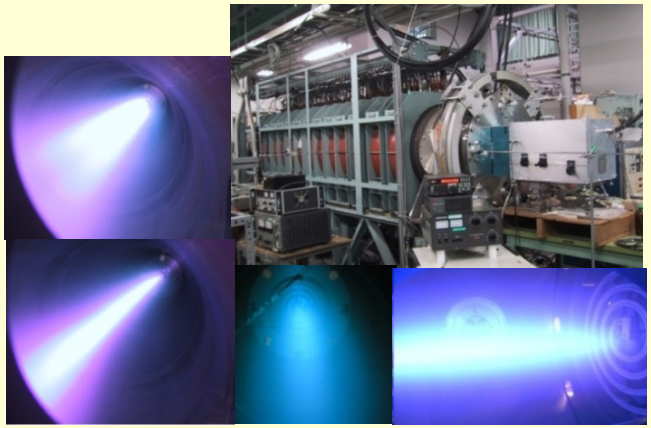
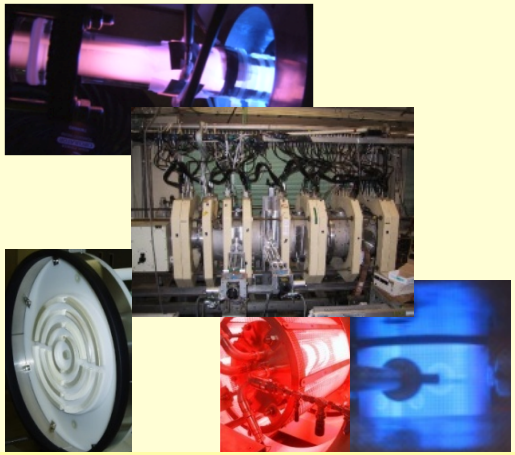
筑波大学平成23年度合同研究会　(7月22日：つくばサイエンスインフォーメーションセンター)

プラズマ端での高密度プラズマ流生成・制御の基礎研究

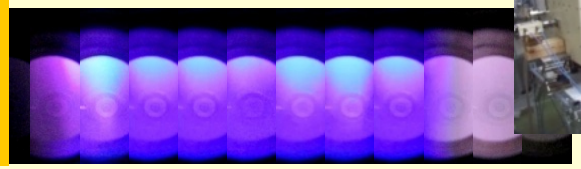




九州大学　大学院総合理工学研究院
東京農工大学 大学院工学研究院　篠原　俊二郎
http://www.tuat.ac.jp/~sinohara/

九州大学　大学院総合理工学研究院　羽田　亨
http://www.esst.kyushu-u.ac.jp/~space/

筑波大
市村真、池添竜也
横山拓郎、宇賀神ゆめと



Outline

広域ヘリコン高密度プラズマ科学の進展

~ MHz, kW ⇒ 10^{13} cm^{-3} : 幅広い運転領域と応用

⇨ 新規スタート：ガンマ 10 対象
関係者との議論と方向性の決定

1. ヘリコン波とは？

プラズマ源の重要性　cf. 高周波プラズマ生成法

分散関係、励起アンテナと応用研究例

2. ヘリコン波プラズマ源の開発と応用 : 我々の研究例

構造形成、密度分布とプラズマ流分布制御

3. 大容量高密度ヘリコンプラズマ : 短軸長化、高ベータ

4．今後の展望 : ヘリコンプラズマによる貢献

➡ プラズマ端での高密度
プラズマ流生成・制御の基礎研究

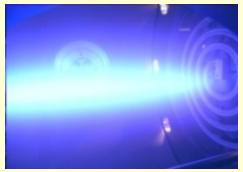
ヘリコン
プラズマ源の
開発と応用
(解説)

Key Issues for Plasma Sources

Basic Studies & Application

★ Helicon Source is Promising !

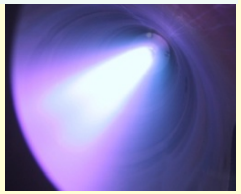
1. High-Density: e.g., High-Speed Processing



$> 10^{13}$ cm^{-3} w/ Flexible Operation

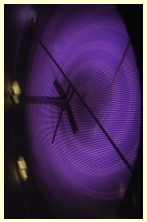
ICP, SW, ECR $< 10^{12}$ cm^{-3}, CCP $< 10^{11}$ cm^{-3}

2. Large Area or Large Volume: Efficiency & Flexibility



$D < 15$ cm $\Rightarrow$ 74 cm, $V < 0.1$ m^3 $\Rightarrow$ 2.1 m^3

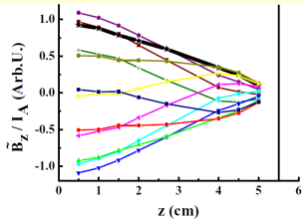
3. Low Aspect Ratio: Efficiency for Application



$A = L/D = 0.5 \Rightarrow 0.075$ *cf.* $A = R/a$

Characterization: Importance

Production, Profile, Wave Structures



★High Beta, Flow: Structure and Instabilities (Fusion, Space Plasma etc.)

