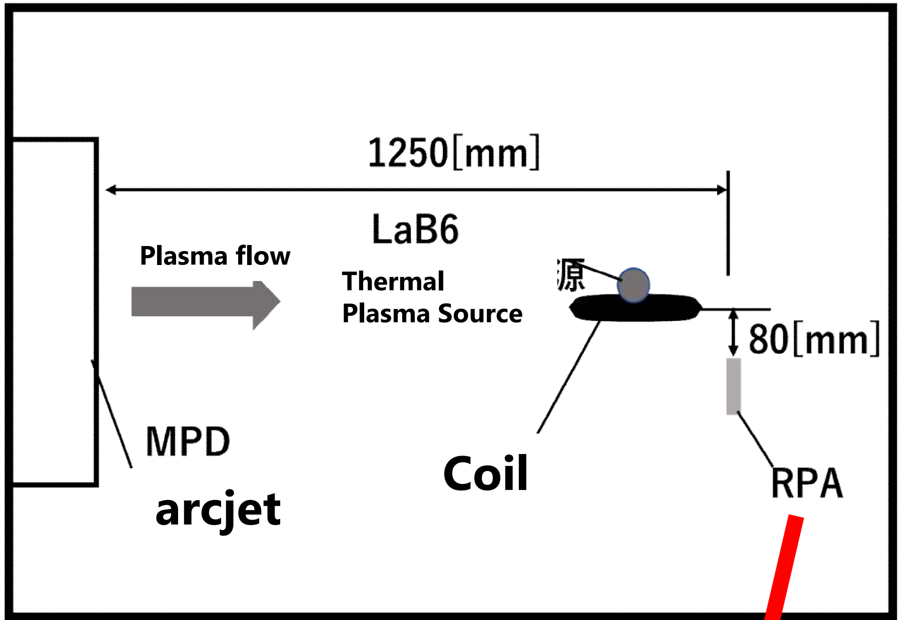


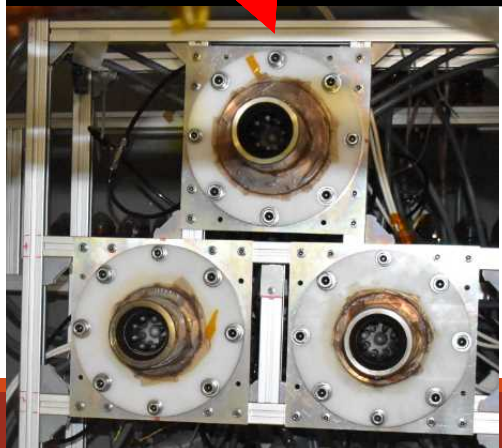
Layout of equipment for experiment

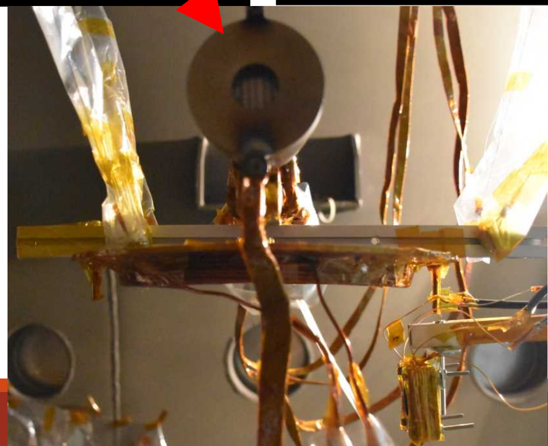
Chamber

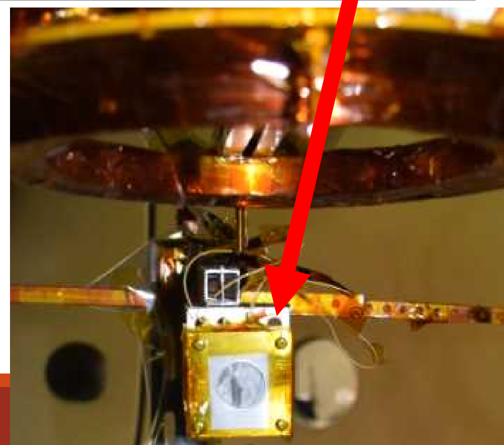


Chamber

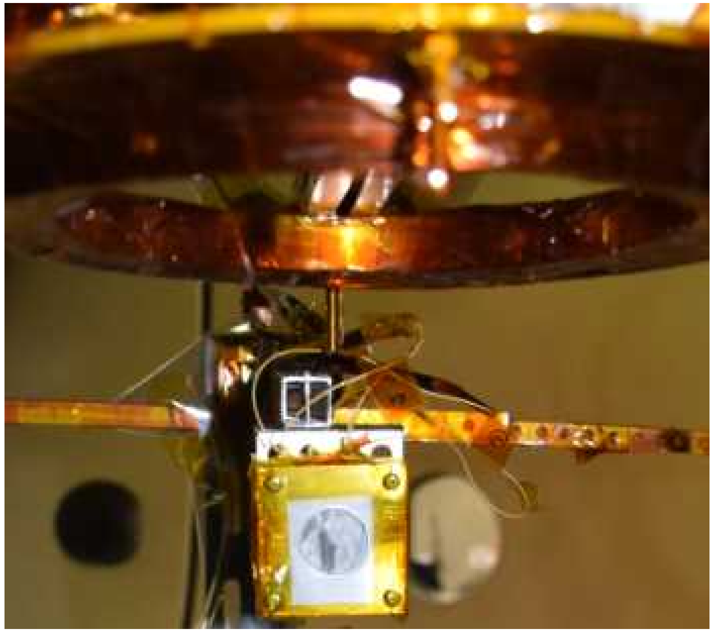


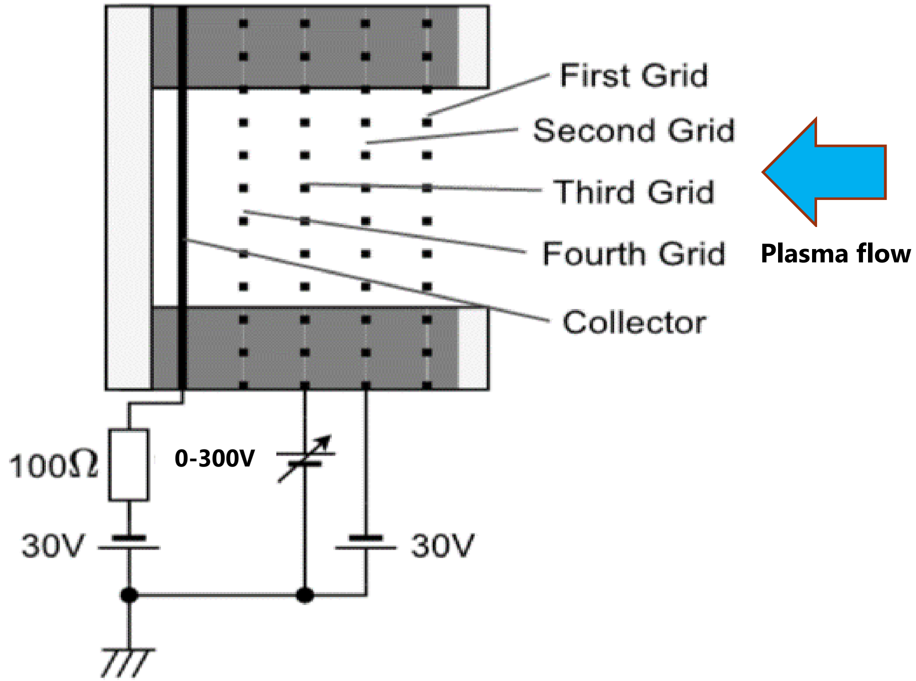


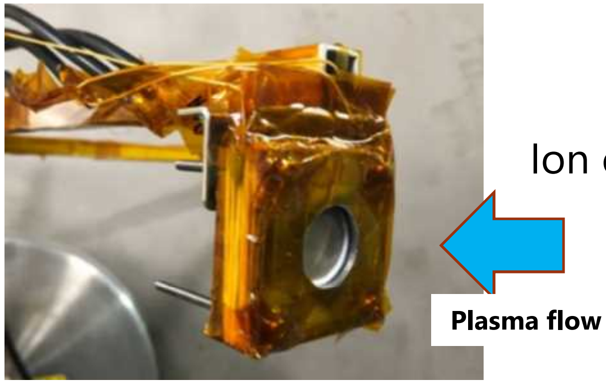




Retarding Potential Analyzer (RPA) for selectively measuring the energy of plasma







Cross-sectional view of RPA

Ion energy distribution function : $f(V) = -\frac{1}{I_{io}}\frac{dI(V)}{dV}$

I_{io} **: Ion current without energy limitation**

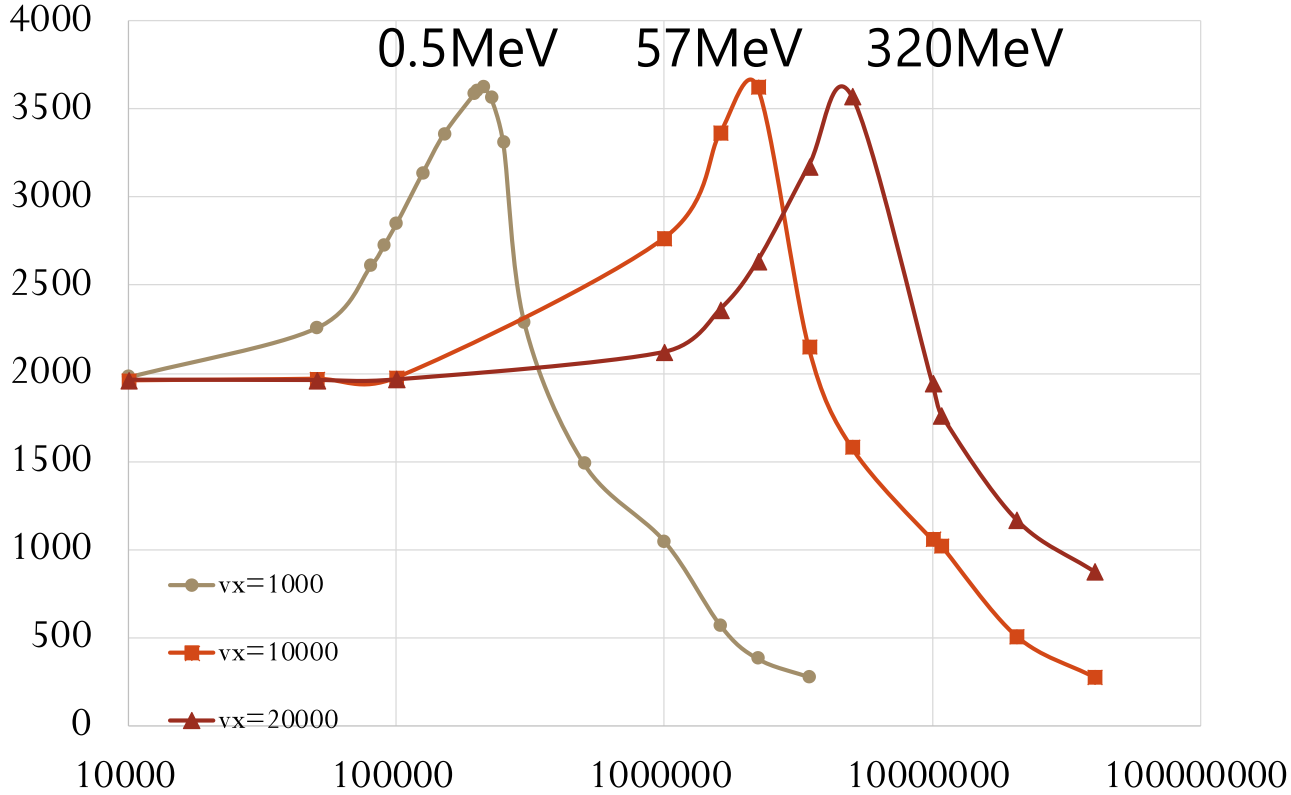
$I(V)$ **: Ion current through a potential**

