第7回原研若手研究会
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電磁加速プラズマ流の制御とマッハプローブの特性評価

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Electric Propulsion, MPD Thruster

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Outline

1. Introduction
2. Electric Propulsion
3. Mach Probe Experiment in the HITOP Device
4. Magnetic Nozzle Acceleration of MPDA Plasma
5. Summary

Introduction

プラズマの“流れ”と電磁場との相互作用

プラズマの閉じ込め改善

径電場とポロイダルフローシア

↓

流れによる渦の分断

↓

断熱層の形成

電気推進機の開発

人工衛星の姿勢制御

↓

惑星間航行

有人火星探査

<u>核融合プラズマ推進</u>

天体プラズマの物理

宇宙ジェットの形成

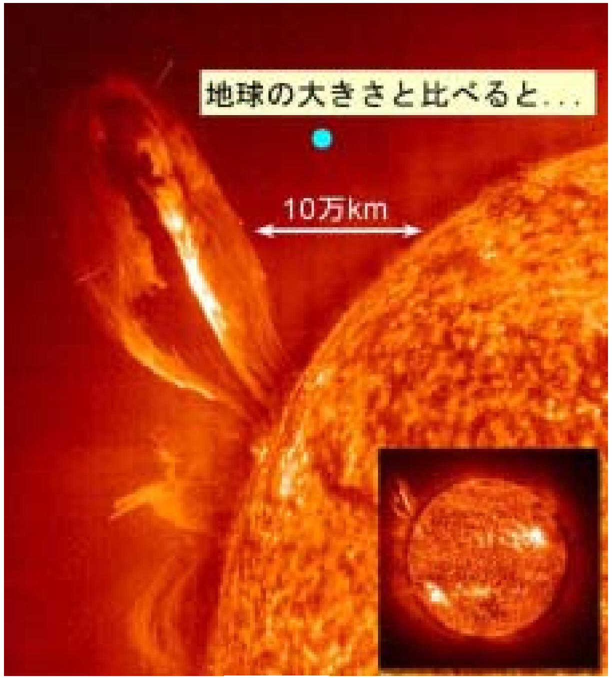
太陽フレア

(太陽のパラドクス)

動圧を利用した高ベータプラズマ閉じ込め

Double-Beltrami流


Image of MUSES-C ion engine



Introduction to Electric Propulsion(EP)

Chemical Propulsion (CP)

- ●Large thrust density
  to lift off the earth gravity
- ●Low I_{sp} (≦500sec)

Electric Propulsion(EP)

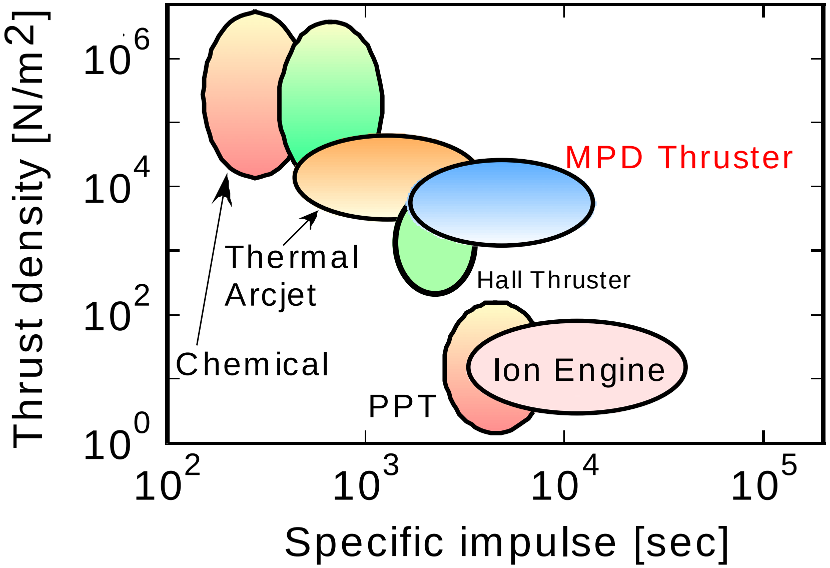
- ●Ionization by electric power
- ●Power source: solar cell, nuclear reactor

- ●High I_{sp} (≧10^3-10^4sec)
  with small consumption of propellant
- ●Useful for interplanetary mission
  long-term station-keeping
  manned Mars mission

Parameters for Thrust Performance

Thrust : $F = \dot{m}U$

Specific Impulse : $I_{sp} = \frac{F}{\dot{m}g} = \frac{U}{g}$ [sec]




Hall thruster


MPD thruster


Thermal arcjet


Ion engine

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Recent Achievement of EP in Japan

Image of MUSES-C ion engine

Ground test of MPDT

>>May 9, 2003

The **MUSES-C** (Hayabusa) spacecraft mounting **four ECR ion thrusters** was successfully launched. Asteroid sample return mission is now under progress.

>>March 18, 1995

The MPD thruster onboard the Space Flyer Unit (SFU) was successfully pulse-operated in space with few misfirings.

(ref.) http://www.isas.jaxa.jp/j/index.shtml

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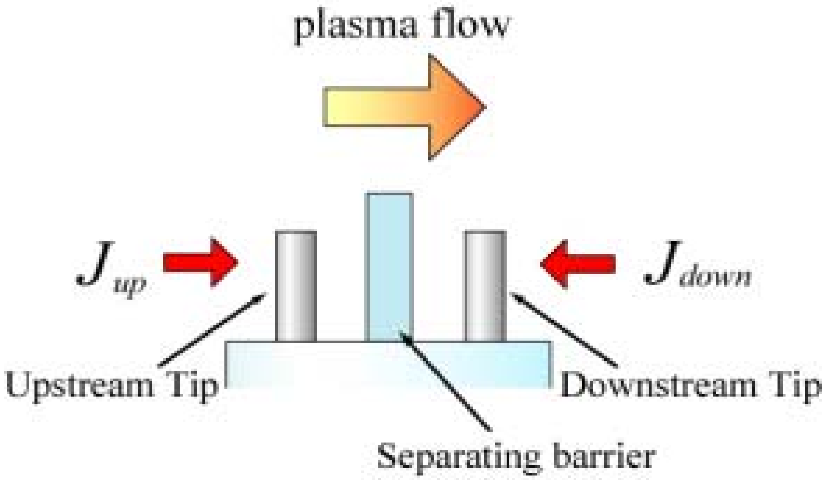
Plasma Flow Measurement

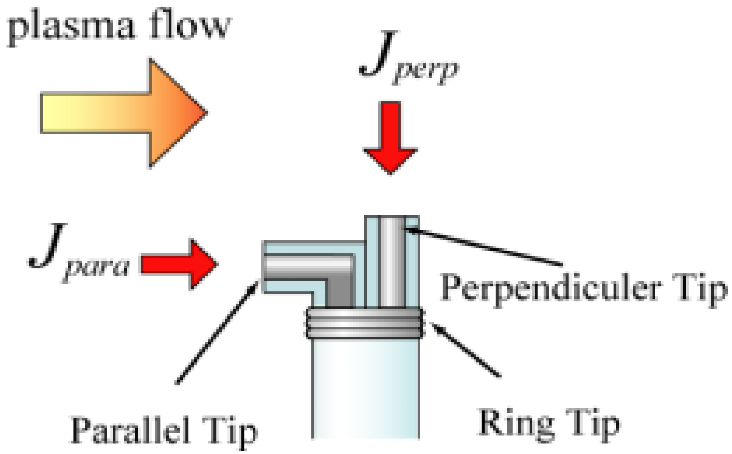
- ➢Laser Induced Fluorescence (LIF)
- ➢Visible-Light Spectroscopy (Doppler shift)
- ➢Mach Probe →簡便で，空間分解能に優れる．

流れに対して異なった方向に捕集面を向け，そのイオン飽和電流値 j_{is} の信号値の違いから流速，イオンマッハ数（M_i = 流速 / 音速）を求める

(a) up-down **タイプ**



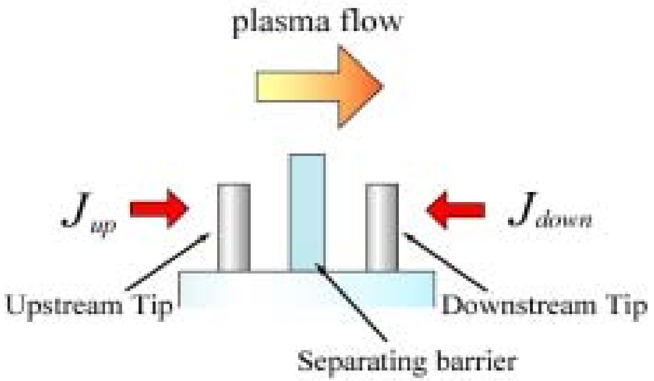
(b) perp-para **タイプ**



Theoretical Model of Mach Probe ~up-down~

＜ up-down タイプ＞

Hudis and Ridsky model (1970) **非磁化プラズマ** 最初にマッハプローブを提案 1次元のエネルギー保存より導出 $M_i << 1, T_i << T_e$
Stangeby model (1984) **磁化プラズマ** 1-D fluid model, 粘性の効果は無視, $M_i < 1$
Hutchinson model (1987) **磁化プラズマ** 1-D fluid model, 粘性による輸送効果を考慮, $M_i < 1$
Chung and Hutchinson (1988) **磁化プラズマ** 1次元Kinetic model，粘性の効果を考慮



$\rho_i < r_p$: 磁化プラズマ

$\rho_i > r_p$: 非磁化プラズマ

M_c を決めるために…

LIFを用いた較正実験：Gunn(2001)

磁化プラズマ中で粘性を考慮したモデルとよい一致（実験は $M_i < 0.4$）

非磁化プラズマ中ではモデルが確立されていない！！

$$\frac{J_{up}}{J_{down}} = \exp\left(\frac{M_i}{M_c}\right) \qquad M_c : \text{const.}$$

Hutchinson PIC Simulation

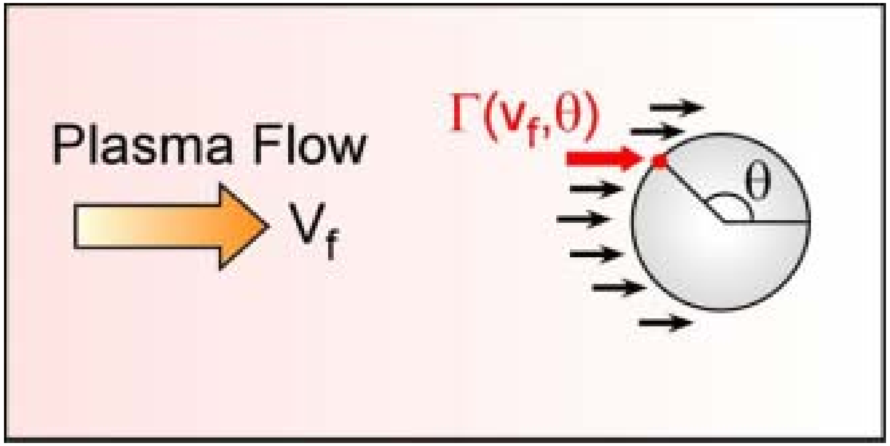
PICコードを用いて，**非磁化プラズマ中**に球プローブがある際，プラズマの流れ（ v_f)に対してある角度(θ)をもった点に流れ込んでくるイオンフラックス $\Gamma(v_f, \theta)$ を計算.