Helicon Wave Plasma

Highly Efficient Plasma Production

Bounded Whistler Wave ⇒ High-Density Plasma

$\omega_{ci} << \omega << \omega_{ce}$ ~ MHz, kW ⇒ 10^{13} cm^{-3}

Wide Operational Region

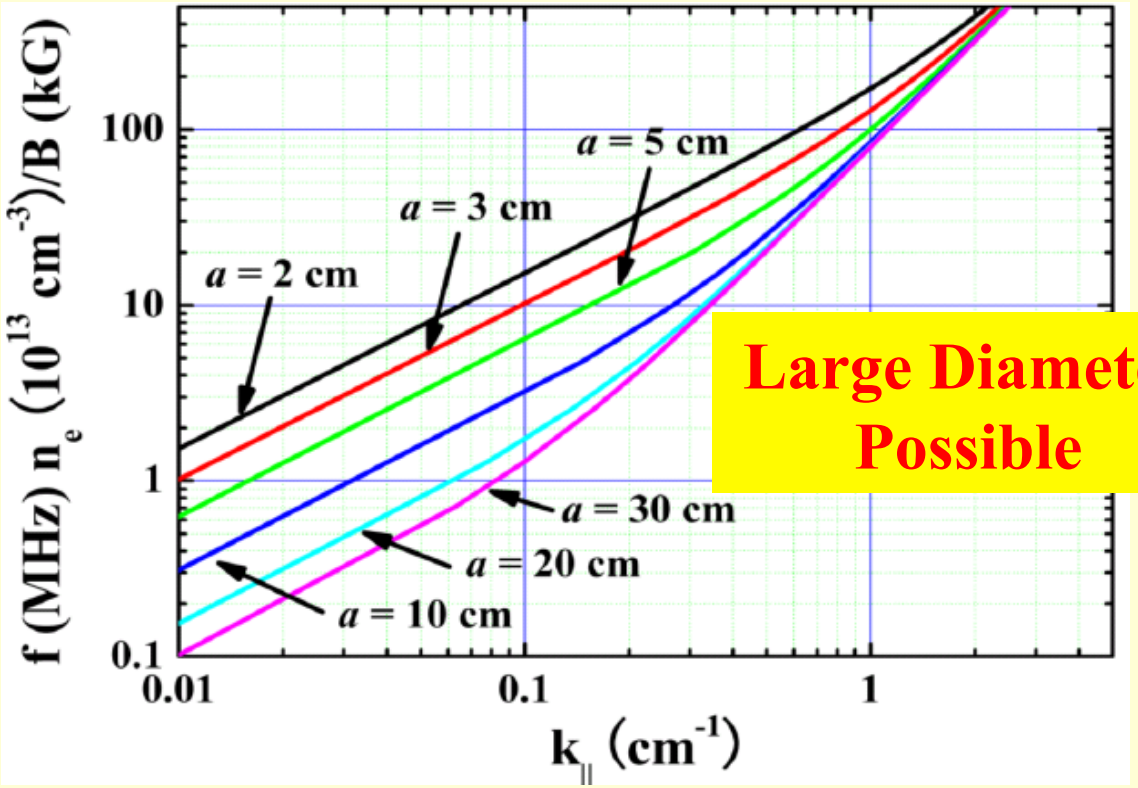
Promising Plasma Source: Many Applications

★ 非線形現象、構造形成

基礎実験、プロセス、
核融合 (e.g., ステラレータ)
ガスレーザー、
宇宙プラズマモデリング
プラズマ加速/ 推進 …

Dispersion Relation

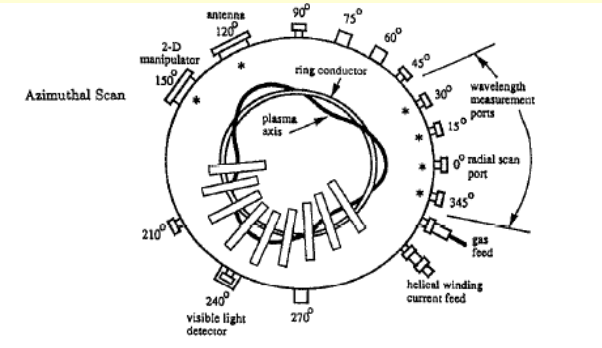
$$k_{\parallel}^2(k_{\parallel}^2 + k_{\perp}^2) = \left(\frac{\omega\omega_{pe}^2}{\omega_{ce}c^2}\right)^2$$



Large Diameter Possible

Examples of Application

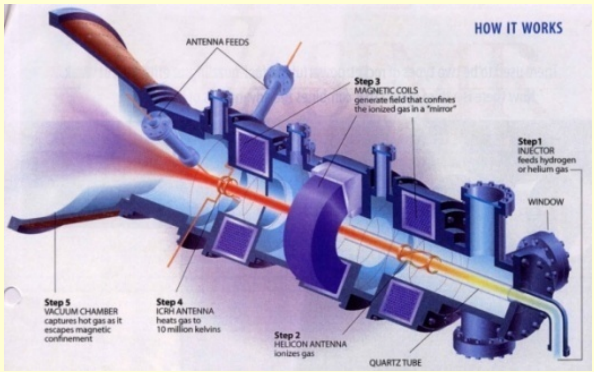
Nuclear Fusion



SHEILA (ANU)
B. C. Zhang *et al*, POP (1995).

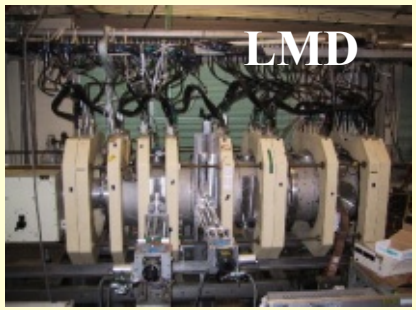
+ Heliotron DR, TJ-K

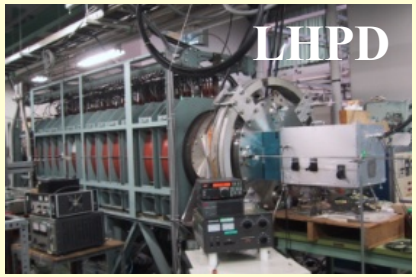
Plasma Thruster



VASIMR
F. R. Chang-Díaz *et al*. (NASA)

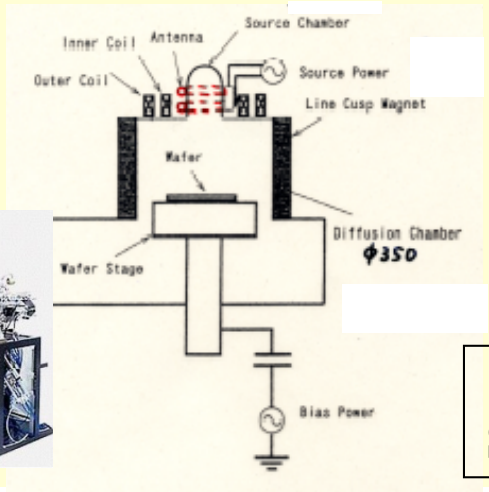
Basic Study, Space Plasma Simulation

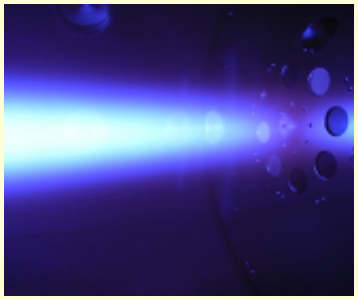




Industrial Application

Etching Device
T. Tsukada *et al*., JJAP (1994).





PWI (Ceramics)
S. Shinohara *et al.* (2009).