Demonstration of ring-current formation

MPD voltage[kV]	Coil current [A]	Ar plasma flow rate for ring current [sccm]	Plasma source LaB6 current for ring current[A]
2.0	100	3.0	100

Imaging results during ring current formation
（Parameters of plasma for ring current ：10^{16}[/m^3], 7[eV] ,v_{th}=7[km/s],rL/L～0.02）

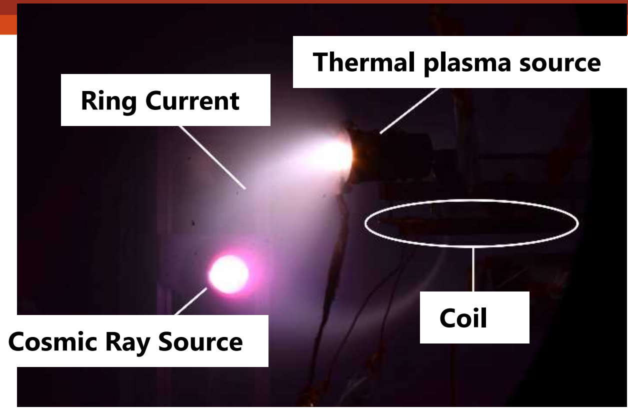
Experimental results of Energy distribution of invaded particles



80eV or less → decrease Shielded by magnetic field

80-200eV → Increase due to trapping by magnetic field

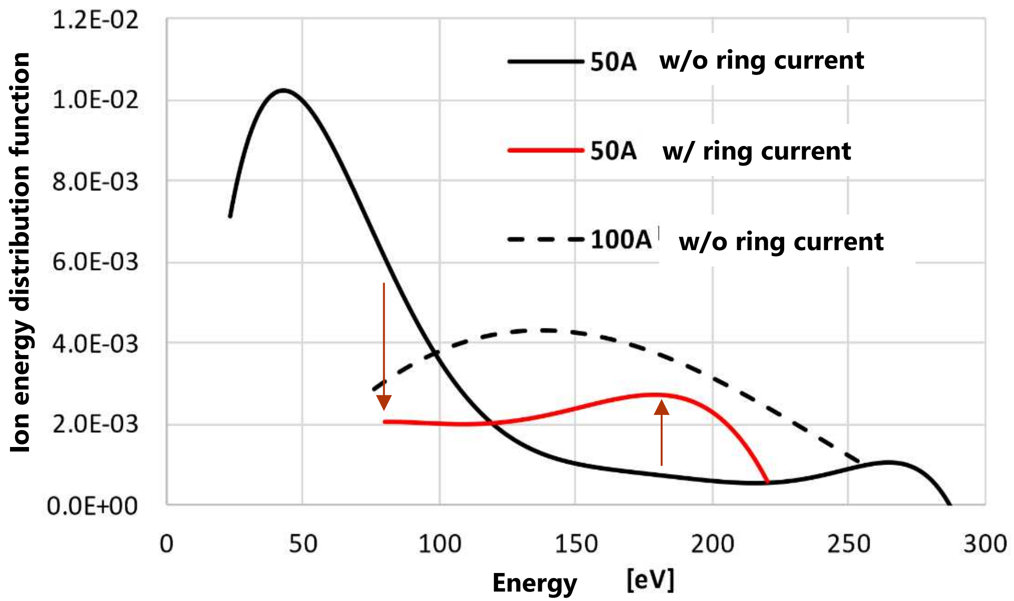
Experimental results with and without ring current (coil current 50 A)



Ring current generation

- **Coil current 50A with ring current**
- **Less than 120eV → Decrease; Shielded by magnetic field**
- **120eV or more → Increased; trapped by magnetic field**

Shielding performance due to the formation of ring current has the same trend as that of increasing coil current

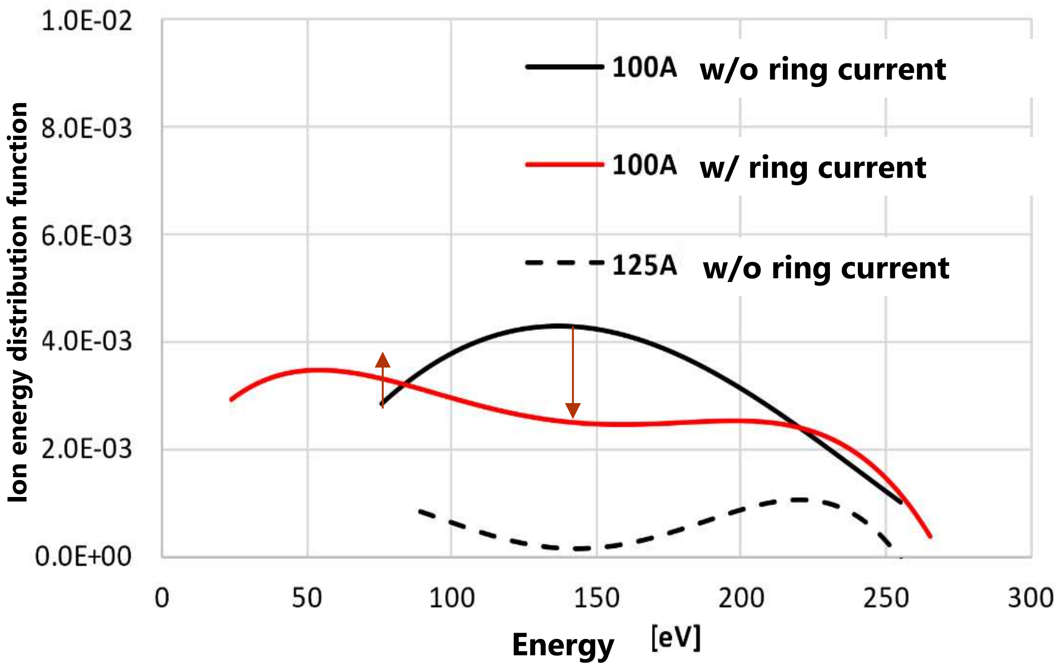


Experimental results with and without ring current (coil current 100 A)

- **Coil current 100A with ring current**
- **Below 80eV → Increase**
- **80eV or more → decrease Shielding from magnetic field**

Because of the stronger magnetic field, even high energies (around 150eV) are shielded.

Ring Current: Same trend as the performance when increasing the coil Current



Summary of Experiments

The energy distribution of charged particles invading a magnetic shield with an additional ring current was observed.

- **Depending on the energy of the charged particles, the behavior of the invading particles was found to be different. The experiment confirmed that low energy particles are shielded, while high energy particles are trapped by the magnetic field and increase.**
- **These results are consistent with the results of the previous numerical analysis.**
- **It was found that using ring current had the same effect as increasing the current in the coil.**

Future Plans

- **Optimization of shield performance by changing parameters of ring current (numerical analysis, experiments)**
- **Measuring the number of invading particles by changing the radiated charged particles and the coil magnetic field; conducting analysis with a 3D hybrid particle model and comparing and verifying the results**

Outline

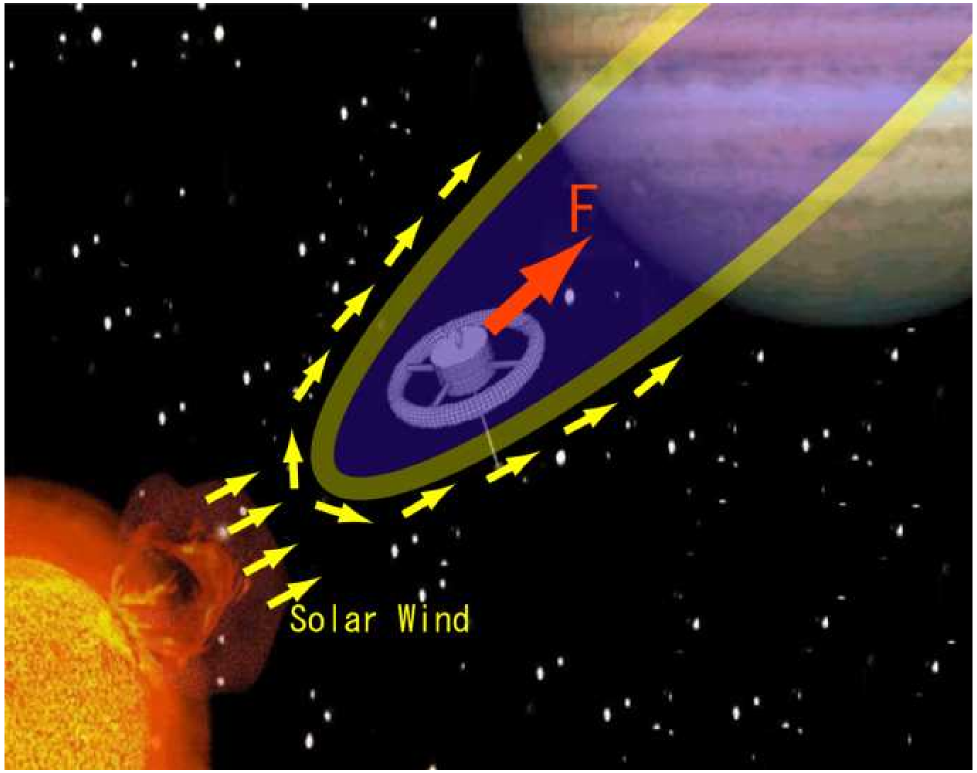
- Self Introduction

- Research on Magnetic Shielding for Protection against Charged Particles of Cosmic Ray

- Research on Magnetic Sails and Magnetic Plasma Sails, which are propelled by receiving solar wind plasma with a magnetic field

Magnetic Sail

- consists of a simple hoop coil
- propulsive force generated by the interaction between the solar wind and artificial magnetic field