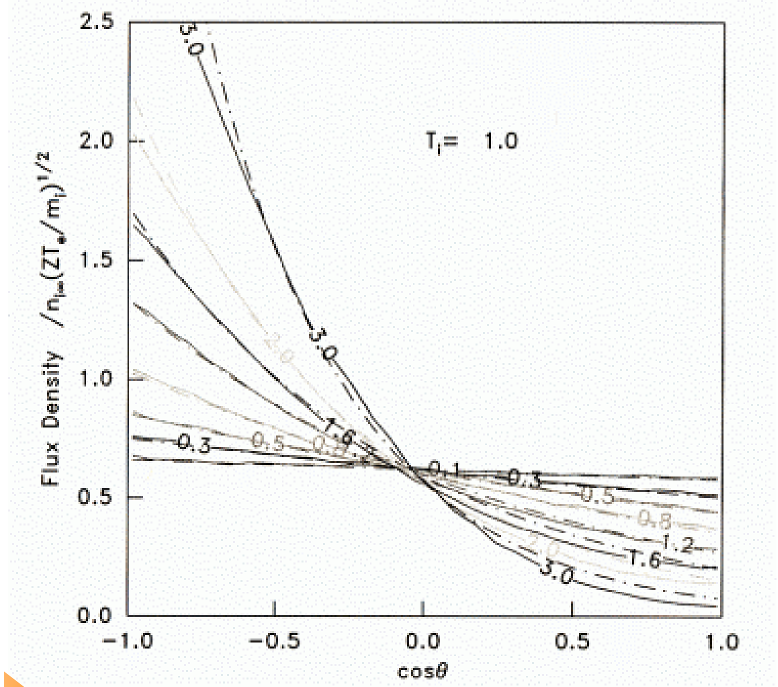
シミュレーションより得られたモデル式

$$\frac{\Gamma(v_f, \pi)}{\Gamma(v_f, 0)} = \frac{J_{up}}{J_{down}} = \exp\left(\frac{M_i}{M_c}\right)$$

ただし　v_f ：$(T_e / m_i)^{1/2}$ で規格化

$\Gamma(v_f, \theta)$: $n_{i\infty}(T_e / m_i)^{1/2}$ で規格化





(example) イオンフラックスのcosθ依存(T_i / T_e =1)；
曲線上の数値はイオンのドリフト速度を表す

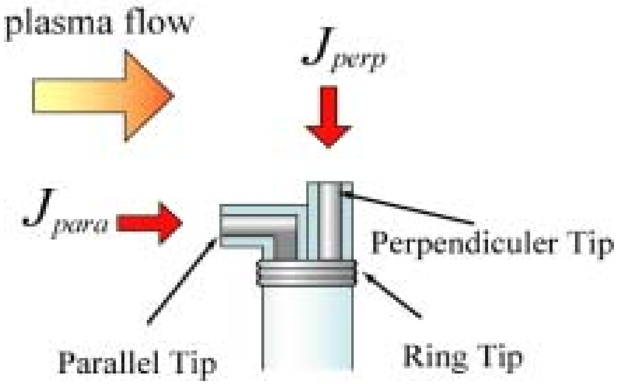
Theoretical Model of Mach Probe ~perp-para~

＜ perp-para **タイプ**＞

通常のプローブの理論よりperp-tip**のイオン飽和電流** $J_\perp$ **は,**

$$J_\perp = \kappa e n_i \sqrt{\frac{\gamma_e T_e + \gamma_i T_i}{m_i}}$$

(κ : T_i / T_e **で決まる定数**)



$M_i > 1$ では…

$$J_\parallel = e n_i U$$

Kuriki and Inutake (1974)

$$\frac{J_\parallel}{J_\perp} = \frac{U}{\sqrt{\frac{\gamma_e T_e + \gamma_i T_i}{m_i}}} = \frac{M_i}{\kappa} \quad \cdots\text{(i)}$$

$M_i << 1$ では…

$$\frac{J_\parallel}{J_\perp} = \exp\left(\frac{M_i^2}{2}\right) \quad \cdots\text{(ii)}$$

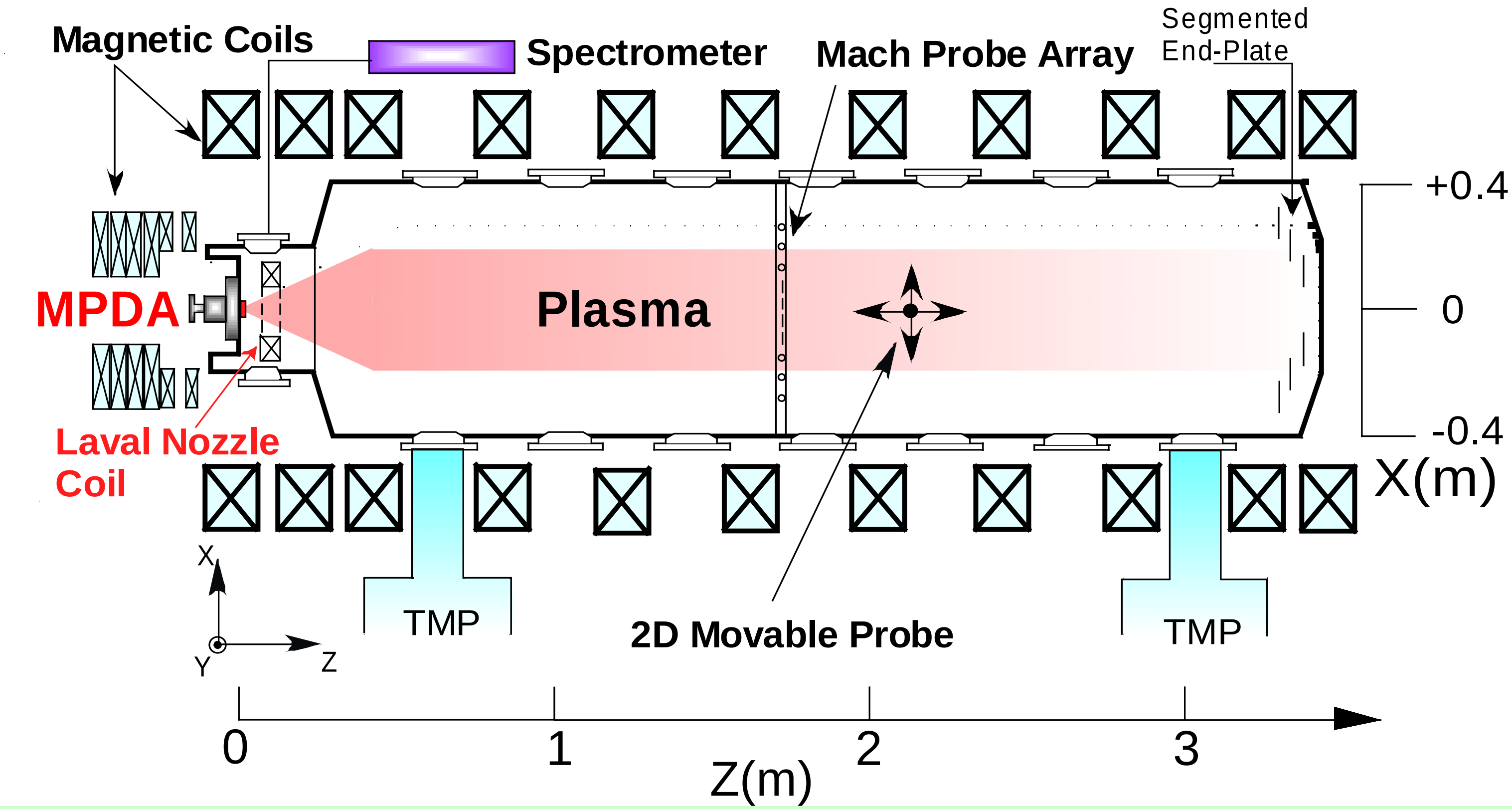
Stangeby and Allen(1971)

(i) ,(ii) **が** $M_i = 1$ **でなめらかに接続するように下式のように** α **を導入**

$$\frac{J_\parallel}{J_\perp} = \exp\left(\alpha \cdot M_i^{\frac{1}{\alpha}}\right) \qquad (\alpha = -\ln\kappa)$$

他の計測方法と比較し, 比例定数を決める較正実験が必要！！

HITOP(High density TOhoku Plasma) Device



Typical Parameters

Cylindrical chamber : length = 3.3 m, inner diameter = 0.8 m

Magnetic field : up to 0.1 T

Ion temperature : 20-40eV

Plasma density : ~10^{15}cm^{-3}(near the MPDA)

Plasma source : MPD Arcjet

Electron temperature : 3-10 eV

Ionization degree : 50-90%

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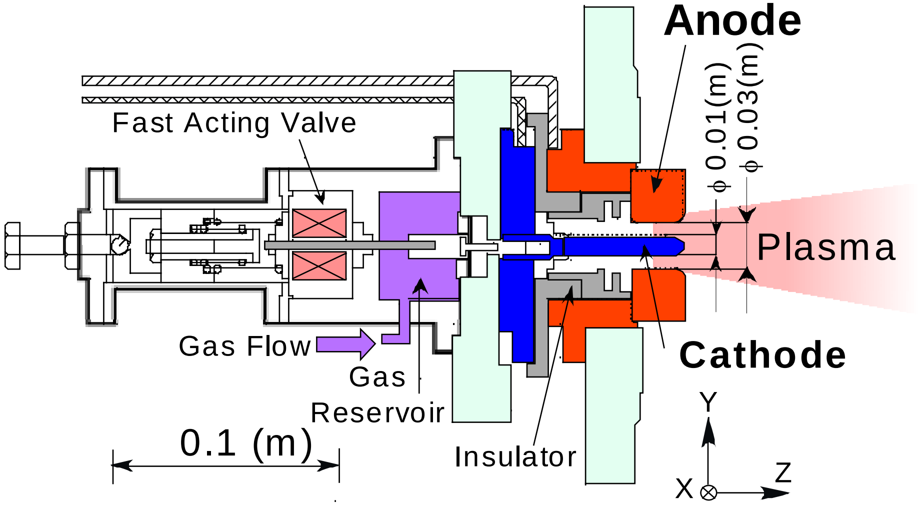
MPD(Magneto-Plasma-Dynamic) Arcjet