Outline

広域ヘリコン高密度プラズマ科学の進展

~ MHz, kW ⇒ 10^{13} cm^{-3} : 幅広い運転領域と応用

新規スタート : ガンマ 10 対象
関係者との議論と方向性の決定

1. ヘリコン波とは？

プラズマ源の重要性　cf. 高周波プラズマ生成法

分散関係、励起アンテナと応用研究例

2. ヘリコン波プラズマ源の開発と応用 : 我々の研究例

構造形成、密度分布とプラズマ流分布制御

3. 大容量高密度ヘリコンプラズマ : 短軸長化、高ベータ

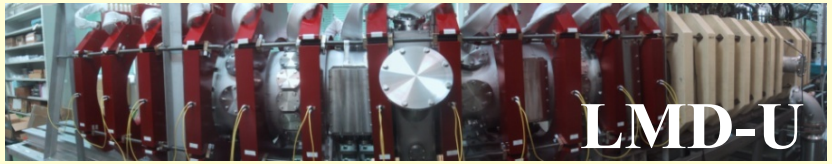
4 . 今後の展望 : ヘリコンプラズマによる貢献

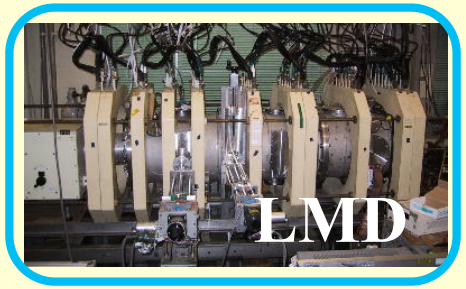
プラズマ端での高密度
プラズマ流生成・制御の基礎研究

代表者

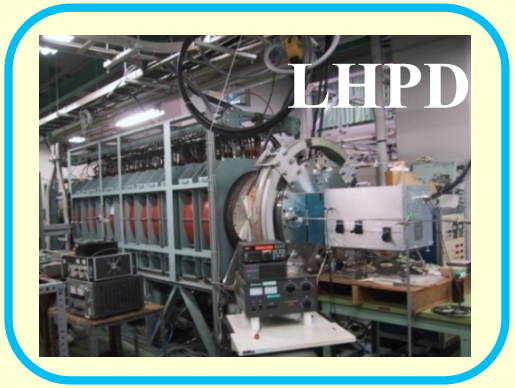
開発した高密度ヘリコンプラズマ源群

制御した7つのユニークな装置：多くの世界記録



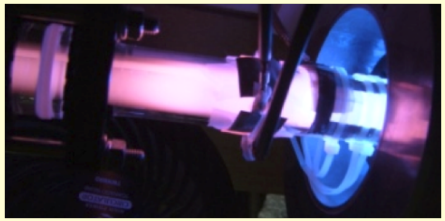


九大 → 東京農工大 (一部)
種々のアンテナ
(40-45 cm$^{\phi}$, 120-374 cm^{l})

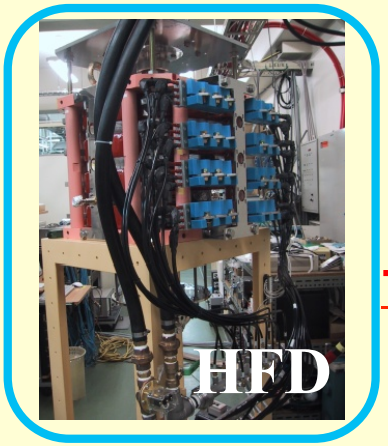


宇宙研
世界最大容量
(74 cm$^{\phi}$, 486 cm^{l})
最小アスペクト比
(A = 0.075)

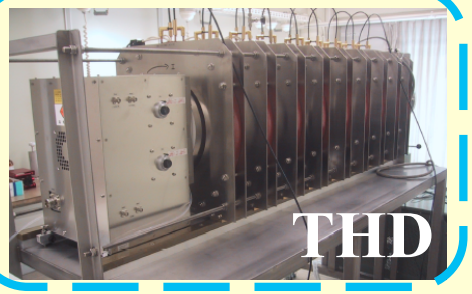
D < 15 cm ⇒ 74 cm, V < 0.1 m^3 ⇒ 2.1 m^3



東京農工大
世界最小容量
(2.5 cm$^{\phi}$, > 4.7 cm^{l})



九大→東京農工大
世界最強磁場 (完成当時)
10 kG
(10 cm$^{\phi}$, 30-100 cm^{l})

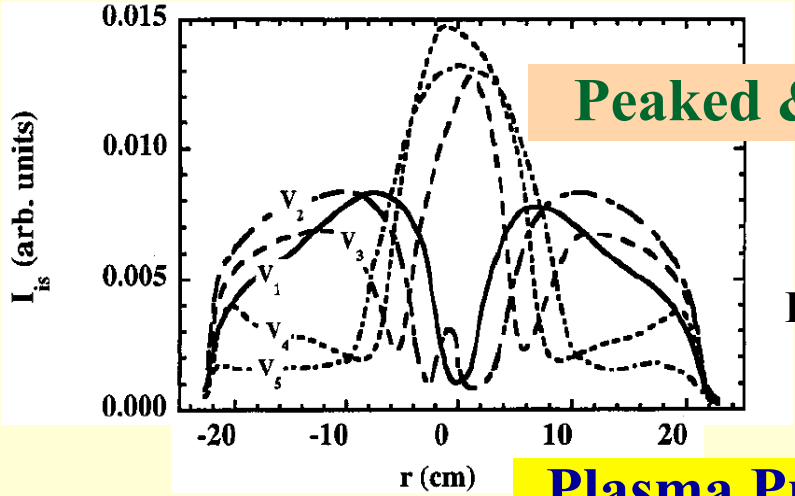


東海大
新アンテナ
(20 cm$^{\phi}$, 100 cm^{l})

LMD Applications (No. 1)

Low Density (Voltage Biasing)

Profile Control

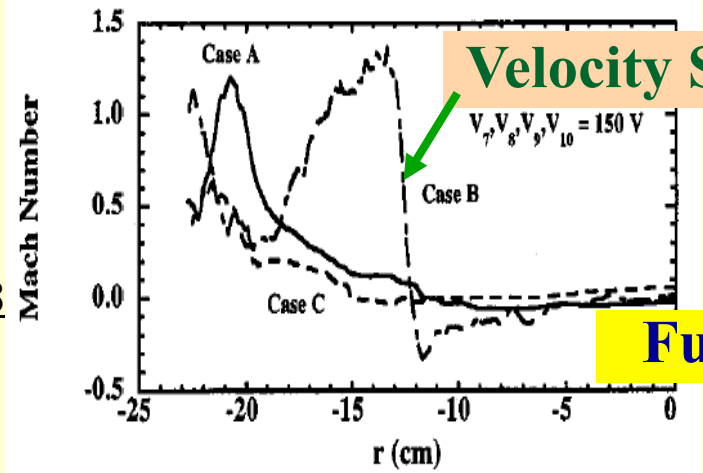


Peaked & Hollow

Phys. Plasmas 8 (2001)1154.