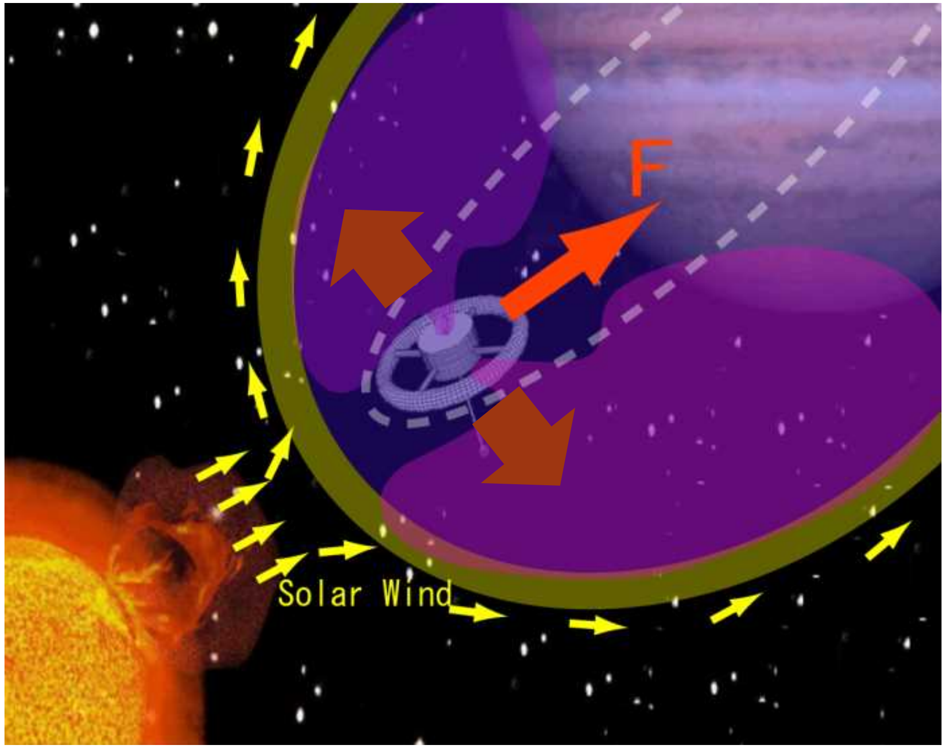
Characteristics

- Propellant less
- Use of solar wind energy (Natural energy)
- Simple structure
- Simple method for changing the thrust vector

- proposed by Zubrin in 1990
- 64km radius of coil, obtain the thrust 20 N

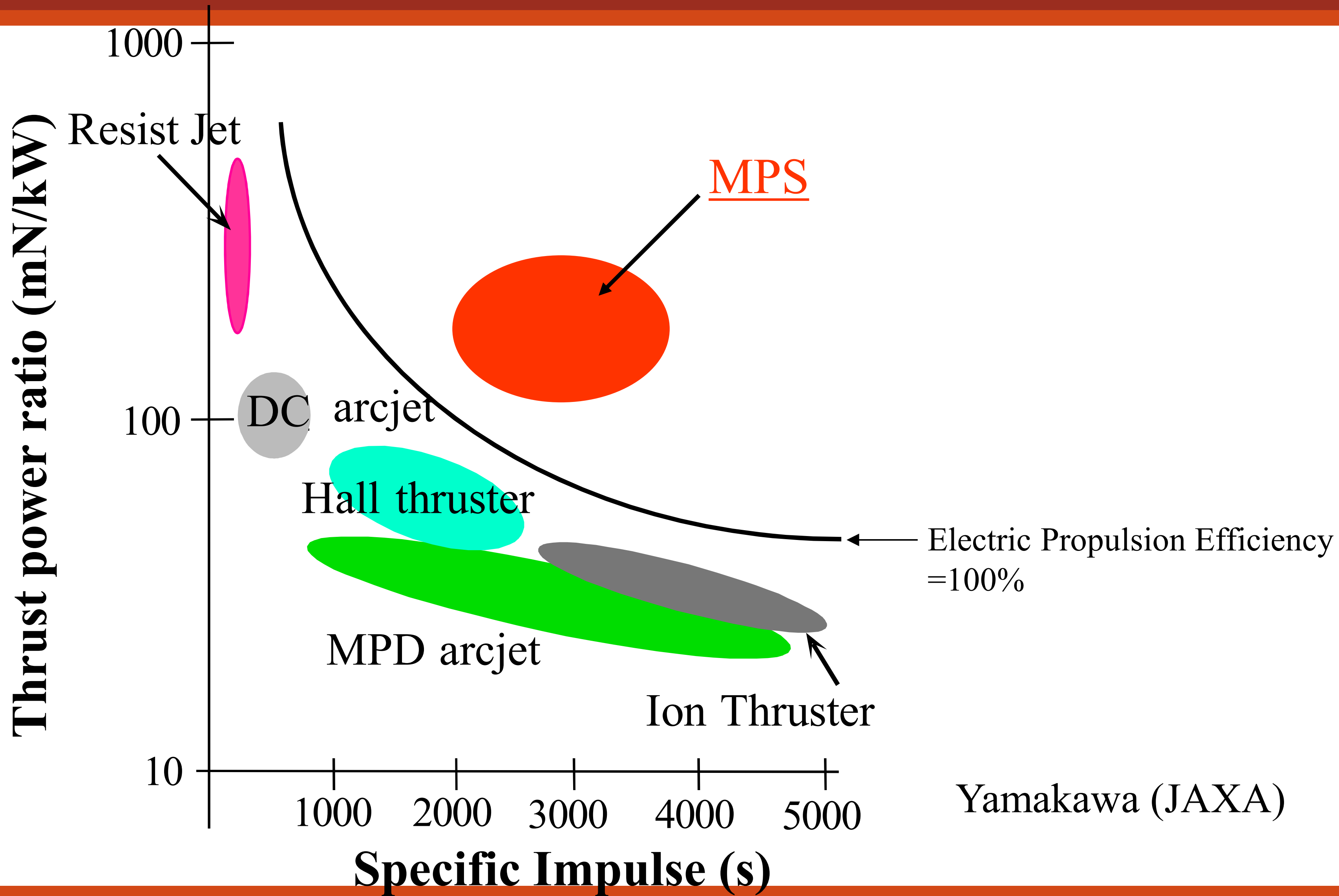
Magsail→Magneto Plasma Sail

- **propulsive force generated by the interaction between the solar wind and inflated magnetic field by plasma Jet injection from the spacecraft**

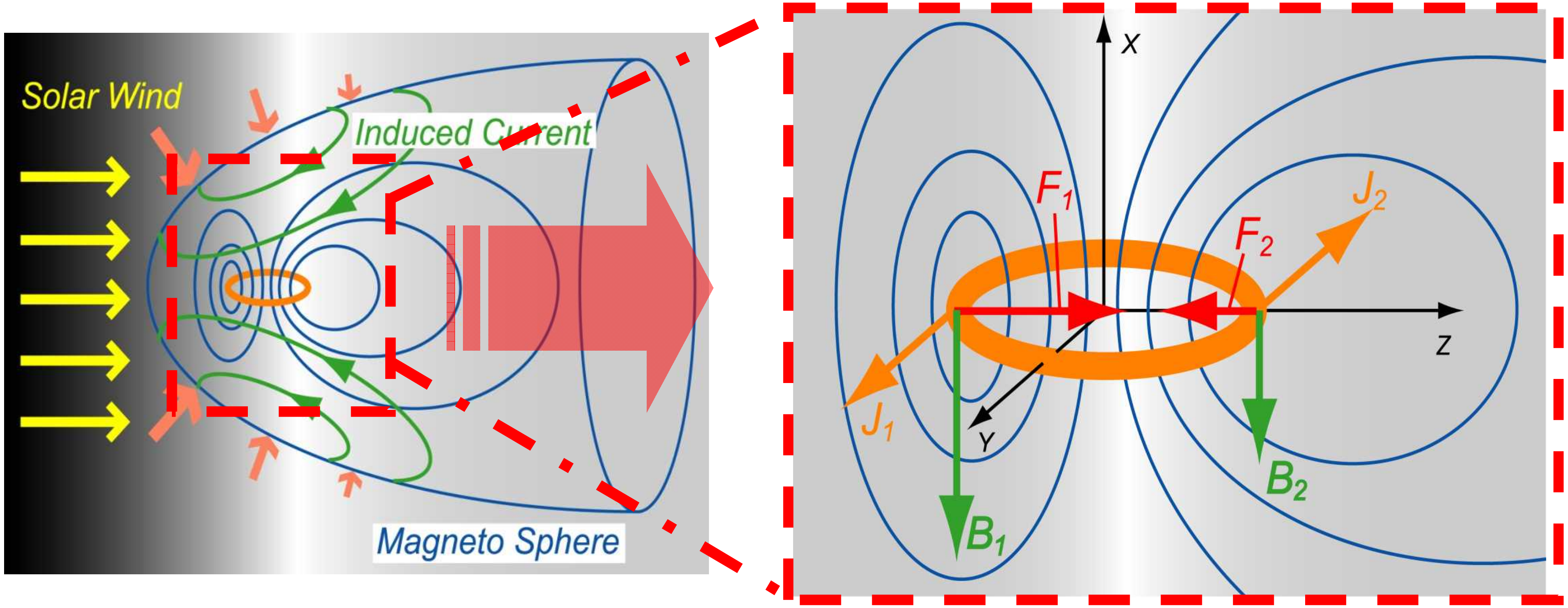


- **Proposed by Winglee (Washington Univ.) in 2000**
- **Redesign by MPS working group in Japan in 2004**
- **Coil size is realistic (∼m), thrust performance :(250mN/KW) is 10 times higher than that of Ion thruster. (To Jupiter, 3.5 year → 2year)**

Thrust performance of electric propulsion



Thrust generation mechanism

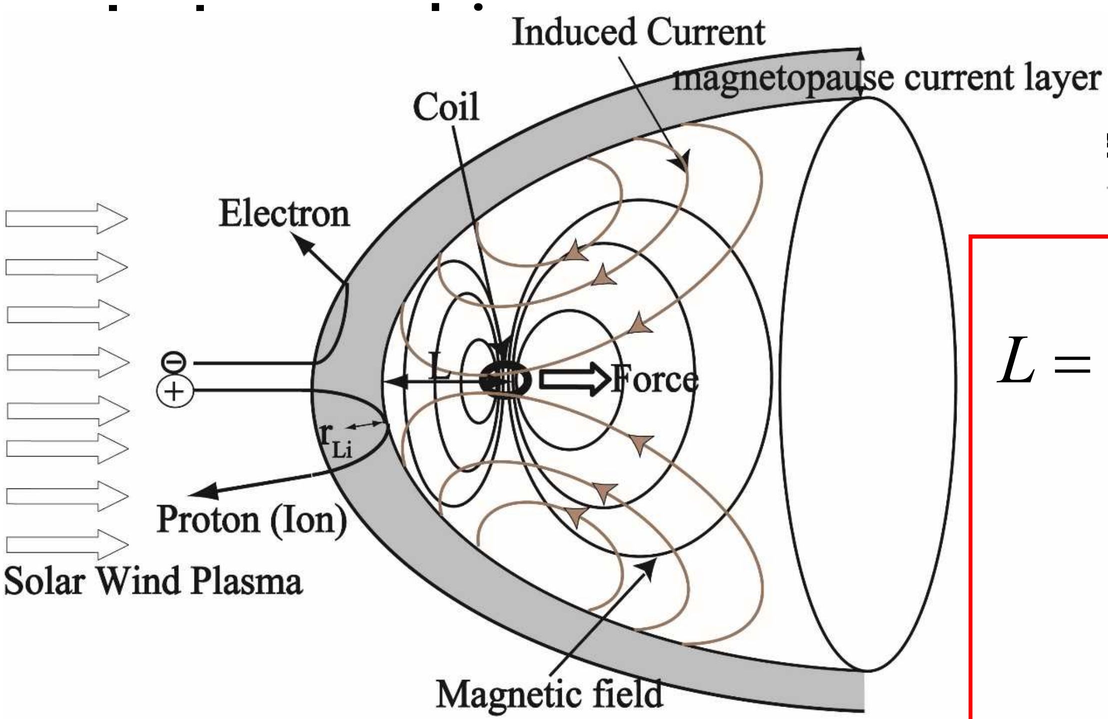


The pressure on the magnetosphere is transferred to the spacecraft via Lorentz force between the magnetic field B_1,B_2 generated by the induce current and the current J_1,J_2 along the coil of the spacecraft.