Cross Section of MPDA

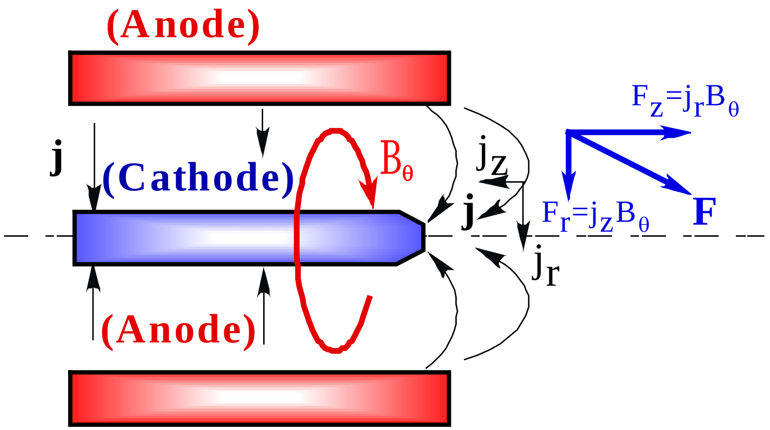


The MPDA has a coaxial structure with a center tungsten rod cathode and an annular molybdenum anode.

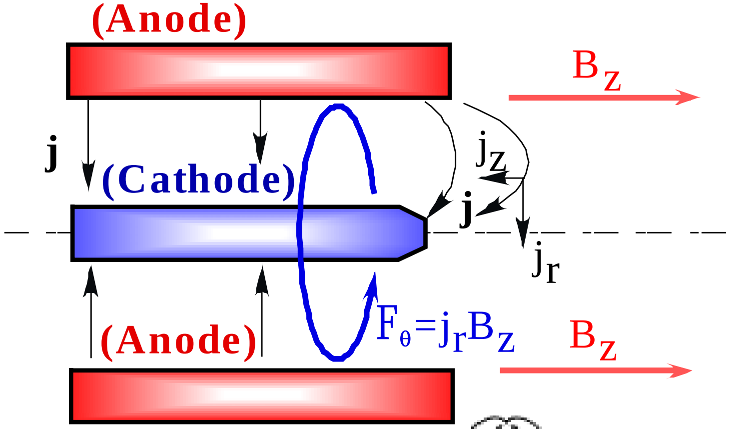
By use of a fast-acting gas-puff valve, a quasi-steady (~1 msec), high-density (up to 10^{15}cm^{-3} near the MPD outlet), highly-ionized plasma is produced.

Principle of Plasma Acceleration

(a) Self-Field Acceleration



(b) With Externally-Applied Field



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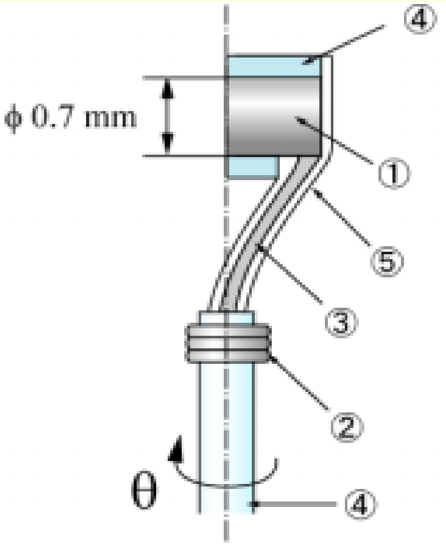
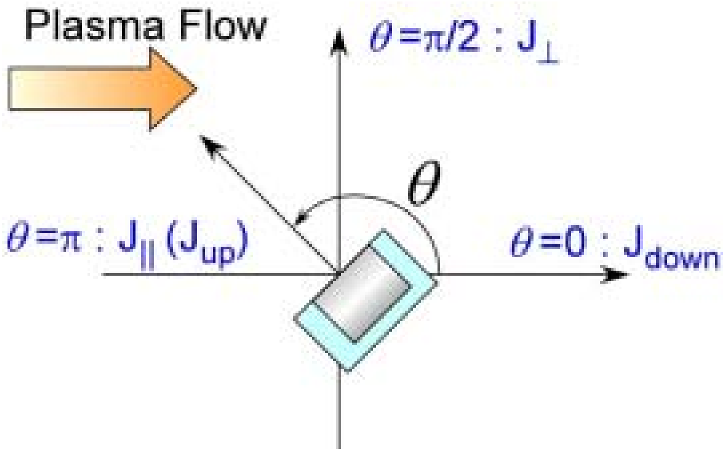
Hutchinsonモデルの検証実験

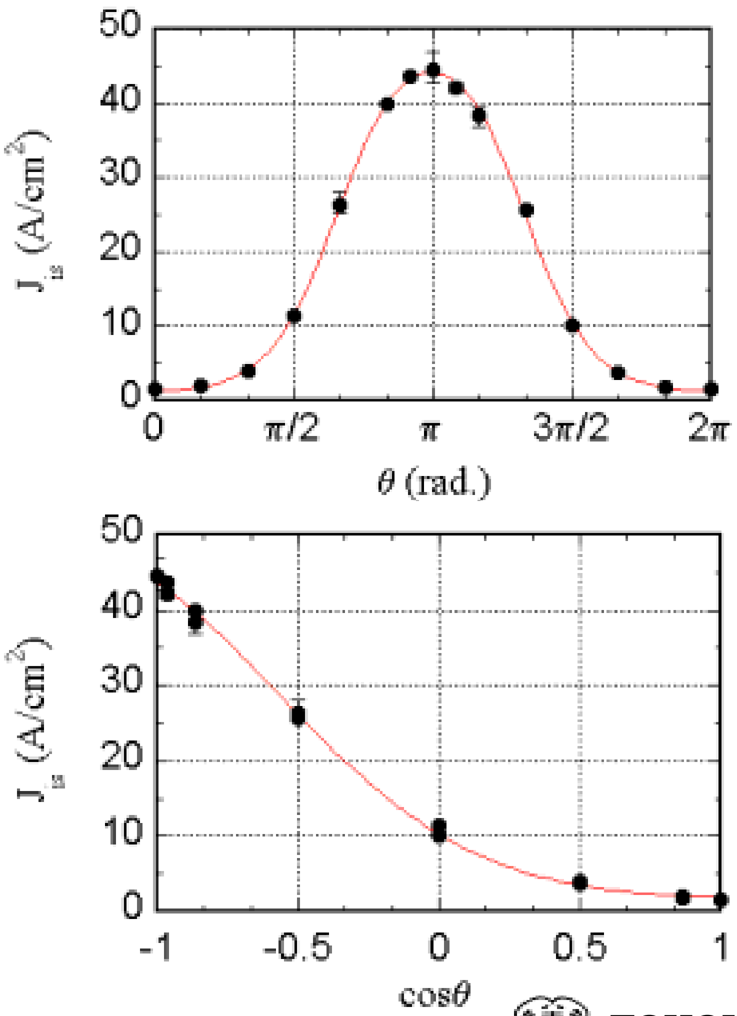
Directional Langmuir probe (DLP)



①プローブチップ
（W線 φ0.7 mm）
②リング型電極
（SUS304）
③電流リード線
（SUS304）
④セラミックチューブ
⑤セラミック皮膜



Ion saturation current distribution
as a function of θ (cos θ)



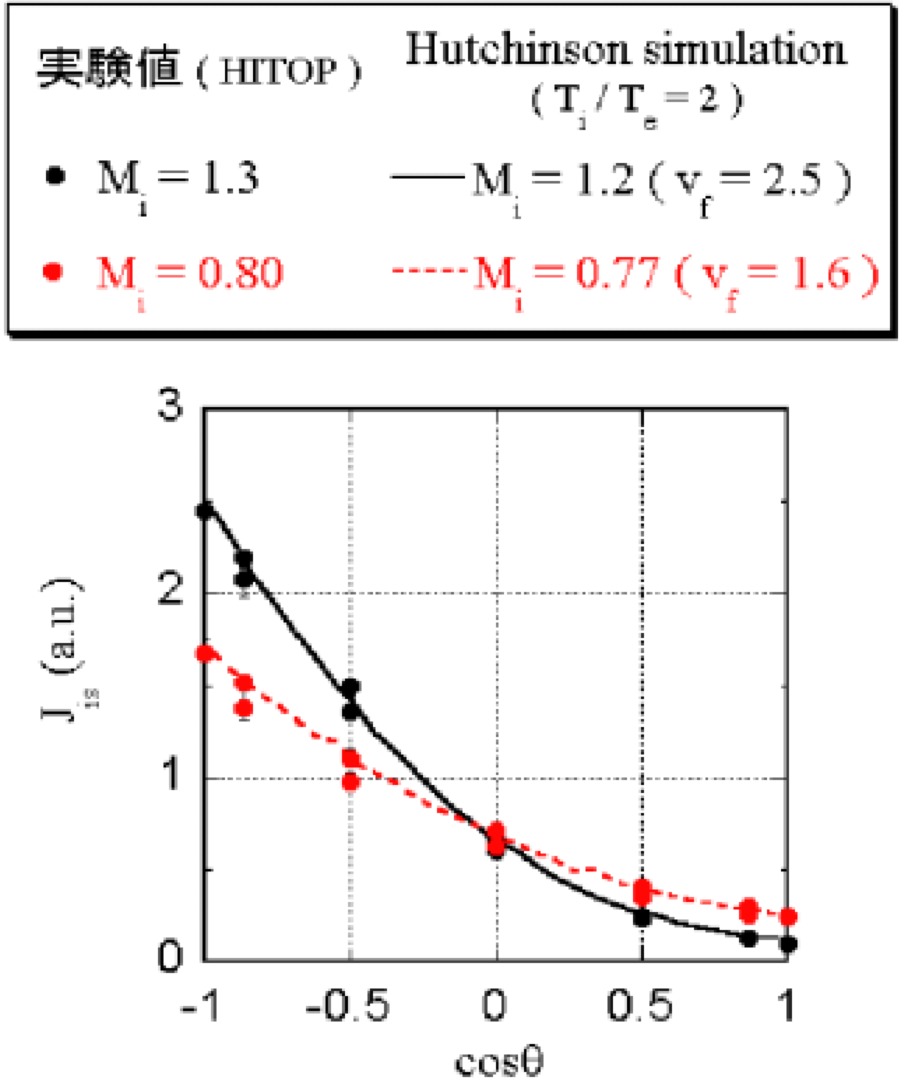
Hutchinsonモデルの検証実験

Hutchinsonモデルとの比較

＜MPDプラズマ＞

- $r_p < \rho_i$ **(非磁化プラズマ)**
- $1.5 < T_i / T_e < 3$

実験値と Hutchinson シミュレーション
(T_i / T_e = 2 の場合) を比較



実験条件

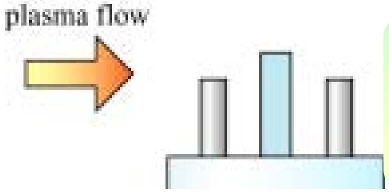
(a) $M_i = 1.3$ (U =28km/s, T_i =8.6eV, T_e =5.3eV)
(b) $M_i = 0.8$ (U =19km/s, T_i =11eV, T_e =6.2eV)

Good agreement !!