Plasma Processing

Plasma Flow Control

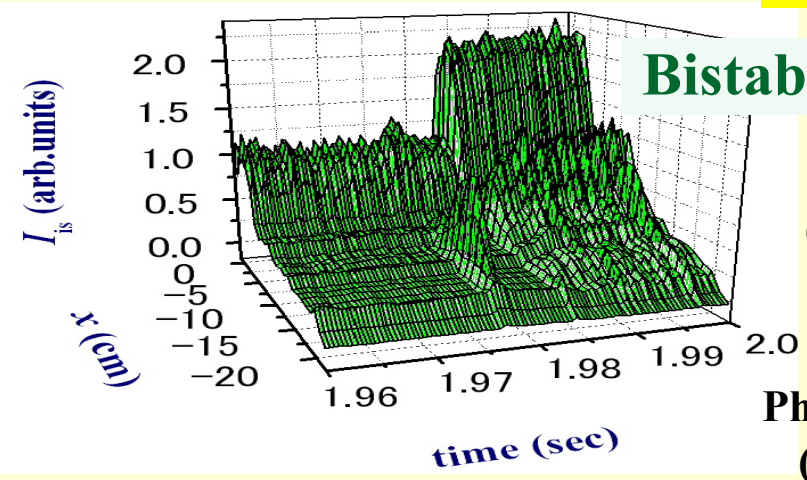


Velocity Shear

Fusion

Density Transition

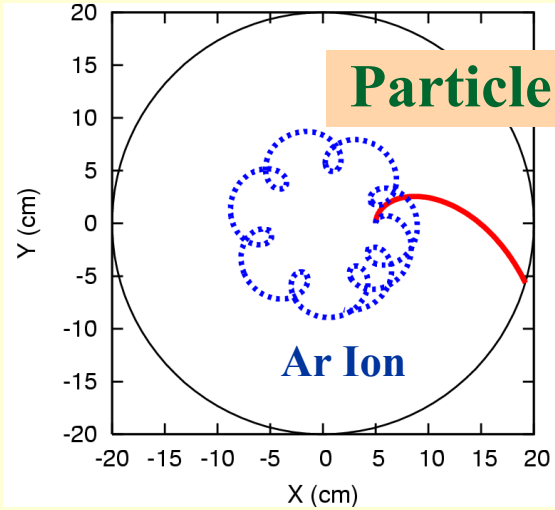
Fusion



Bistable

Hysteresis (Statistics)

Phys. Plasmas 9 (2002) 4540.



Particle Orbits

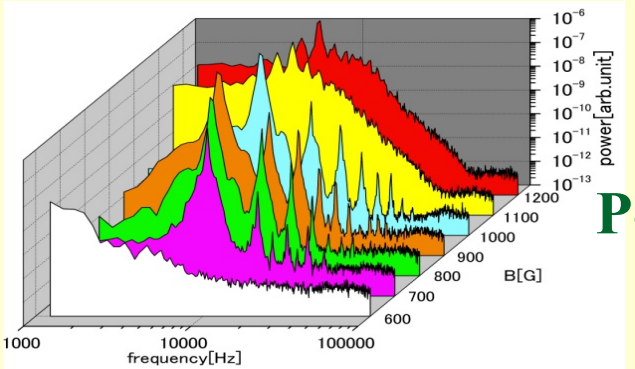
Jpn. J. Appl. Phys. 46 (2007) 4276.

Mass Separation

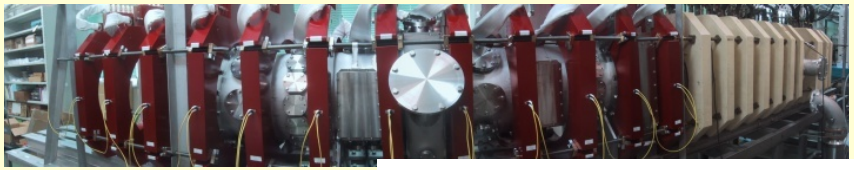
$$v_\theta = \frac{\omega_{ci} r}{2}\left(-1 \pm \sqrt{1 - 4E_r/rB_z\omega_{ci}}\right)$$

LMD-(U) Applications (No. 2) High Density

Turbulence Study

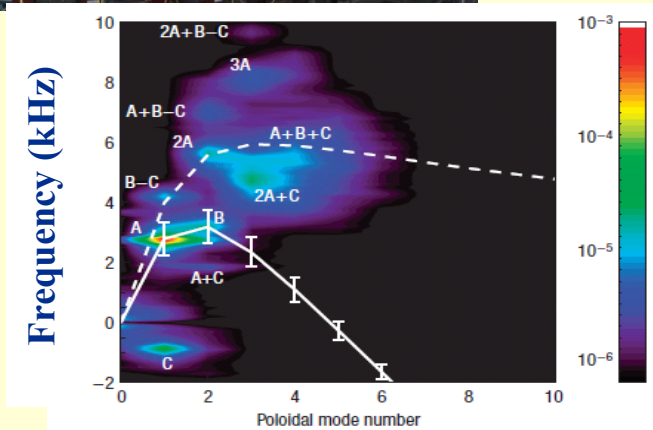


Power Spectra



SPR (JSPS)

P.I.: Prof. S.-I. Itoh

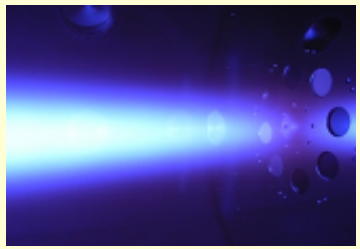


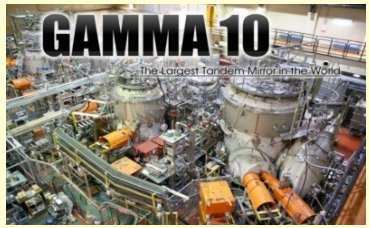
Mode Coupling

Poloidal Mode

(Nature Phys. 4 (2008) 721 etc.)