$F \propto$ Induced B $\propto$ Induced J $\propto$ <u>Size of Magnetosphere</u>

Interaction : Solar wind and Magnetic field

- **Definition of L**
  - **pressure balance between the dynamic pressure of the solar wind and the magnetic pressure.**
  - **F (Thrust) strongly depends on the area of magnetosphere S (= πL^2).**



-> Ion kinetic Scale)

ons have been

$$L = \sqrt[6]{\frac{M^2}{8\pi^2 \mu_0 n m v_s^2}}$$

M: magnetic moment,

n: density of solar wind

m ： mass of hydrogen ion

v_s ： velocity of solar wind

Hybrid Particle-In-Cell code

- **Basic equations**

Ion momentum equation

$$m_i \frac{d\mathbf{v}_i}{dt} = Ze(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) \qquad \frac{d\mathbf{x}_i}{dt} = \mathbf{v}_i$$

Electron momentum equation

$$n_e m_e \frac{d\mathbf{v}_e}{dt} = -en_e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B} + \eta\, \mathbf{J}) - \nabla P_e$$

Ampere's law (Darwin Approximation)

$$\nabla \times \mathbf{B}_p = \mu_0(\mathbf{J}_e + \mathbf{J}_i)$$

Faraday's law $\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$

Current density $\mathbf{J}_e = -en_e\mathbf{v}_e, \mathbf{J}_i = en_i\mathbf{v}_i$

Position of each particle $x_i^{n+1} = x_i^n + \mathbf{v}_i^{n+1/2}\Delta t$

Position of each velocity $\mathbf{v}_i^{n+1/2} = \mathbf{A}^{-1}\mathbf{S}$

Electric field (Plasma Region)

$$\mathbf{E}^n = \frac{1}{n_i}\left\{\frac{1}{\mu_0 Z_e}(\nabla \times \mathbf{B}_p^n) \times \mathbf{B}^n - \frac{1}{Ze}\mathbf{J}_i^n \times \mathbf{B}^n - \frac{T_e}{e}\nabla n_i^n\right\}$$

Electric field (vacuum region)

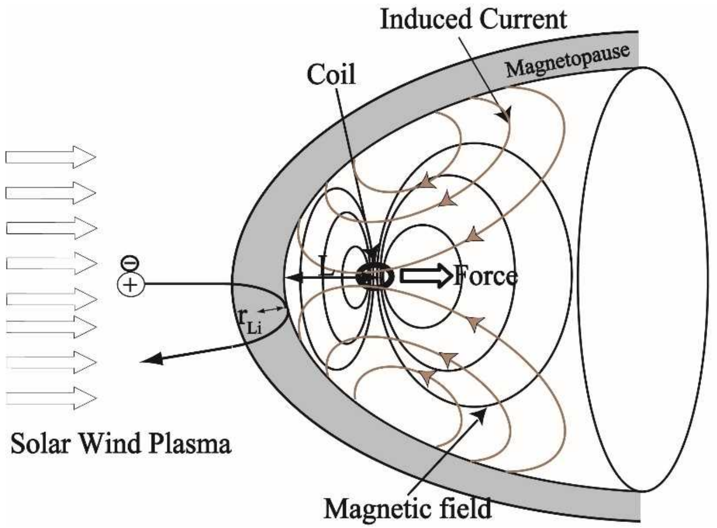
$$\nabla^2 \mathbf{E} = 0$$

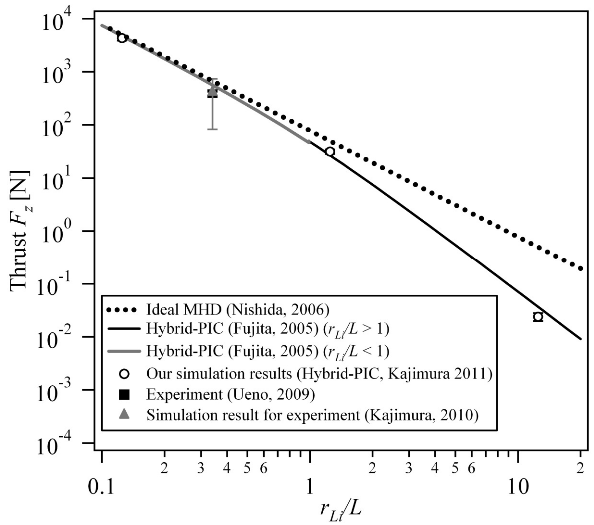
Electron energy equation is not used.
(Te=const)

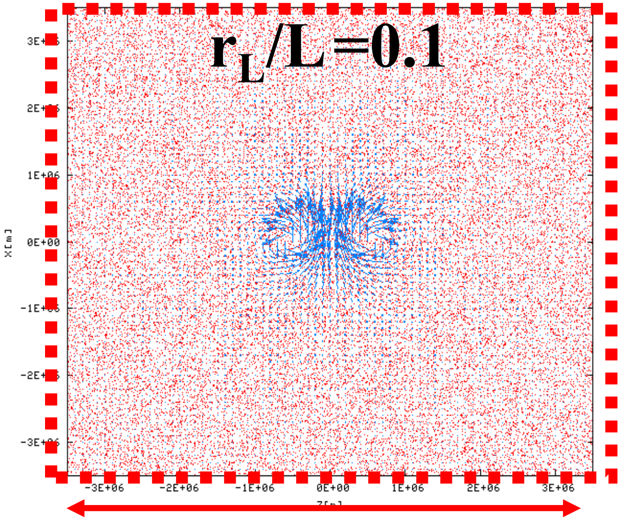
Ion particle : Leap-Frog method
EM field: CAM-CL method (By Matthews)

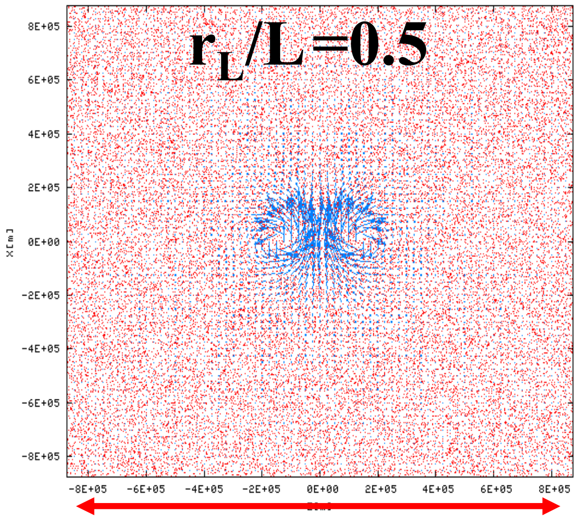
Harned, D. *Journal of Computational Physics*, Vol. 47, No. 3, 1982, pp. 452-462.