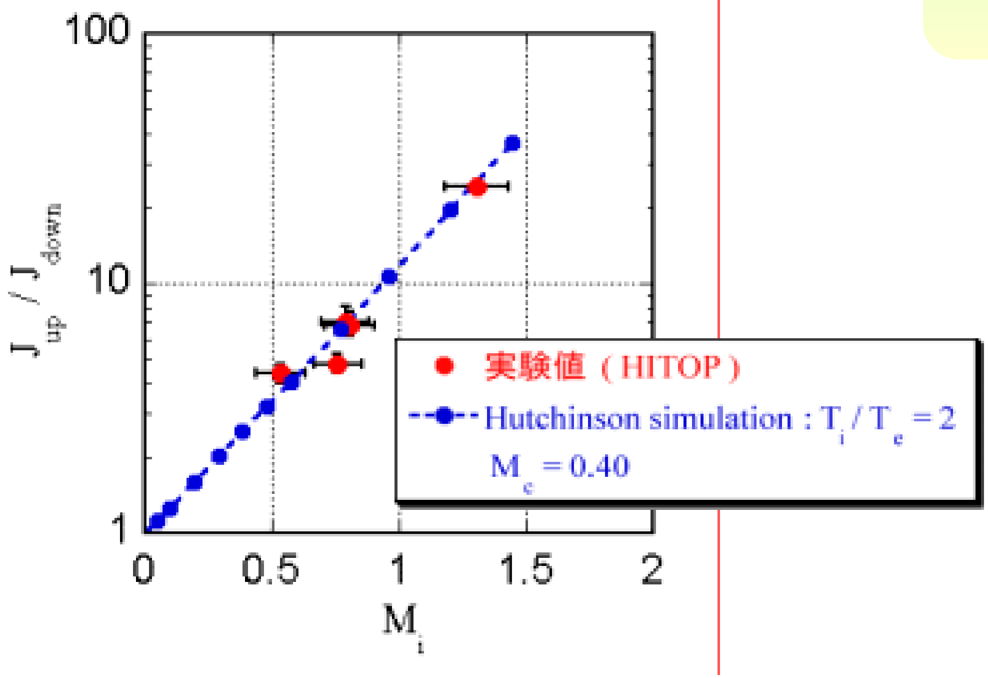
cosθ = -1 での値で 規格化

Mach Probe Calibration ~分光計測による較正~

up - down タイプ

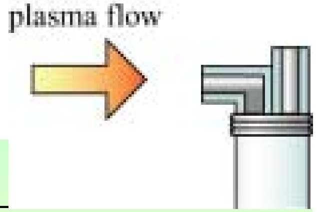


$$\frac{J_{up}}{J_{down}} = \exp\left(\frac{M_i}{M_c}\right)$$



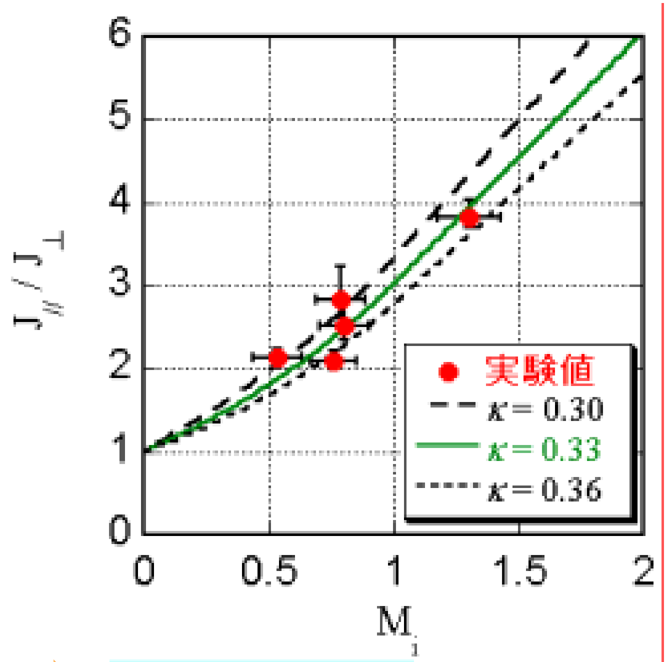
$M_c = 0.40$

perp - para タイプ



超音速流 ($M_i > 1$) : $\frac{J_\parallel}{J_\perp} = \frac{M_i}{\kappa}$

亜音速流 ($M_i < 1$) : $\frac{J_\parallel}{J_\perp} = \exp\left(\frac{M_i^{\alpha}}{\alpha}\right)$ $\left(\alpha = \frac{1}{\ln\kappa}\right)$



$\kappa = 0.33$

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up - down タイプ ↔ **perp - para タイプ**

$$M_i = M_c \cdot \ln\left(\frac{J_{up}}{J_{down}}\right)$$

($M_i > 1$) $$M_i = \kappa \cdot \frac{J_{\parallel}}{J_{\perp}}$$

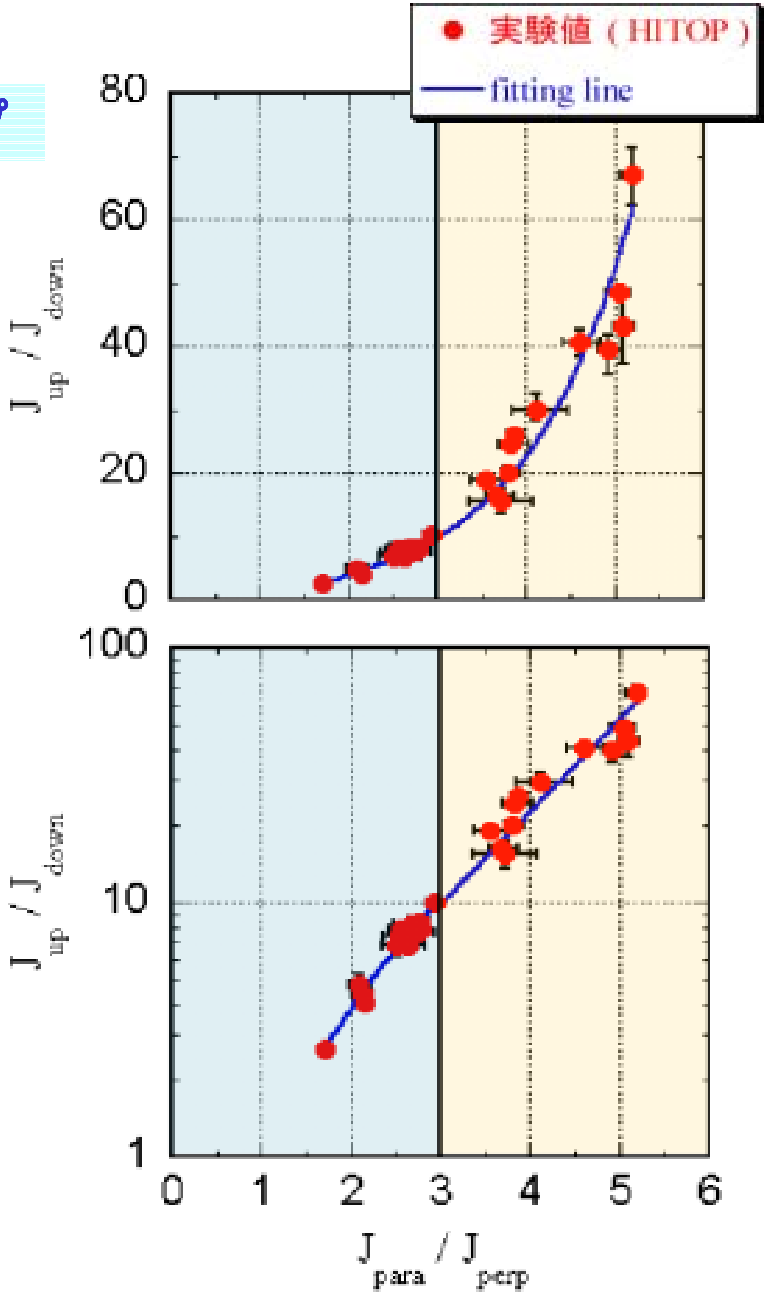
($M_i < 1$) $$M_i = \frac{1}{\alpha^{\alpha}} \cdot \left[\ln\left(\frac{J_{\parallel}}{J_{\perp}}\right)\right]^{\alpha}$$

$(\alpha = -\ln \kappa)$

$M_i > 1$ $$\frac{J_{\parallel}}{J_{\perp}} \propto \ln\left(\frac{J_{up}}{J_{down}}\right)$$