PWI (Ceramics)





Basic & Application Studies

★ Linear Machine

Fusion, Basic Plasma, Propulsion, Space Plasma, Processing …

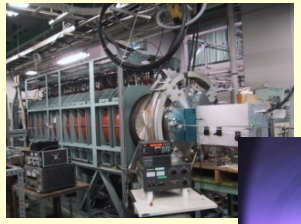
我々のまとめ

ヘリコン科学成果

“ World Famous ”

期待されるターゲットプラズマ：高密度、幅広い運転領域、制御性

生成機構解明、機能性プラズマ生成/インテリジェント制御

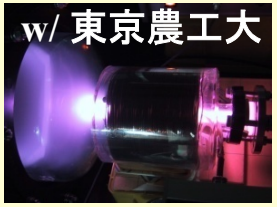


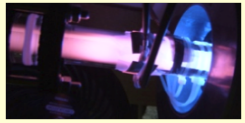
アンテナ開発、特許 2 件取得

w/ 東海大

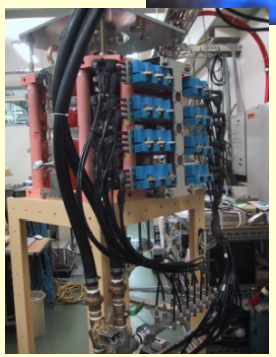
世界最大容量：2.1 m^3
世界最小容量：23 cm^3
世界最強磁場：10 kG
世界最薄　　：5.5 cm

(最大と最小直径、最小軸長)





★ プラズマ推進



プラズマ分布制御

種々の

プロセス源

超音速プラズマ流制御

遠心/異種イオン

分離

遷移現象　　安定性：基礎/核融合

乱流研究　　安定性：基礎/核融合

国内外への広い波及効果

基礎研究用プラズマ源
半導体関連、機能性材料
材料照射
新領域への展開
(滅菌、ダスト、新配位)

Outline

広域ヘリコン高密度プラズマ科学の進展

~ MHz, kW ⇒ 10^{13} cm^{-3} : 幅広い運転領域と応用

新規スタート : ガンマ 10 対象
関係者との議論と方向性の決定

1. ヘリコン波とは？

プラズマ源の重要性　cf. 高周波プラズマ生成法

分散関係、励起アンテナと応用研究例

2. ヘリコン波プラズマ源の開発と応用 : 我々の研究例

構造形成、密度分布とプラズマ流分布制御

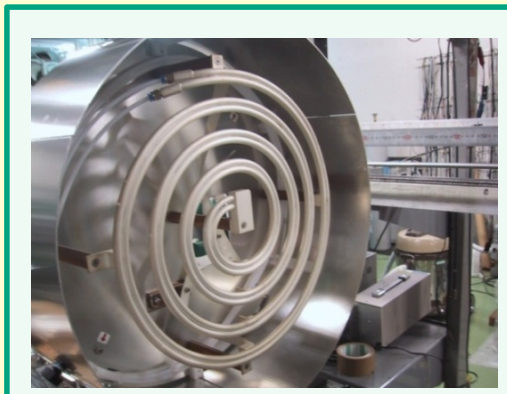
3. 大容量高密度ヘリコンプラズマ : 短軸長化、高ベータ

4 . 今後の展望 : ヘリコンプラズマによる貢献

プラズマ端での高密度
プラズマ流生成・制御の基礎研究

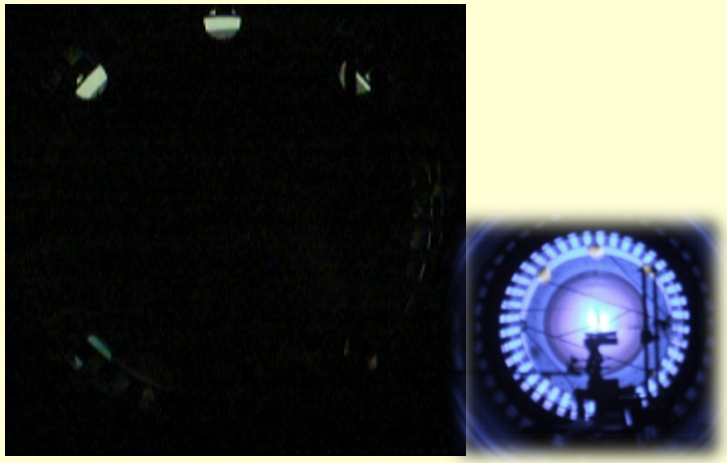
The Largest Helicon Device

(Third Type)