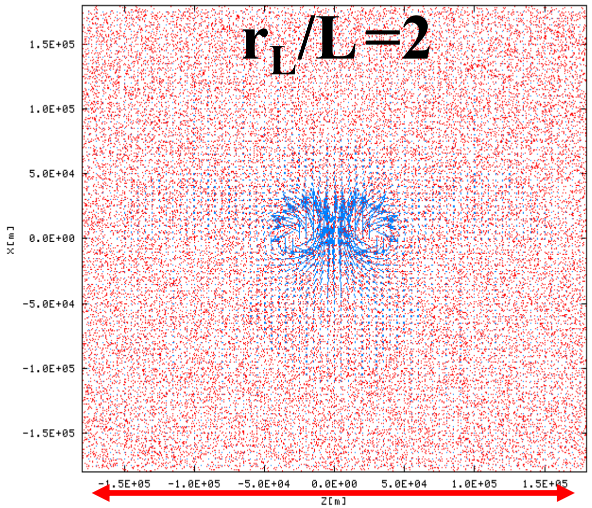
Thrust evaluation of Magnetic sail





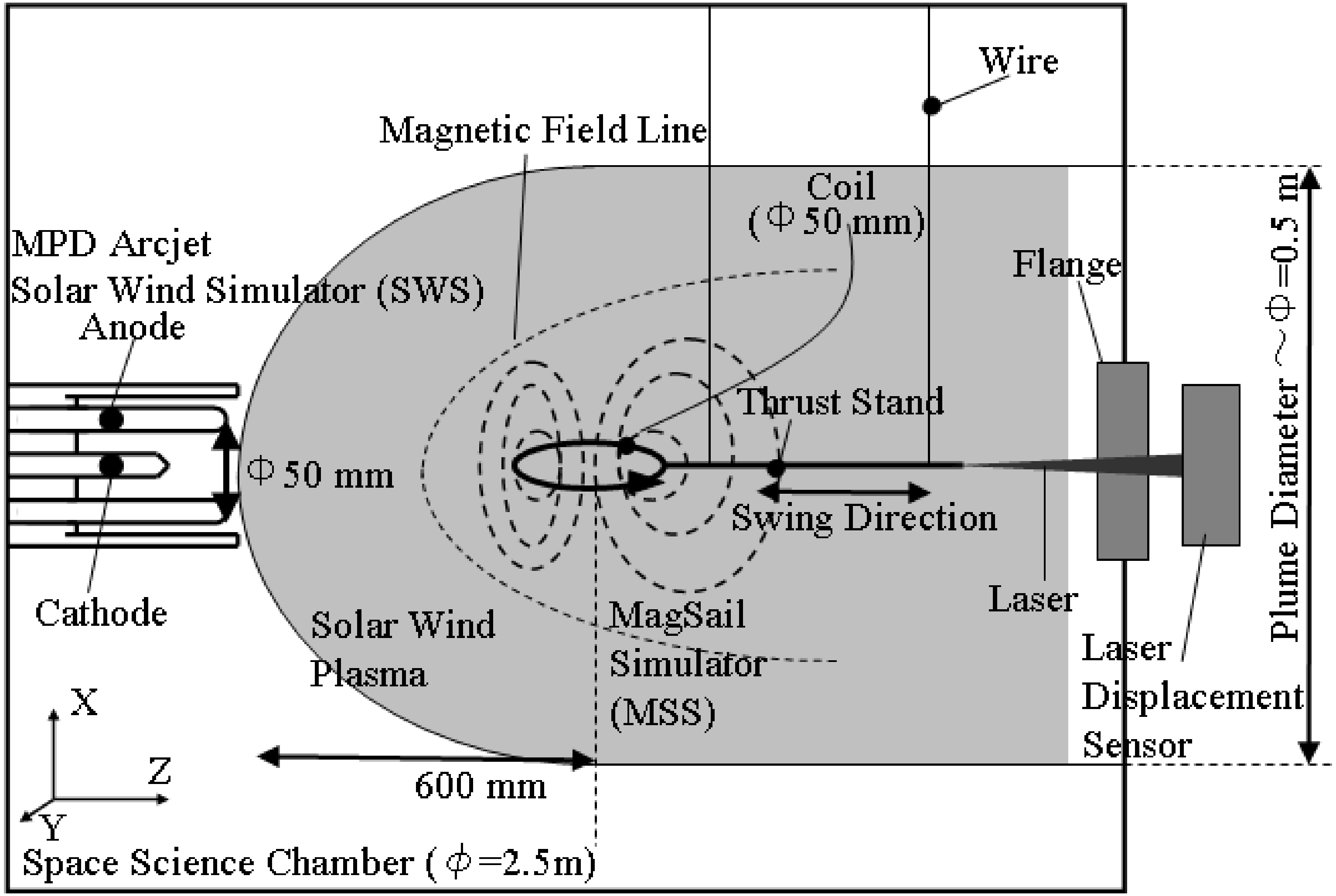




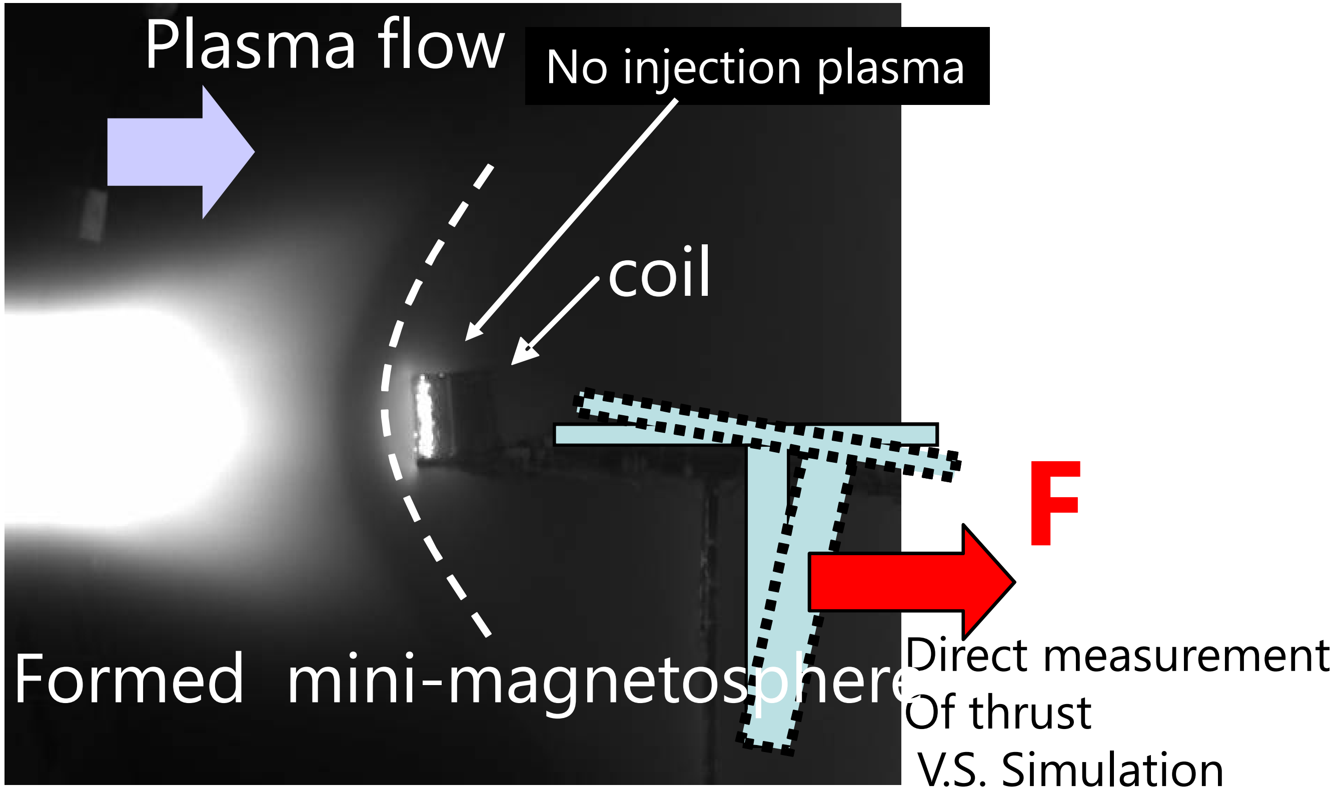


*Y.Kajimura, Journal of Propulsion and Power, Vol. 26, No. 1, January–February (2010), pp. 159–165.

Ground Experiment in JAXA



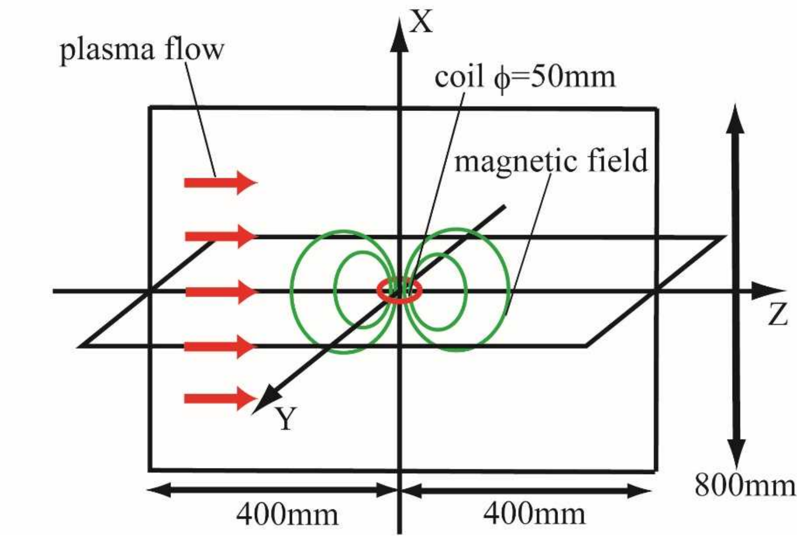
Ground Experiment in JAXA



Direct measurement of the thrust obtained from certain size of magnetosphere (assumed to be already inflated)

K. Ueno, Technical Note, JOURNAL OF PROPULSION AND POWER Vol. 25, No. 2, 2009.

Simulation model and parameters

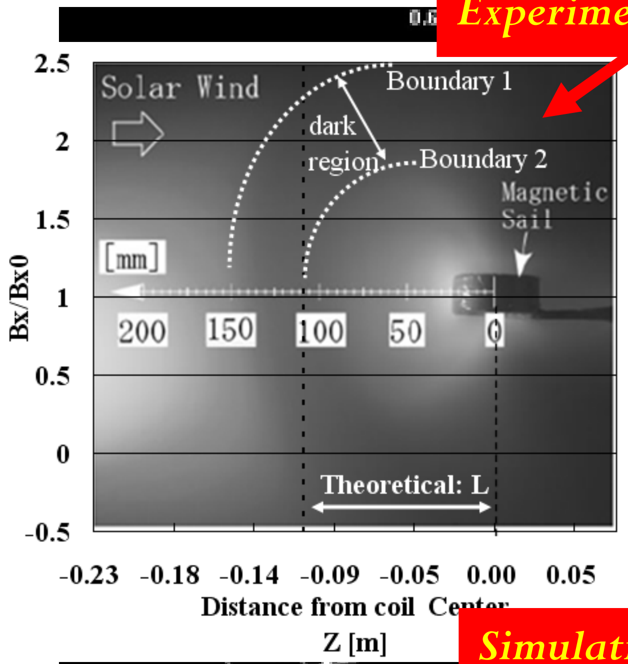


Simulation parameters	
dx	0.1 c/ω_{pi}
dt	0.01 $(1/\omega_{ci})$
Number of particles per cell	150 /cell
Mesh number	80*80*80

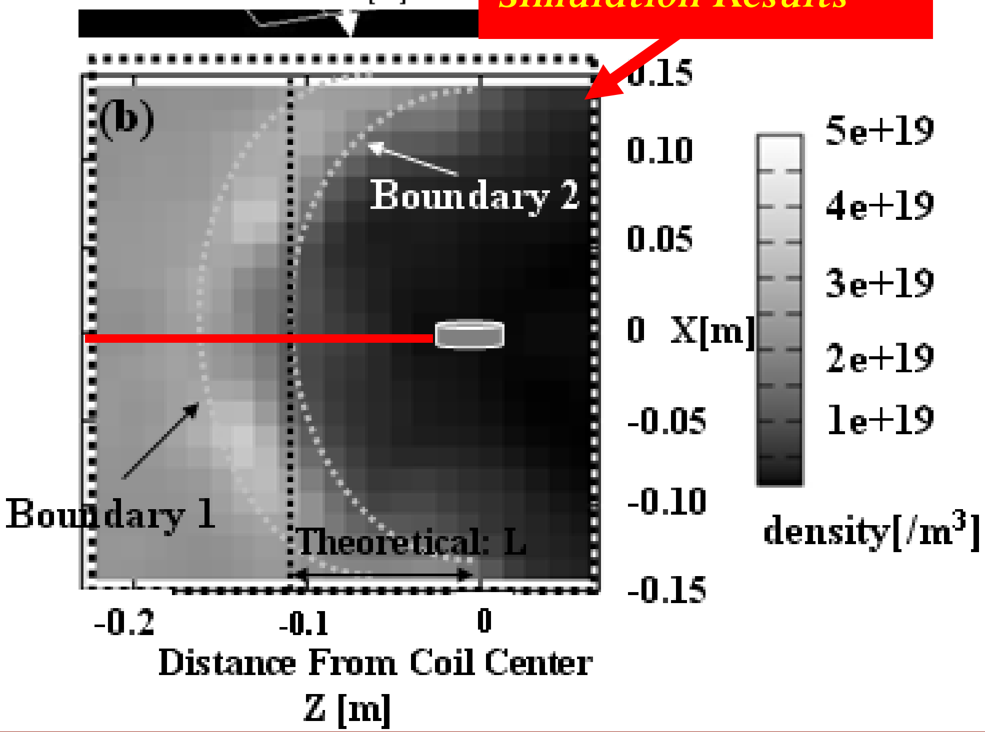
Parameters	Laboratory experiment	Space	Simulation
Solar wind parameters			
Plasma	Proton	Proton	Proton
Velocity : u_{sw} , km/s	25±7	400	25
Density : n_{sw} , m^{-3}	1.2e+19 ± 4.7e+17	5.0E+06	1.2E+19
Electron temperature : T_e , eV	0.9	10	0.9
Ion temperature : T_i , eV		30～70	0.9
Mass flow rate, g/s	0.4		0.4
Electric conductivity, /Ωm	2000		2000
Coil parameters			
Coil radius, m	0.025		0.025
Coil current, A	210		210
Number of turns	20		20
B -field at the center of coil, T	0.11		0.11
representative size of magnetosphere : *L* , m	0.066	120,000	0.066
Dimensionless parameters			
Mach number	3	8	3
Ratio of Ion Lamor radius to *L*	0.83	0.83	0.83
Magnetic Reynolds Number: *Rm*	<15	1.0E+08	<15