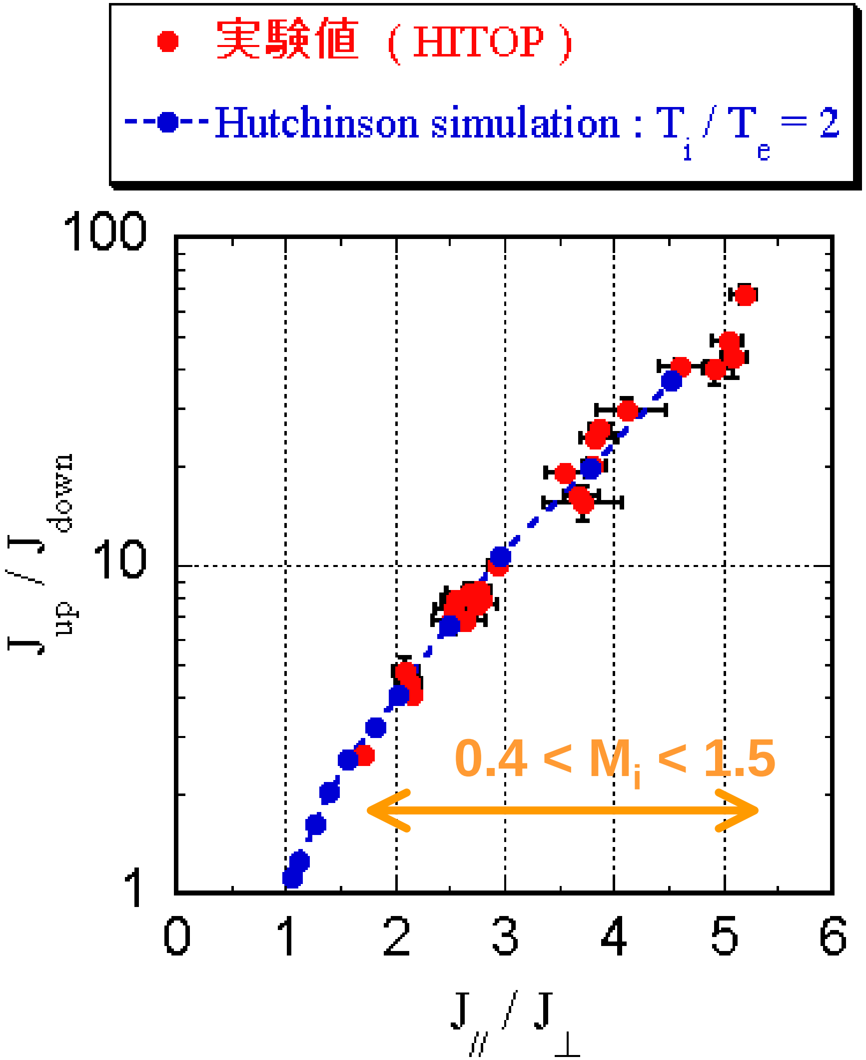
$M_i < 1$ $$\ln\left(\frac{J_{up}}{J_{down}}\right) \propto \left[\ln\left(\frac{J_{\parallel}}{J_{\perp}}\right)\right]^{\alpha}$$

$(\kappa = 0.33 \ \ (\alpha = 1.1))$



up - down タイプ ⟷ **perp - para タイプ**

Comparison between exp. and PIC simulation



DLPによる計測結果

PIC シミュレーションによる結果

$0.4 < M_i < 1.5$ **の広い範囲で良い一致を示した**

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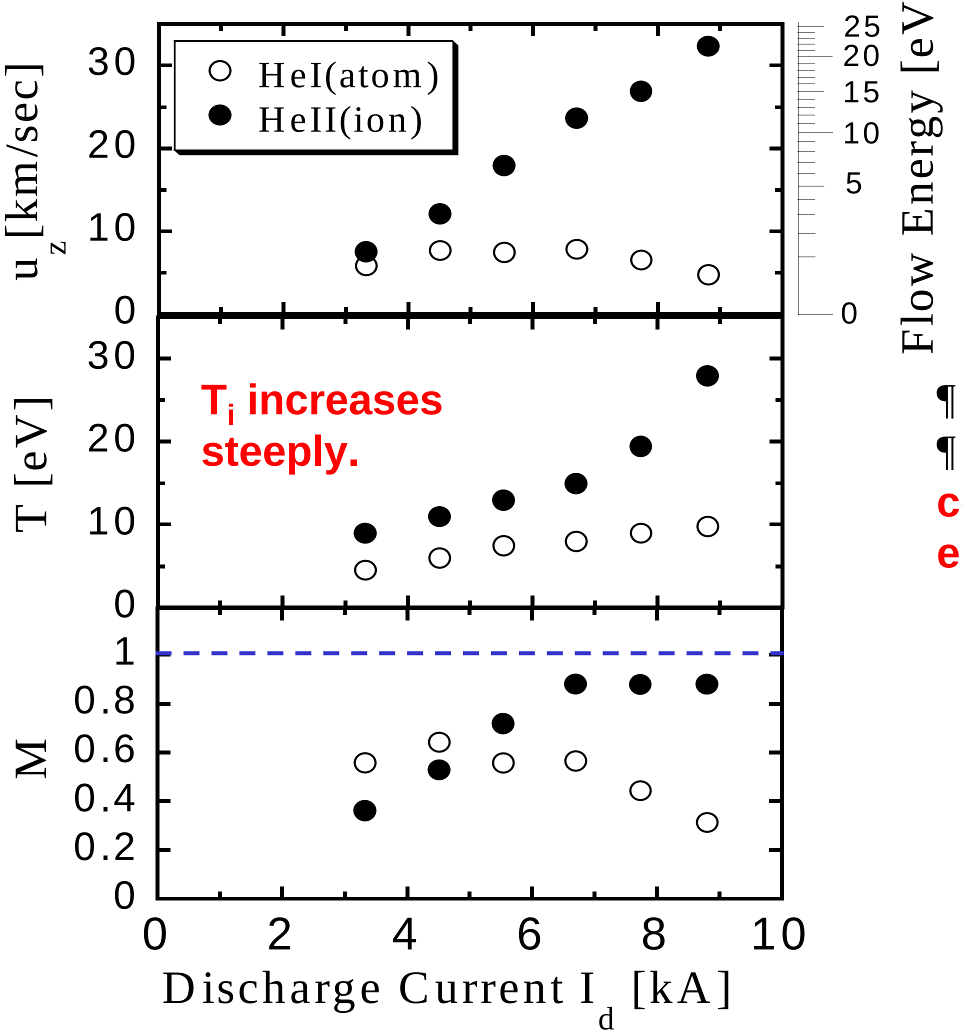
Anomalous ion heating in the MPDA Plasma

I_d=8.6kA, dm/dt=0.06g/s(He),
B_0=1kG(uniform) at Z=4cm



T_i increases steeply.

$$M_i = \frac{u}{C_s} = \sqrt{\frac{m_i u^2/2}{k_B(\gamma_i T_i + \gamma_e T_e)/2}} < 1$$

i.e. Thermal energy > Flow energy

¶ Why is the Mach number limited?

¶ What is the mechanism of the conversion the input energy to the thermal energy?

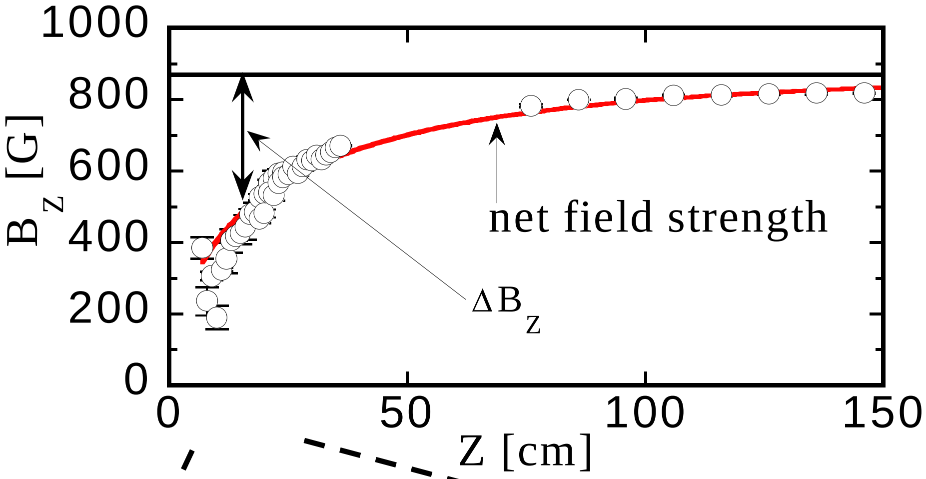
Detailed measurement of

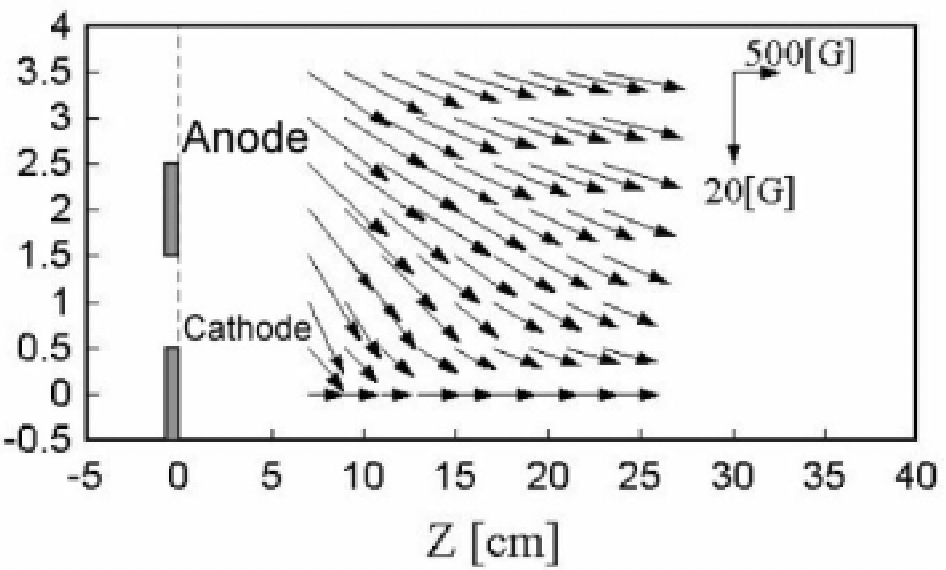
- j×B force field
- flow field

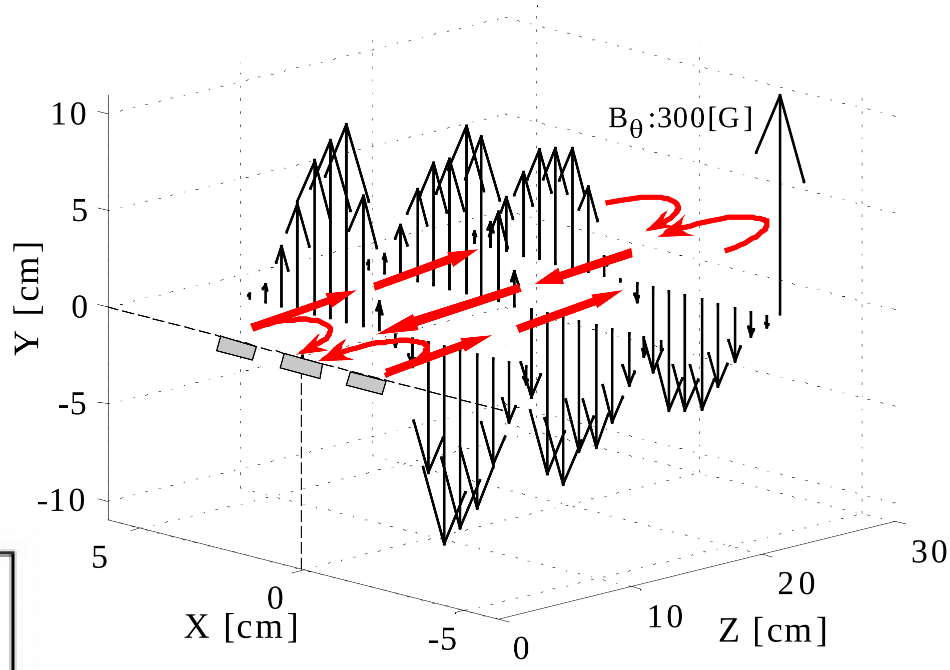
Spatial Distribution of jxB Force

Magnetic Field distribution in the Vicinity of MPDA

I_d=7.2kA, V_d=200V,dm/dt=0.1g/s(He), B_0=870G(uniform)