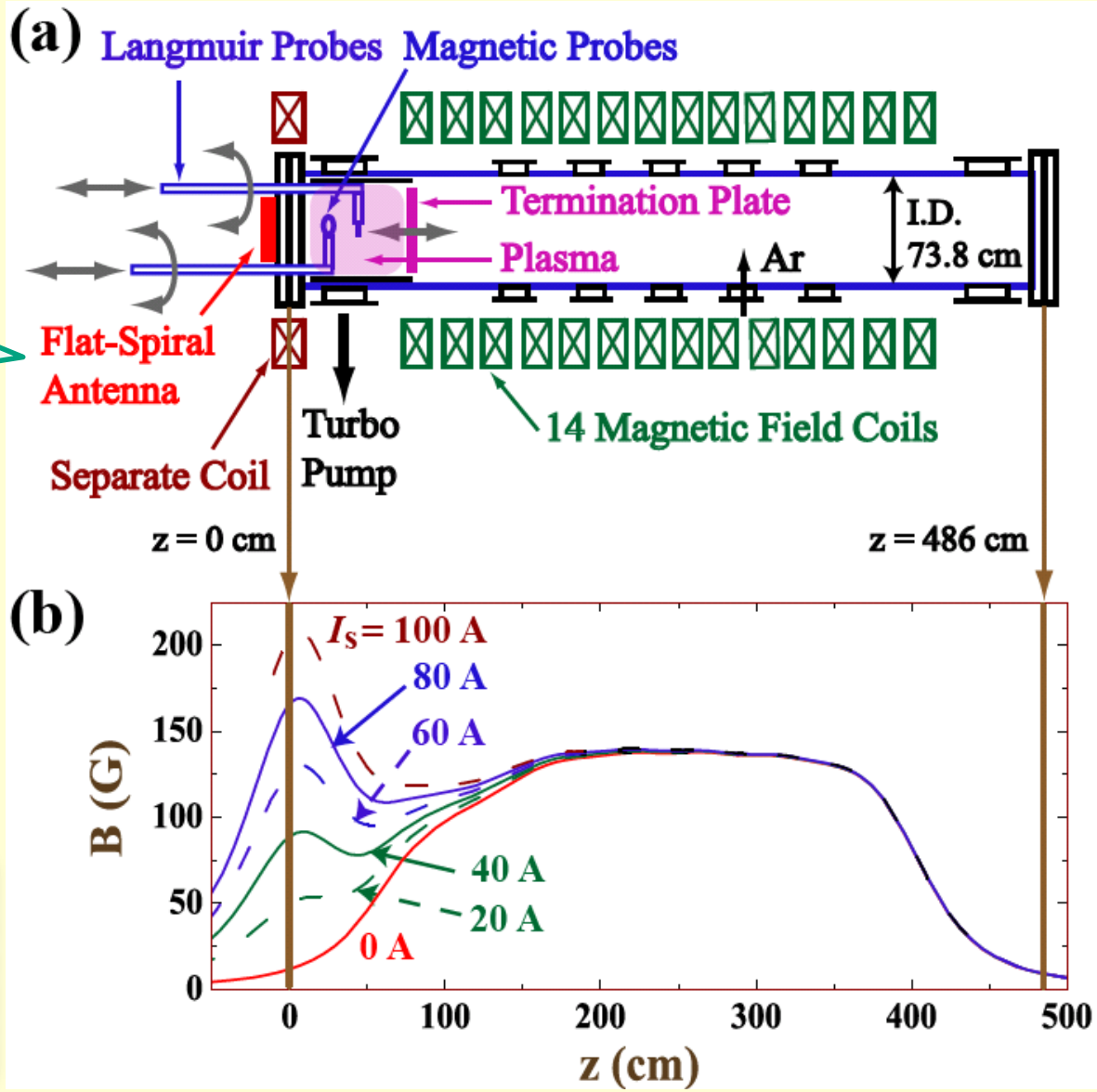


(43 cm$^{\phi}$,0.5-4 Turns)

(Outside Quartz Window)