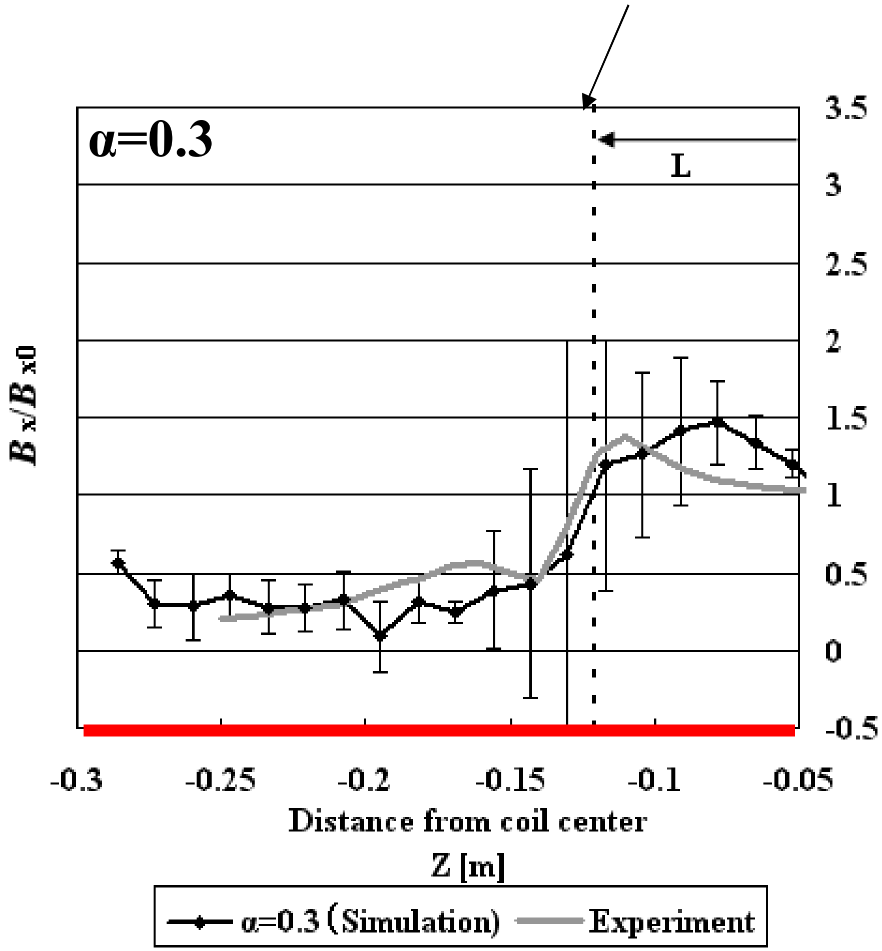
Simulation and Experimental Results (Magnetic field)