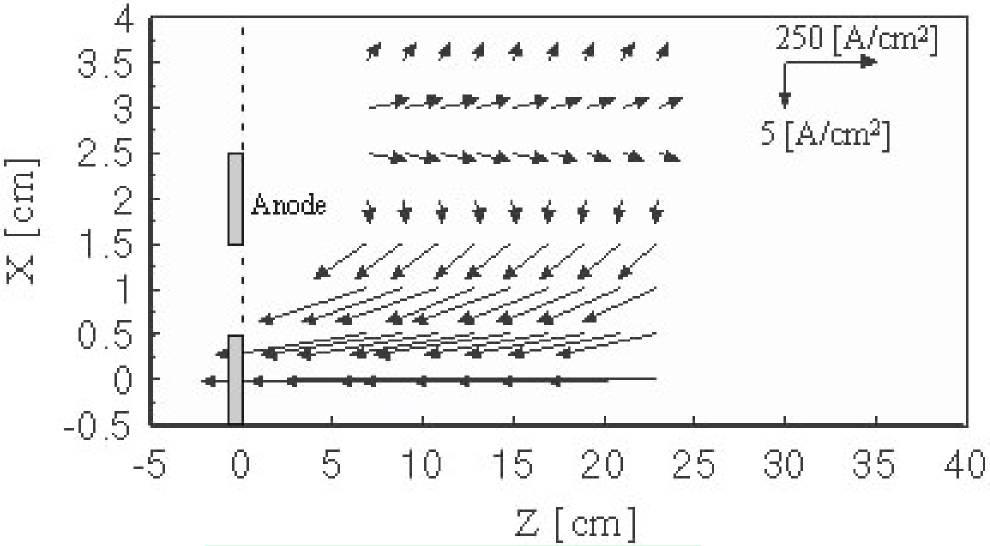


deformation of magnetic field

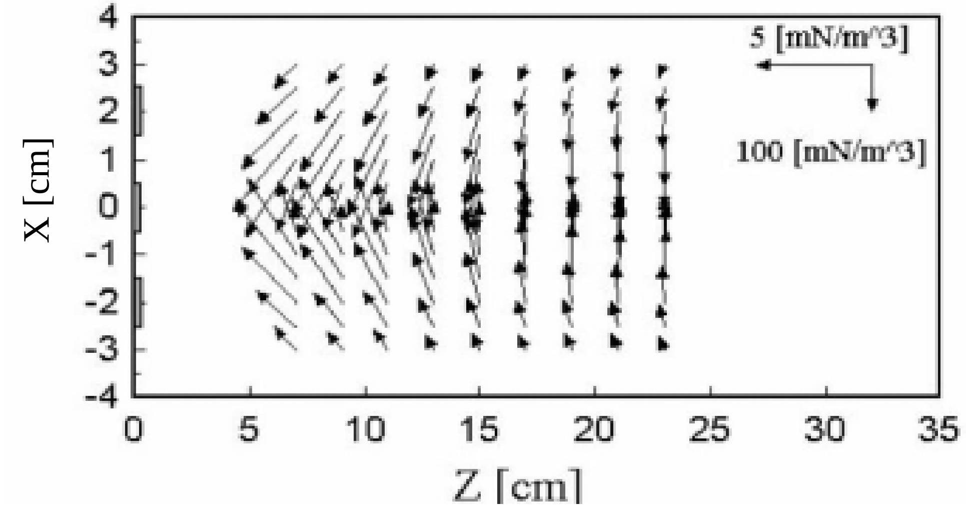
Spontaneous formation a helically-converging magnetic nozzle in the vicinity of MPDA outlet.

Spatial Distribution of jxB Force

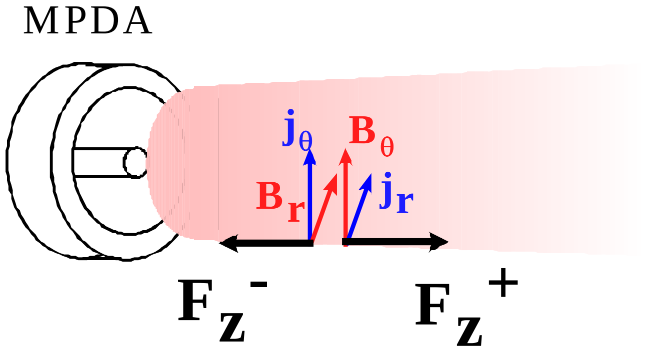
Plasma Current Distribution



jxB Force Distribution



Schematic of the drag force generation



$$F_Z = \underbrace{-j_\theta B_r}_{F_z^-} + \underbrace{j_r B_\theta}_{F_z^+}$$

Drag force

Accelerating force

Energy Balance in the MPDA Plasma Flow

Generalized Bernoulli's Equation Related to the Applied-Field Acceleration**

$$\frac{1}{2}\left(u_z^2+u_\theta^2\right)+\frac{\gamma}{\gamma-1}\frac{P}{\rho}+\frac{B_\theta^{\ 2}}{\mu_0\rho}-\frac{B_\theta B_z u_\theta}{\mu_0\rho u_z}=\text{const.}$$

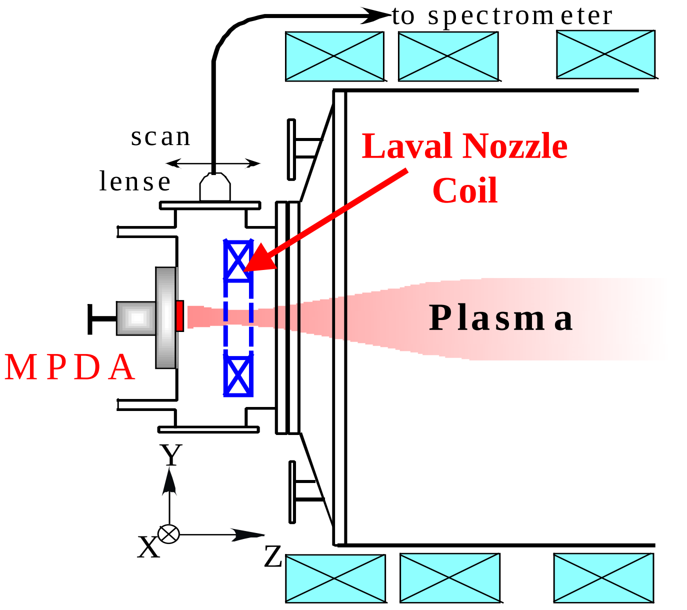
Flow energy $\sim 10^8$

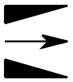
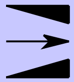
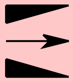
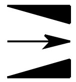
Self-field energy $\sim 10^7$

Thermal energy $\sim 10^9$

Additional energy $\sim 10^7$

Thermal > Flow. $T_i / T_e \sim 2$. …. ***Why?***



	$M_i<1$		$M_i>1$	
A				
M	↘	↗	↗	↘
U	↘	↗	↗	↘
T	↗	↘	↘	↗
ρ	↗	↘	↘	↗

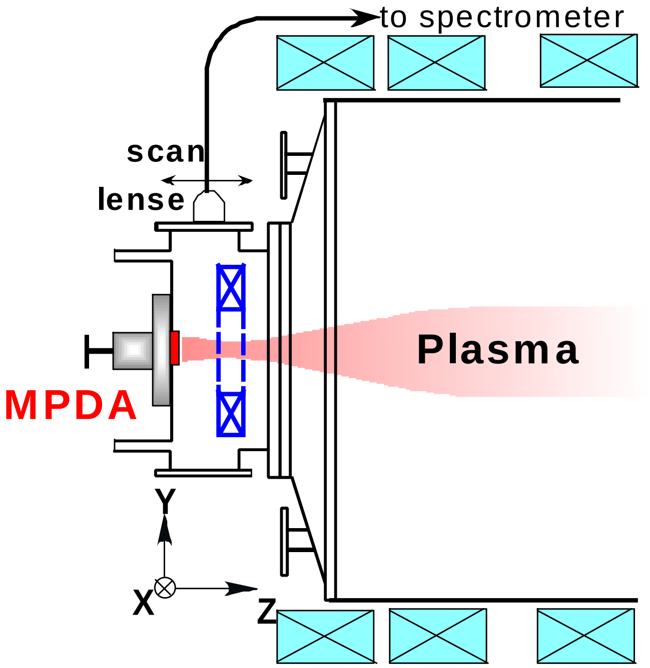
Magnetic nozzle

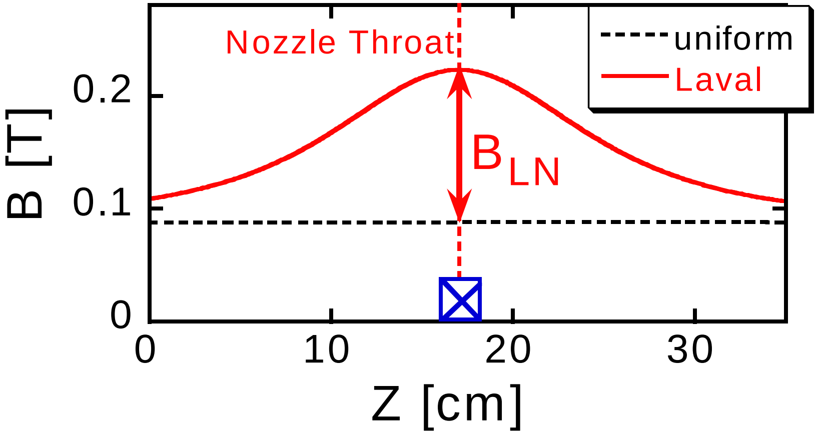
Thermal energy → **Flow energy**

Momentum Conversion

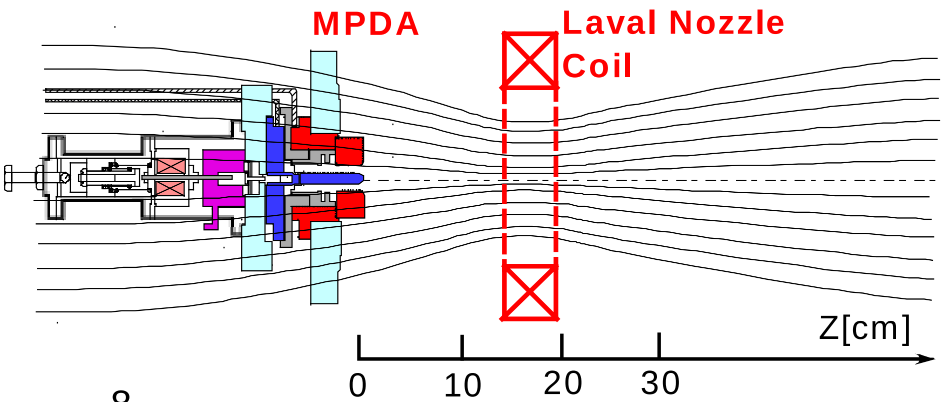
** K.F. Schoenberg *et al*. ; Phys of Plasmas, **5**, p.2090 (1998)