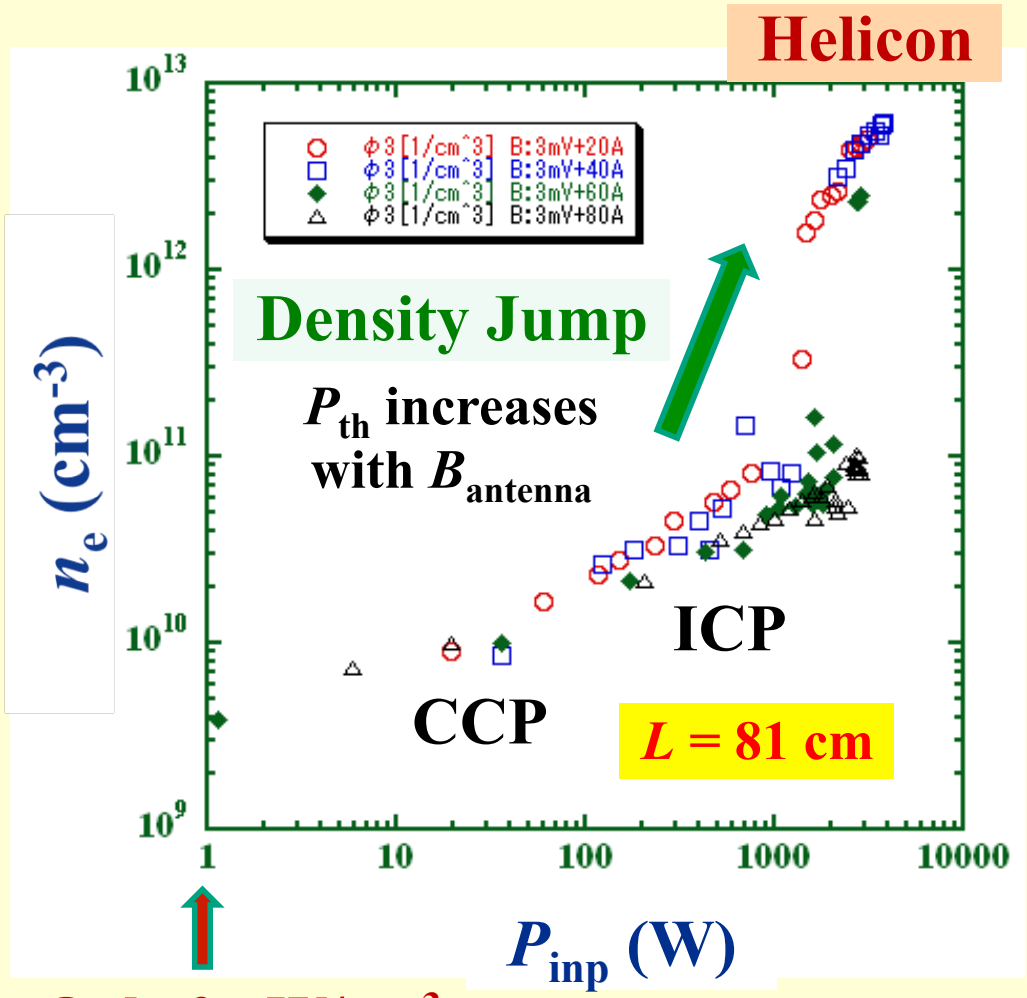


From End, Viewing Antenna



D = 74 cm

Excellent Production Efficiency n_e vs. P_{inp}



Only 3 μW/cm^3

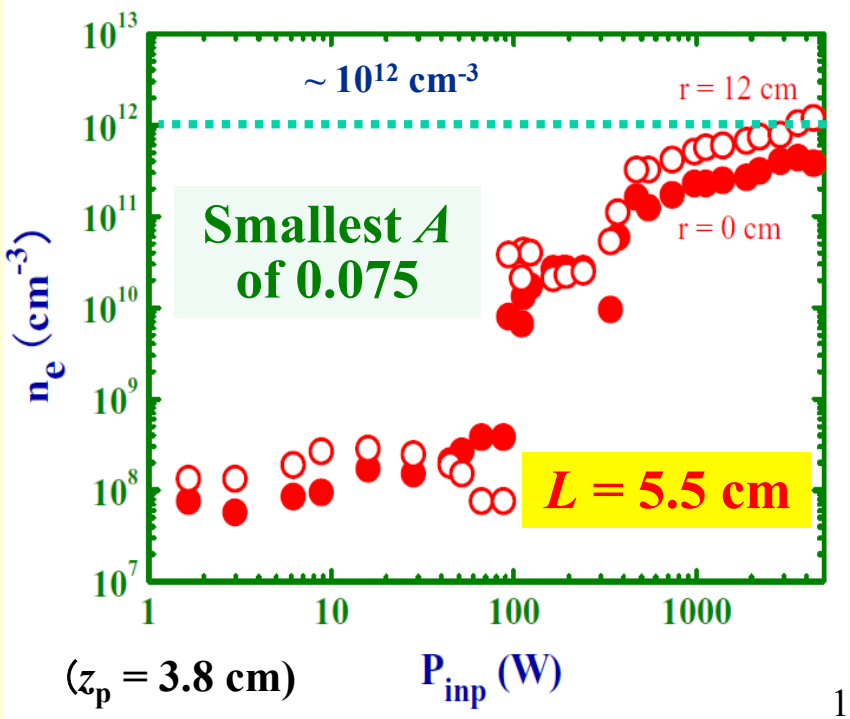
(z_p = 45 cm)

cf. ICP: ~ 10^{12} cm^{-3} (L = 10cm)

n_e close to 10^{13} cm^{-3} with P_{inp} < 4 kW

L = 486 cm

Excellent Production Efficiency of ~ 10^{15} Particles/W



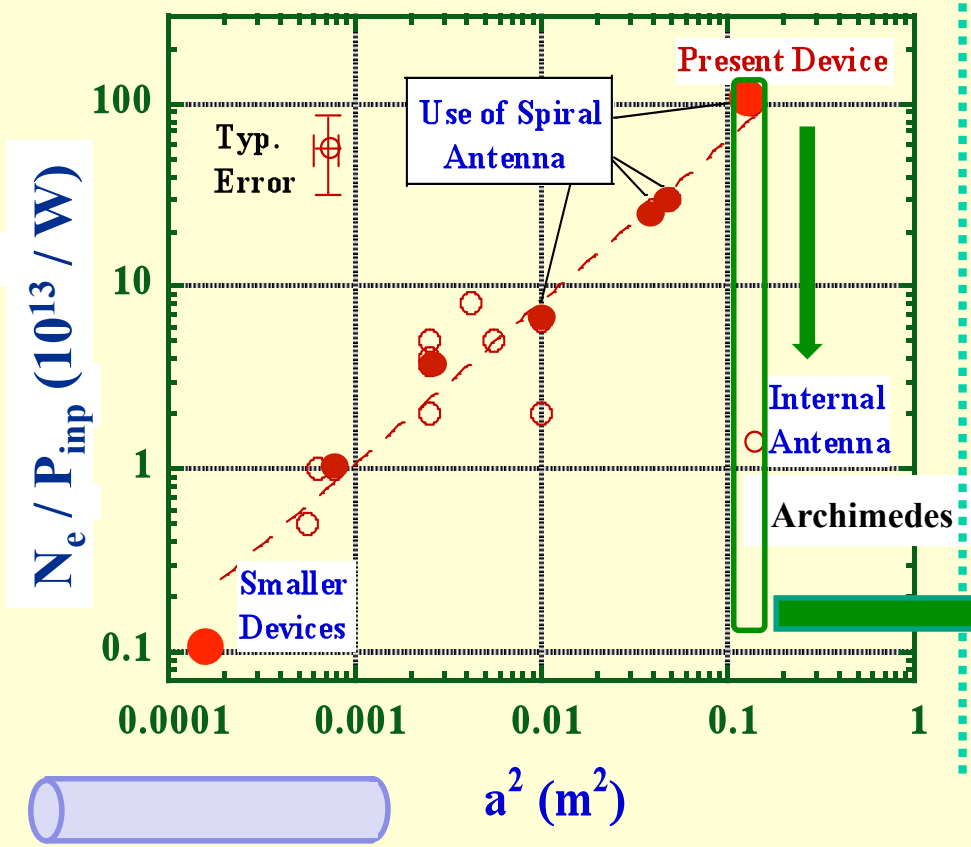
(z_p = 3.8 cm)

Particle Production Efficiency (Exp.)

Loss Across the Field

Small Radius a
Long Axial Length L
Weak Magnetic Field B

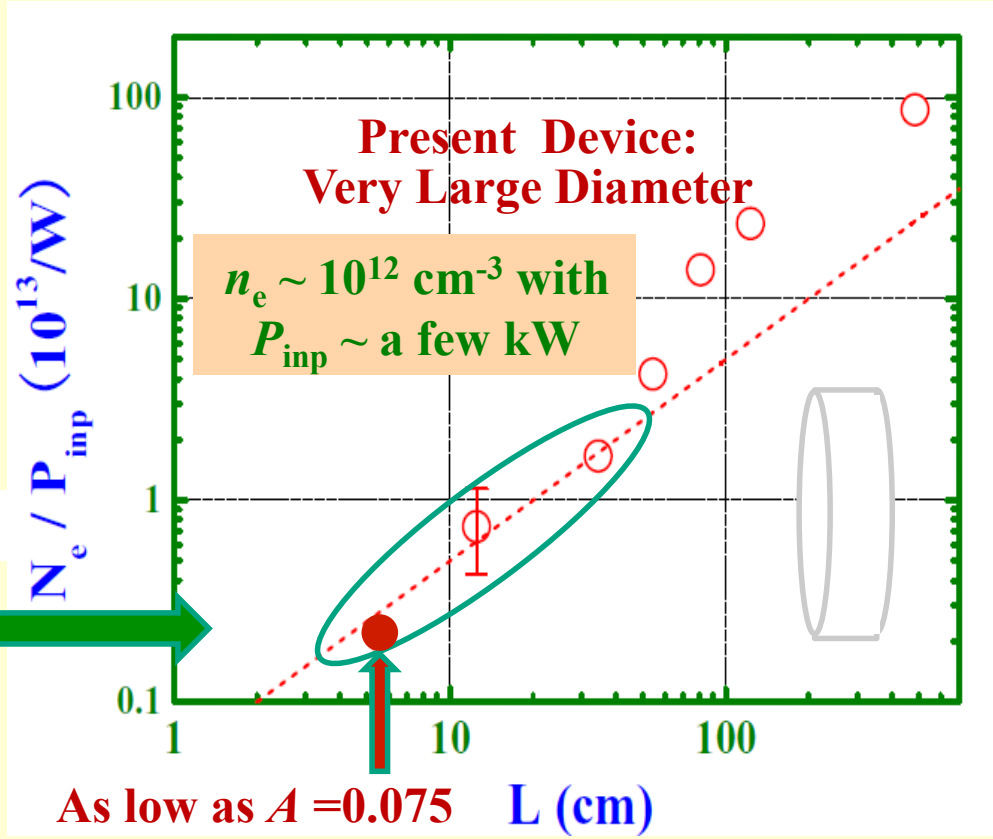
$$N_e / P_{inp} \propto a^2$$



Loss Along the Field

Large a
Short L
Strong B

$$N_e / P_{inp} \propto L$$



High Beta Effect

Basic, Fusion
& Space Physics

★ MHD Conditions

Beta = Plasma Pressure / Mag. Pressure
Industrial Application: Efficiency

Normalized Scale Lengths (ρ/a)
Hall Parameter ($\Omega_c \tau$)
Resistive Time (Characteristic Time)
cf. Mag. Reynolds Number

+ New Findings !?