Experimental Results

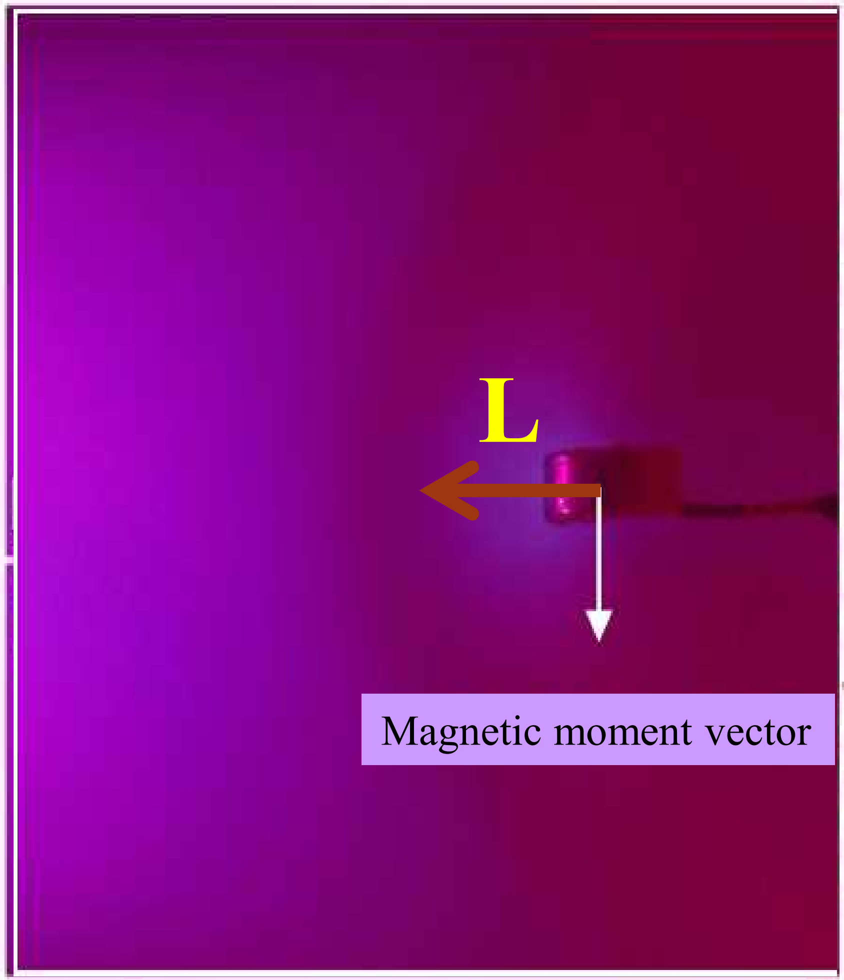


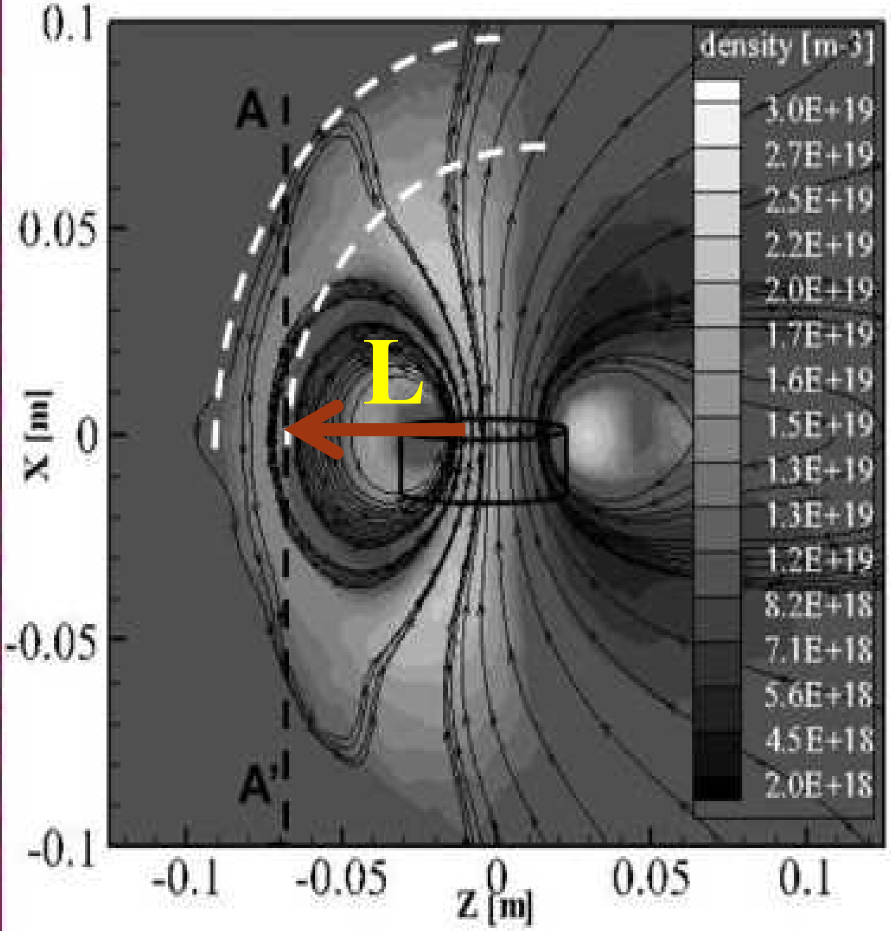
Simulation Results





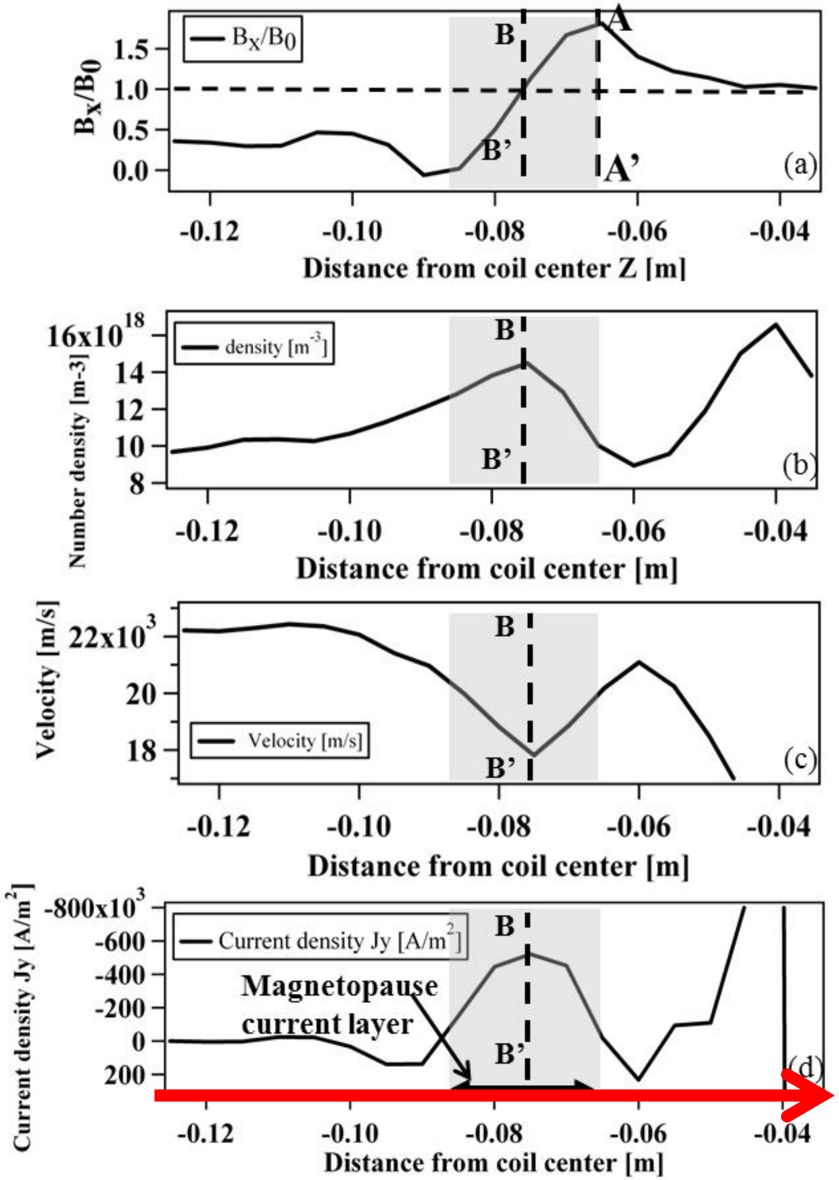
Result: Experiment vs. Simulation



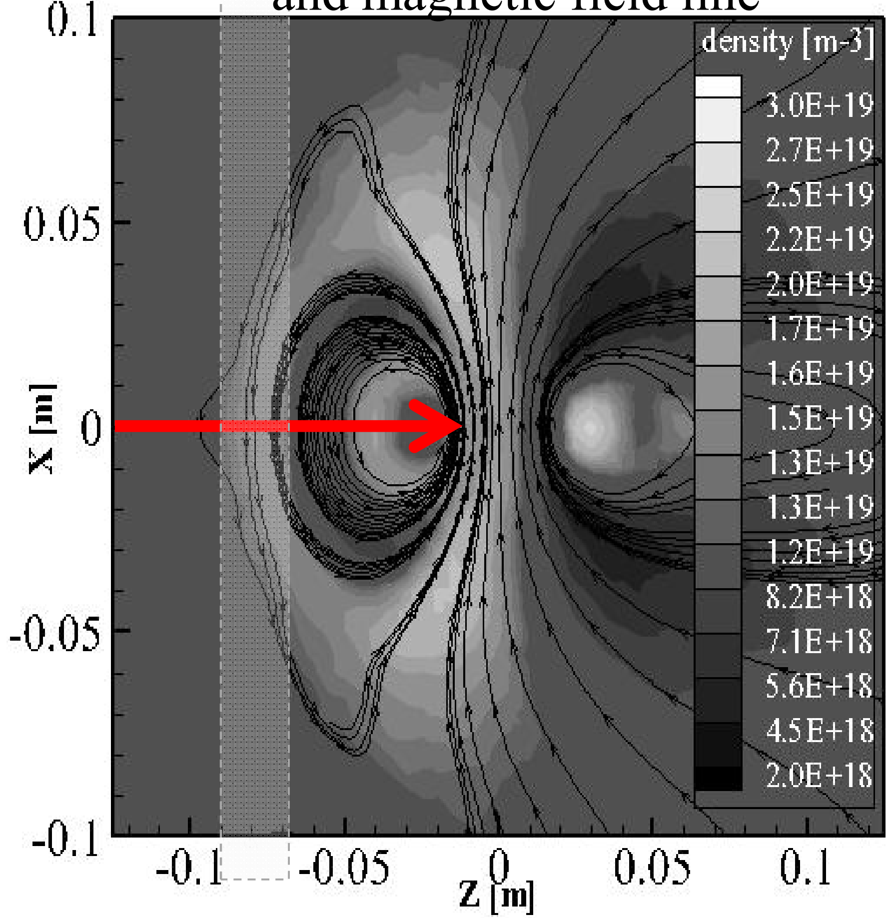


- **Size of magnetosphere L → good agreement**
- **What happened in dark region? →plasma density is high**

Simulation Result



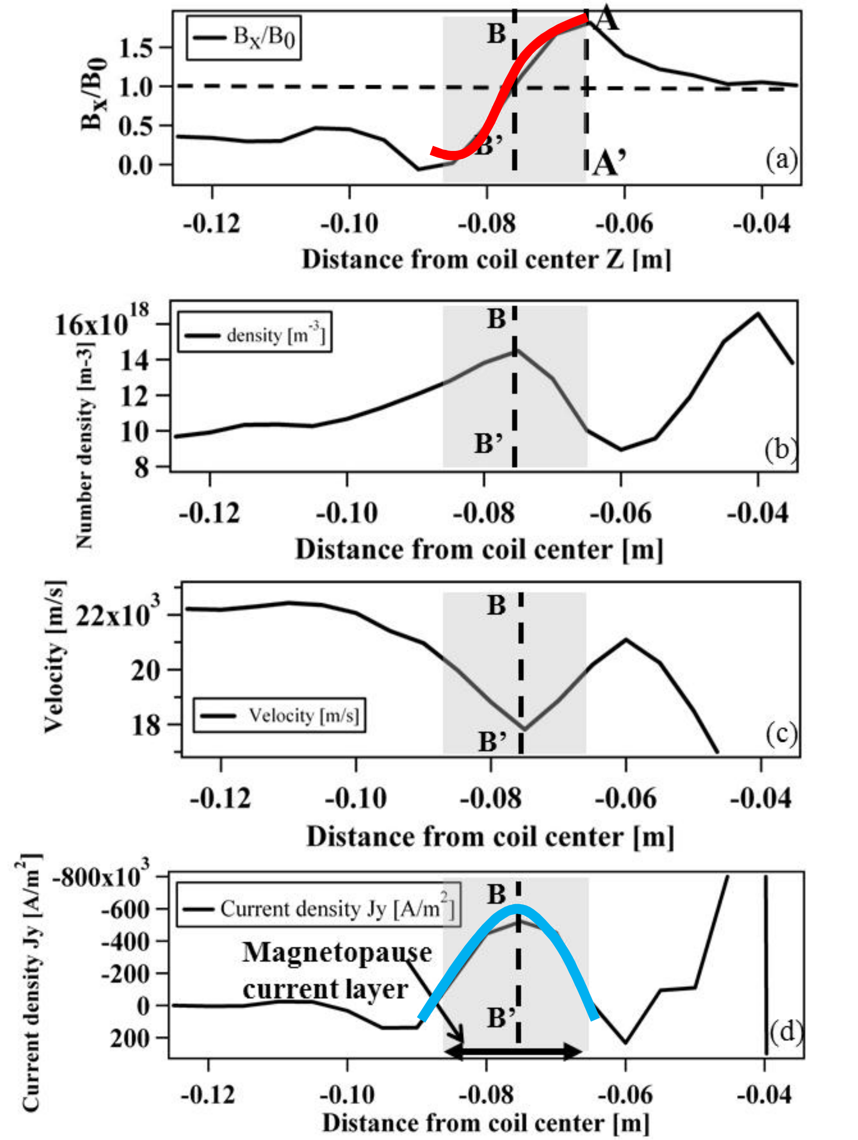
Contour plot of Ion Number density and magnetic field line



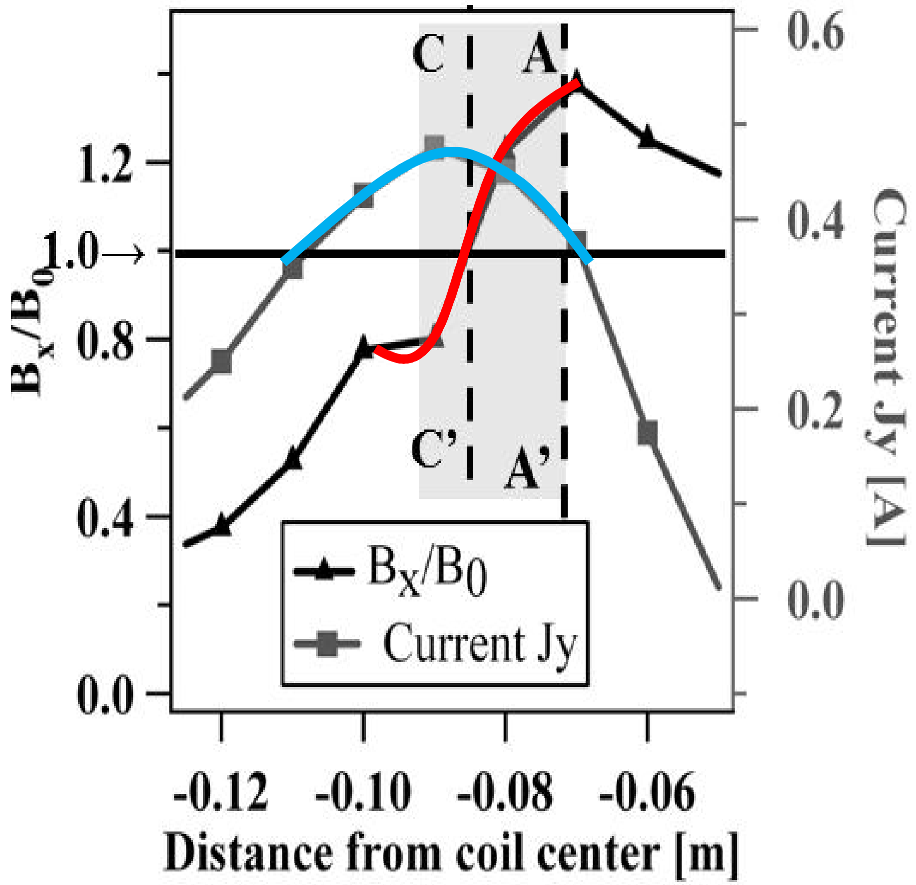
- B-field
- Number density
- Velocity, Current density