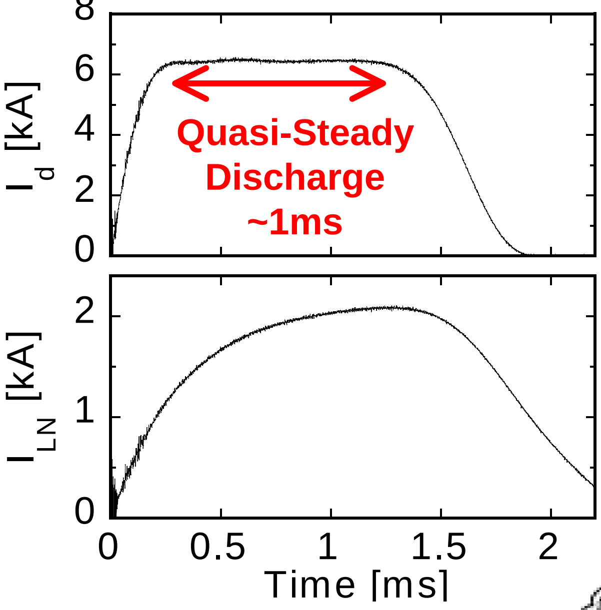
Magnetic Laval Nozzle Formation





Magnetic Field Line Profile in Vacuum





(a) Discharge Current: I_d

(b) Nozzle Coil Current: I_{LN}

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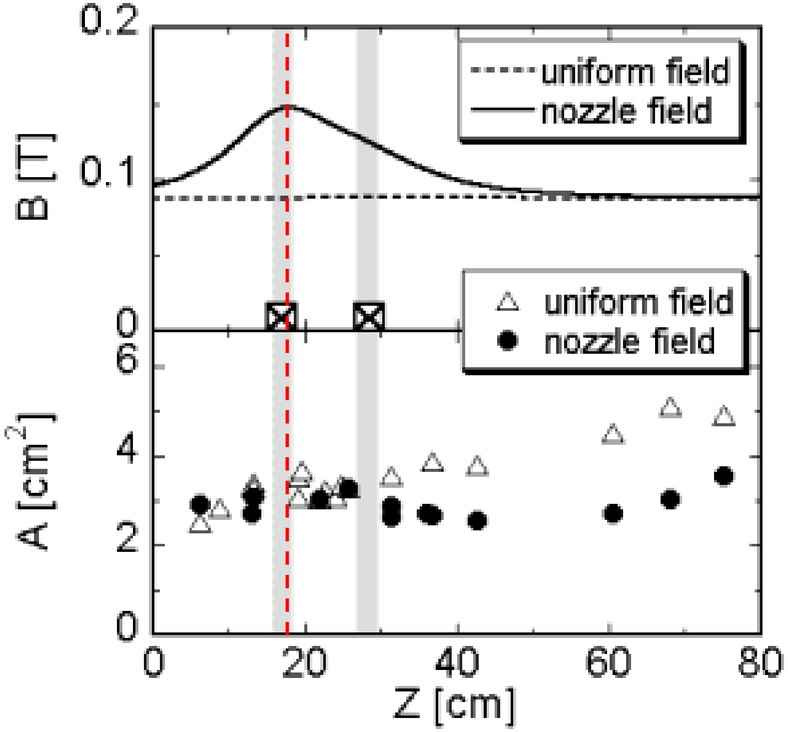
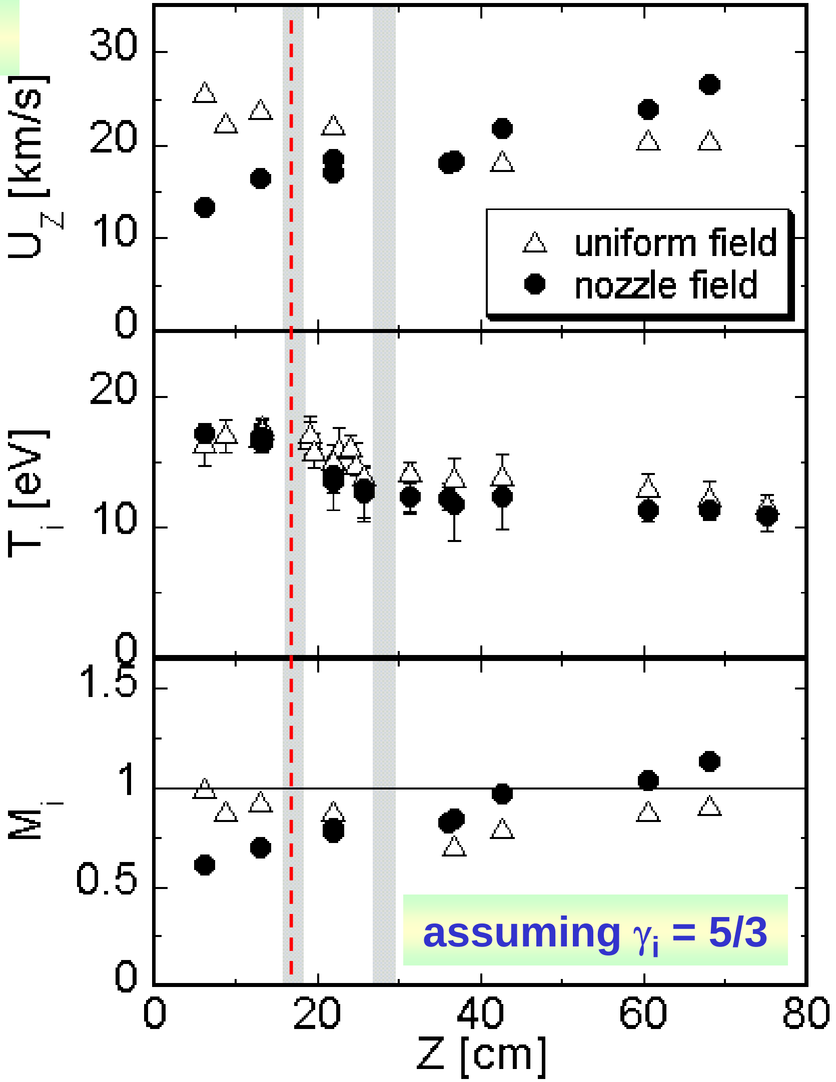
Characteristics in Magnetic Laval Nozzle

Improvement of Acceleration Performance

I_d = 7.2kA, dm/dt = 0.1g/s (He),
Nozzle Throat at Z=17cm.





assuming γ_i = 5/3

The thermal energy is converted to the flow energy by passing through the Laval nozzle and a supersonic plasma flow is achieved.

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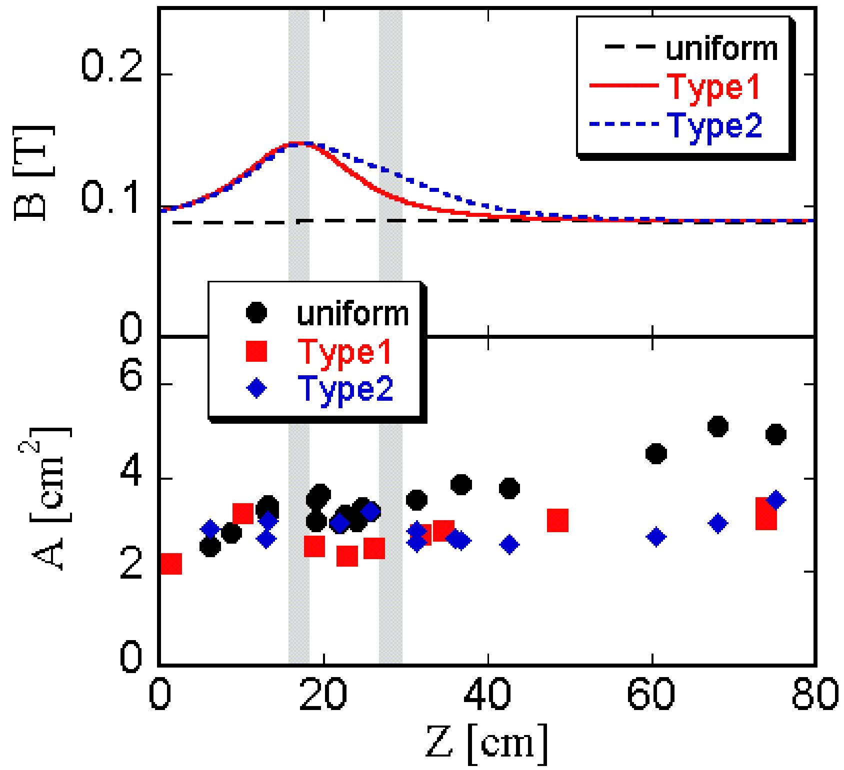
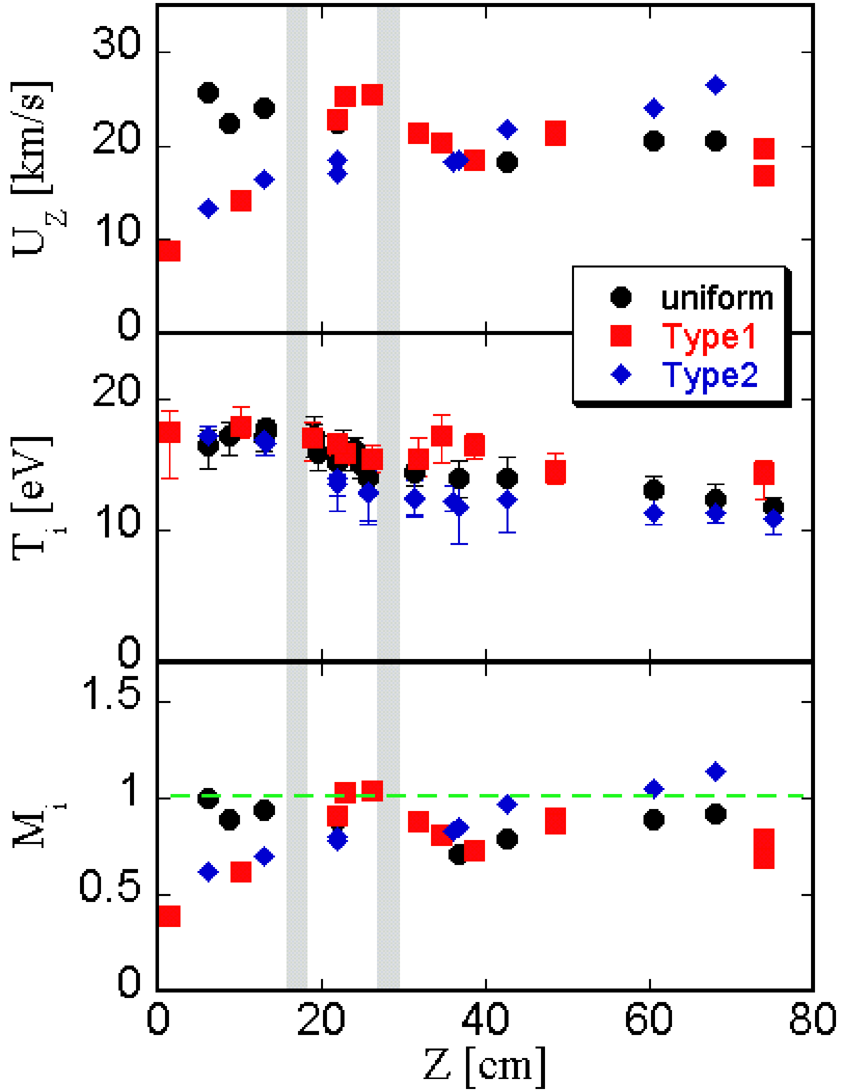
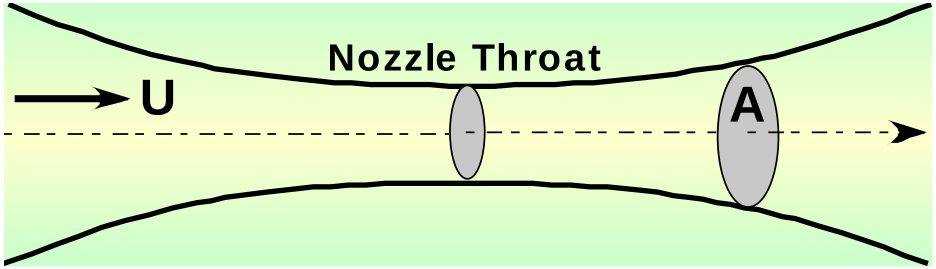
Various Behavior in the Laval Nozzle





1-D Isentropic Flow Model

The MPD plasma flow is modeled by a one-dimensional adiabatic flow with a constant entropy at any cross section along a flux tube.

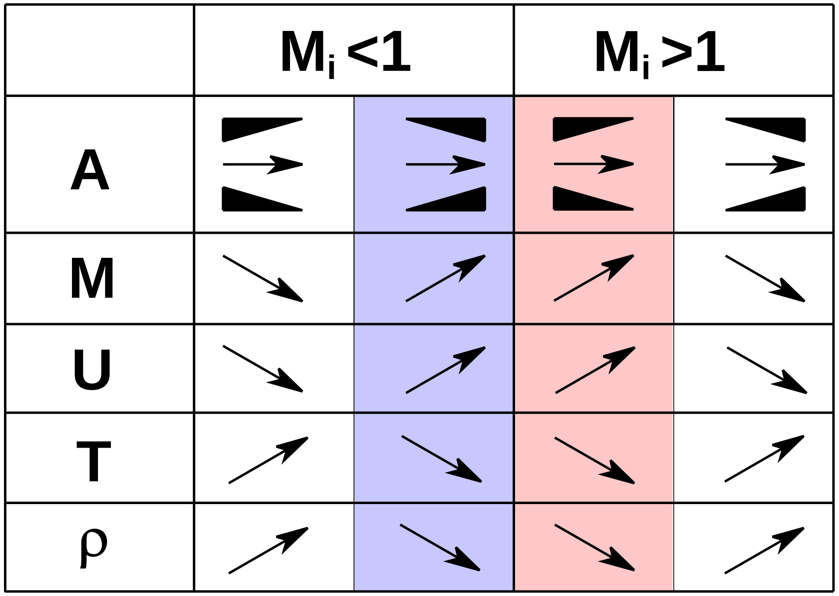


$$\frac{dM}{M} = \frac{2+(\gamma-1)M^2}{2(M^2-1)}\frac{dA}{A}$$

$$\frac{dU}{U} = \frac{1}{M^2-1}\frac{dA}{A}$$

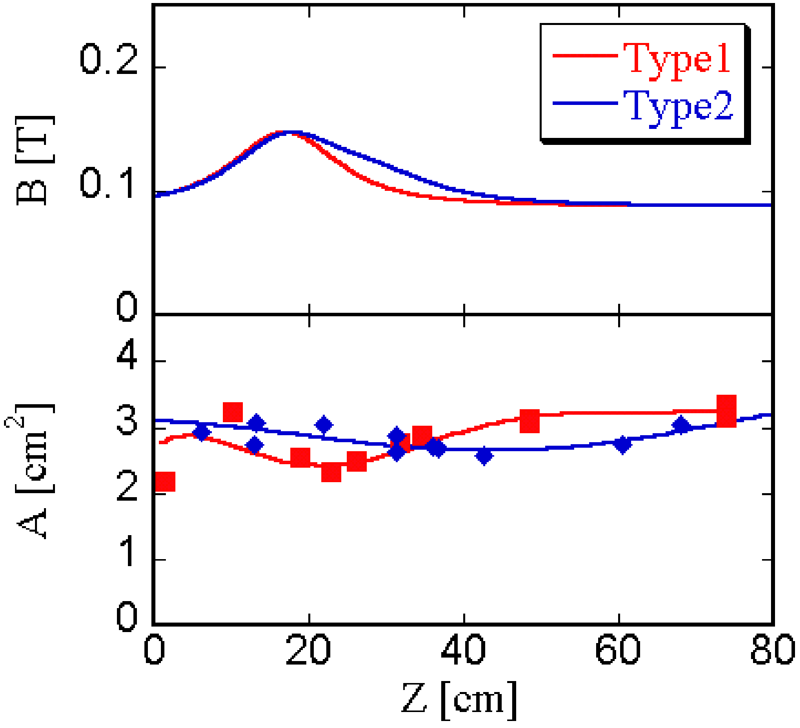
$$\frac{dT}{T} = \frac{(\gamma-1)M^2}{M^2-1}\frac{dA}{A}$$

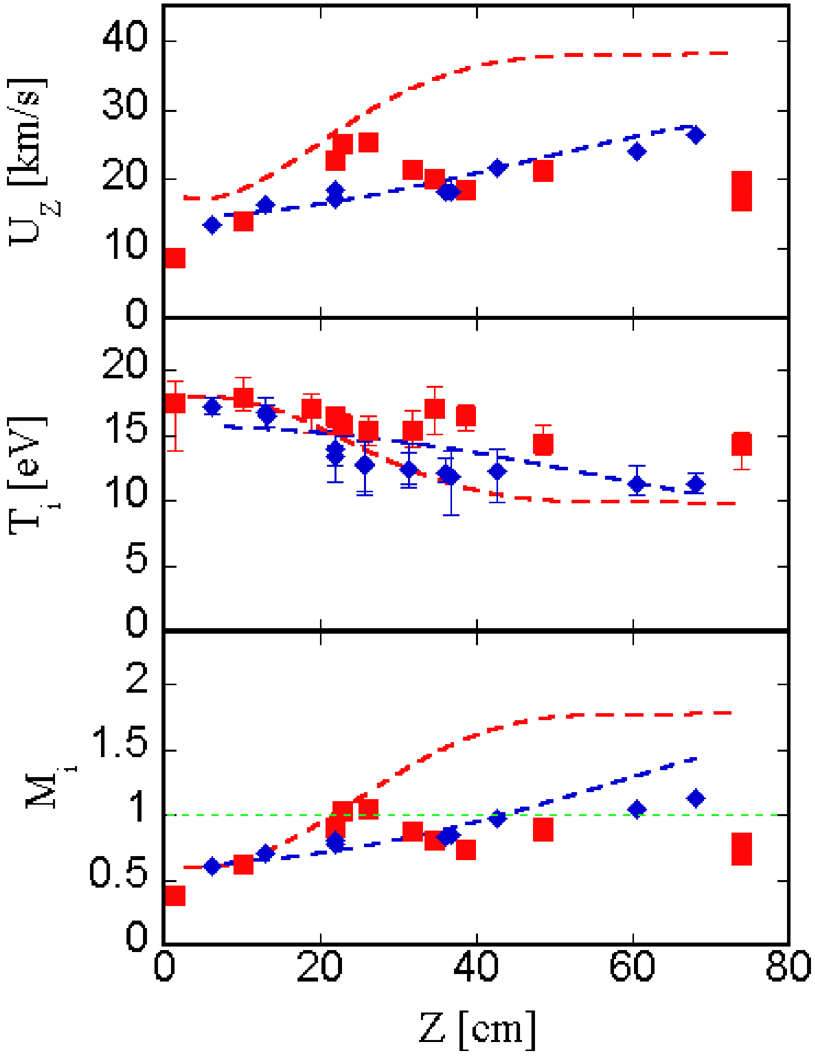
$$\frac{d\rho}{\rho} = \frac{M^2}{M^2-1}\frac{dA}{A}$$



	M_i <1		M_i >1	
A	<	>	<	>
M	↘	↗	↗	↘
U	↘	↗	↗	↘
T	↗	↘	↘	↗
ρ	↗	↘	↘	↗

Comparison with 1-D Isentropic Flow Model





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Summary

東北大学におけるMPDアークジェットを用いた高ベータ･高速プラズマ流の生成と制御に関する最近の研究結果を紹介した.

- DLPを用いたマッハプローブの較正実験
- MPDアークジェットプラズマ中の電磁場計測
- 磁気ラバールノズルによるプラズマ加速

高ベータ･高速プラズマ流の制御

アドバンスト核融合, 宇宙ジェットの構造解明
および電気推進機開発への貢献