Simulation and Experimental Results

Simulation



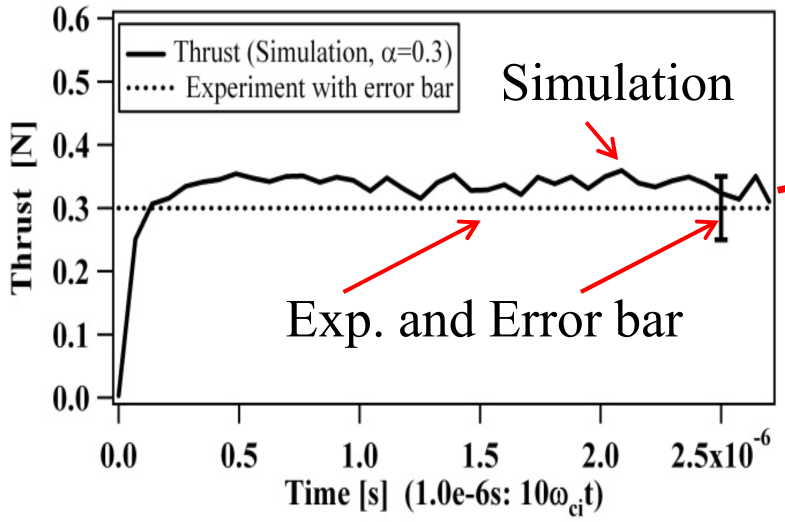
Experiment

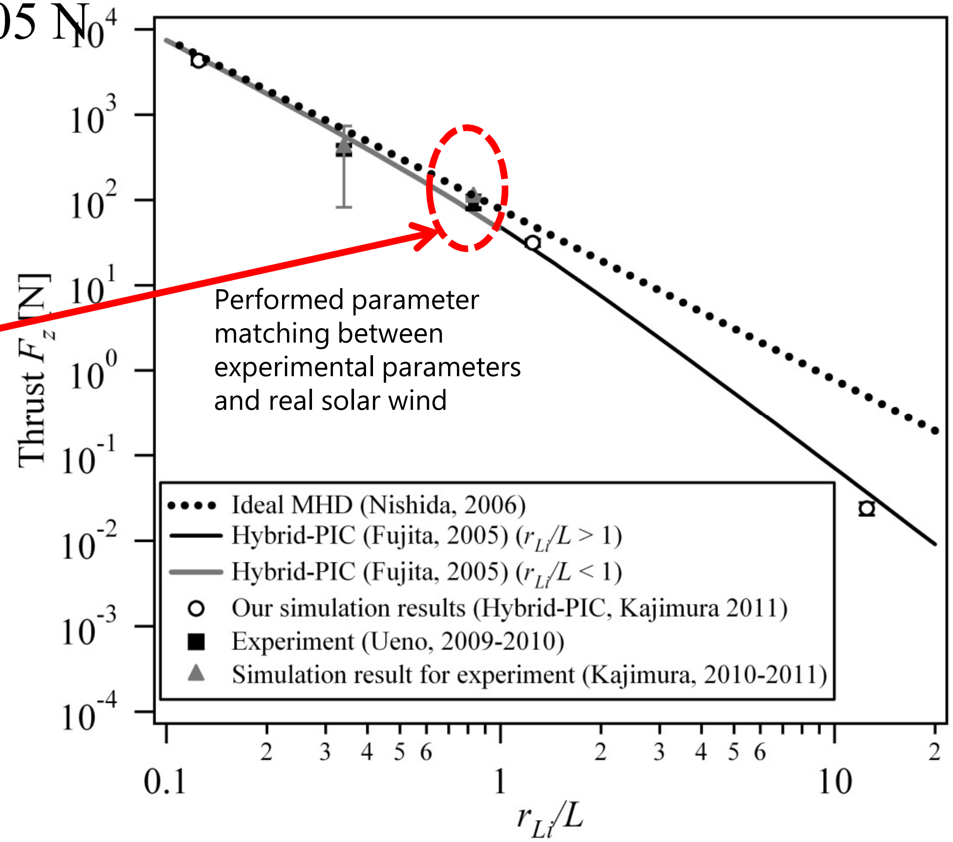


- B-field
- Current density

Simulation and Experimental Results

- Direct measurement in Exp 0.3 ± 0.05 N
- Simulation Result: 0.34± 0.01 N

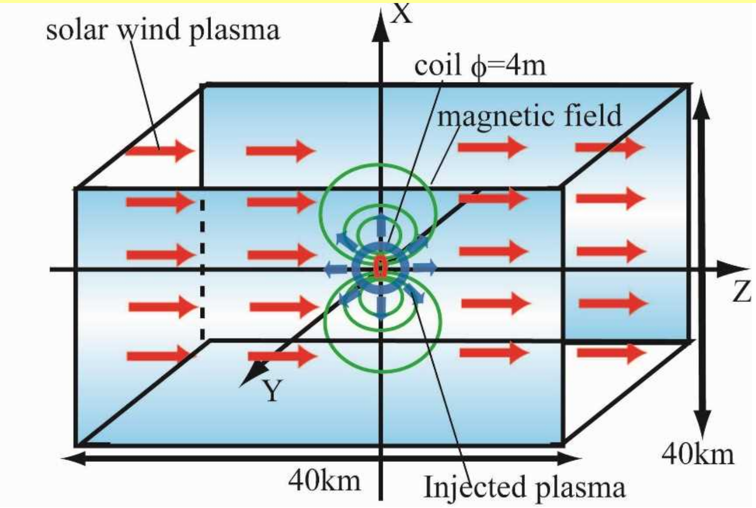




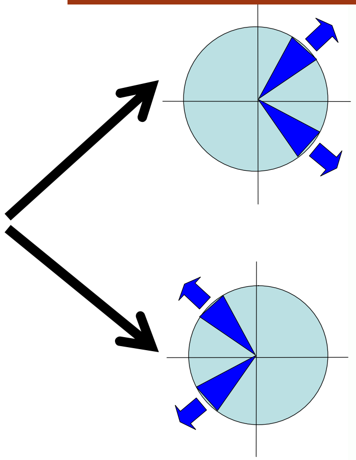
The time averaged value of the thrust in the simulation **is 0.34± 0.01 N** which is within the error of the experimental result, **0.3 ± 0.05 N**. The ion-neutral collision is one of the important issues that influence the difference between the experimental and simulation results. (w/o collision : F_simulation=0.4N)

Thrust estimation of magnetic plasma sail

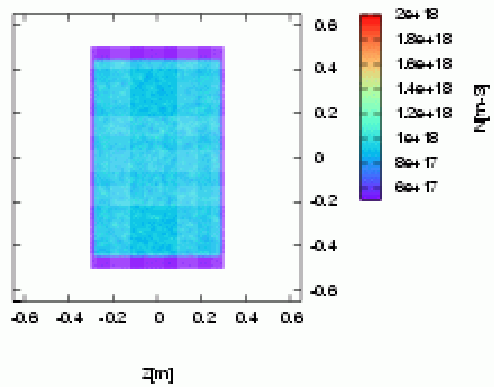
Magnetic Sail(r=2m 10^6AT, L=1.6㎞,0.2mN

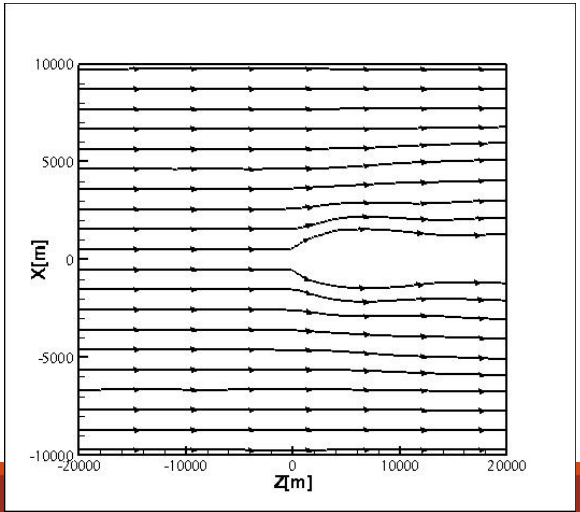


Injection direction, injection volume



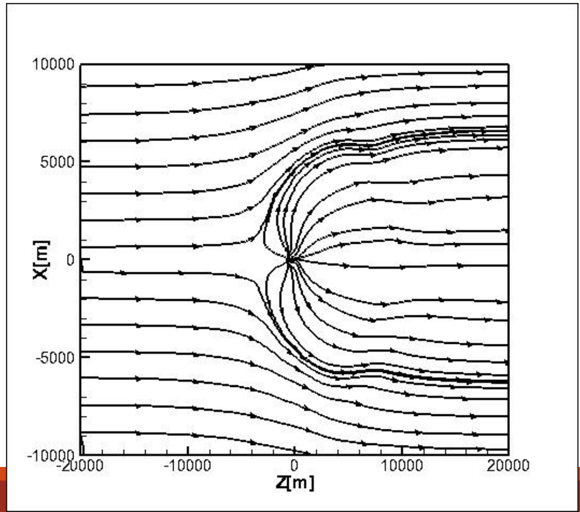
parametric study



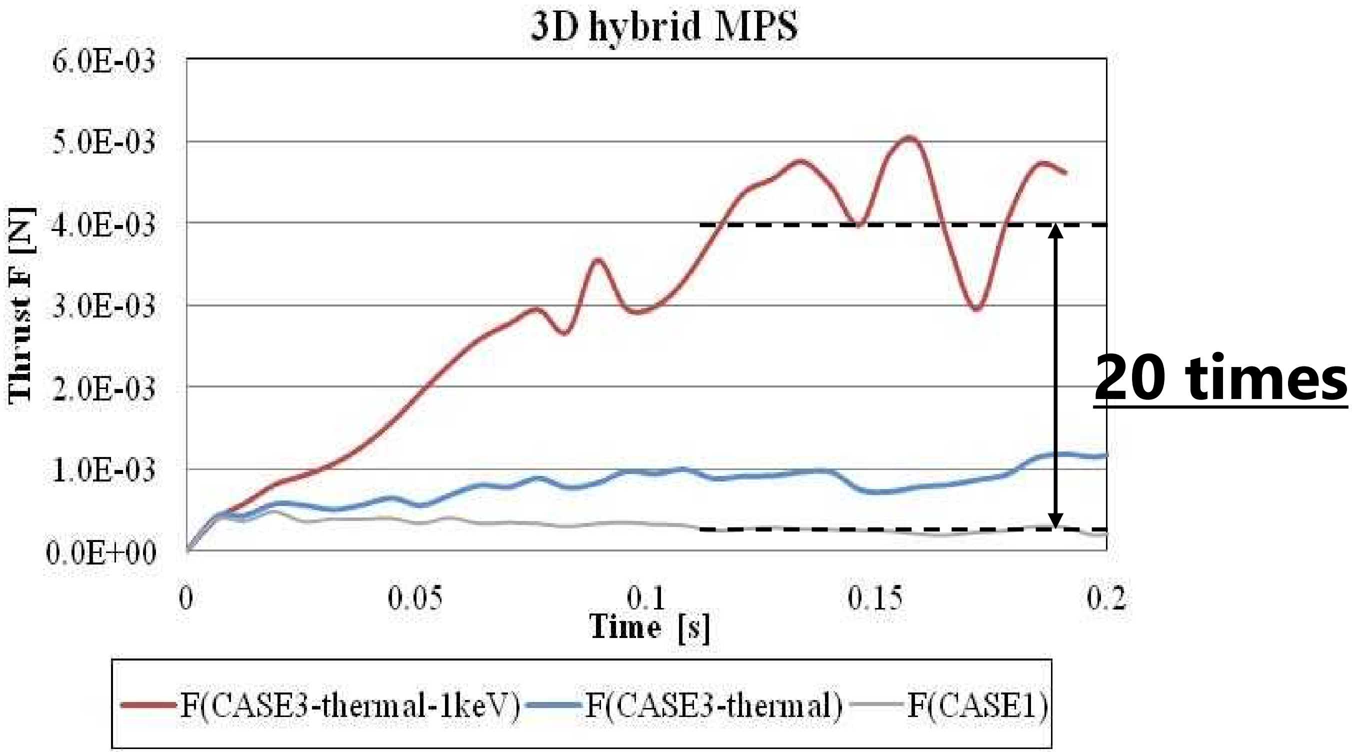


Plasma streamlines before and after injection.

Maximum 20 times



Thrust estimation of magnetic plasma sail



<u>20 times the magnetic sail thrust (2m radius, 10^6AT→4mN)</u>

Summary (MPS, Magnetic Sail)

- It is found that the **dark region** around magnetospheric boundary appearing in the experimental photograph corresponds to the region where the **plasma density increases** due to the plasma trapped by the magnetic field.

- The **width of the magnetopause current layer has a good agreement** between the simulation result and experimental result.

- The predicted thrust value of **0.3 N** obtained by the hybrid simulation agrees well with the experimental result when simulation is carried out by considering the ion-neutral collision effect.

- It was found that a thrust of 4 mN could be obtained for a magnetic plasma sail using plasma injection. This is 20 times higher than the thrust of the magnetic sail. However, this result is one order of magnitude lower than the performance of the ion engine.

Summary

- Research on Magnetic Shielding for Protection against Charged Particles of Cosmic Ray

- Research on Magnetic Sails and Magnetic Plasma Sails, which are propelled by receiving solar wind plasma with a magnetic field

END

（Thank you very much for your kind attention)