★ Diamagnetic Effect:
Spatio-Temporal Structures
(+ Particle Behavior & Excited Waves)
cf. Magnetic Hole

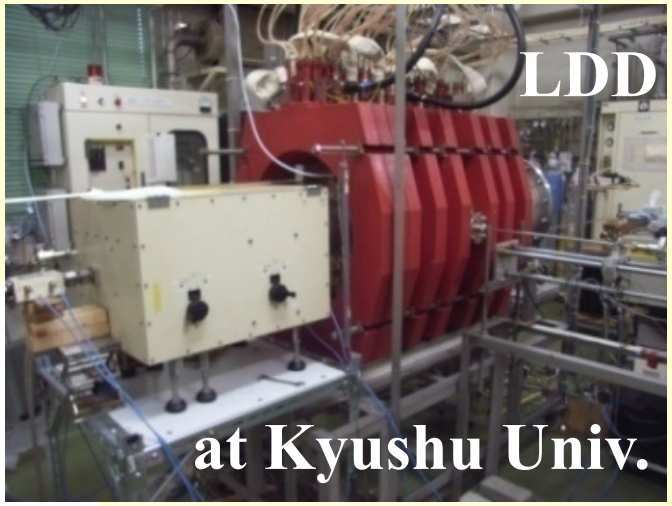
★ Induced Instabilities:
Mirror, Fire Hose, Alfven Ion Cyclotron,
Drift Alfven Instabilities …

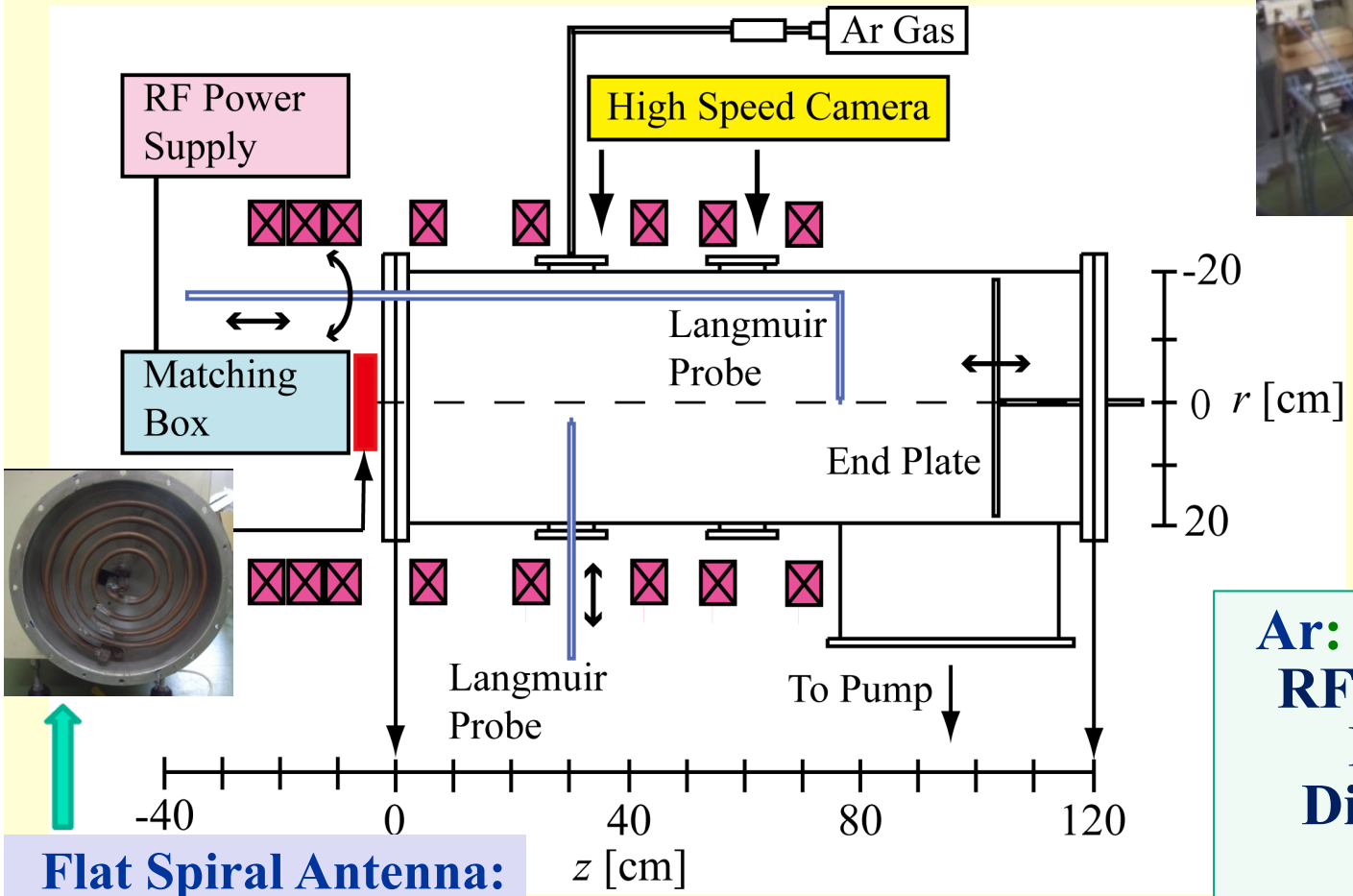
★ Initial Try of Reaching High Beta Value with Low Magnetic Field

cf. ★ Low Aspect Ratio

Large Diameter (Helicon) Device

Up to 0.16 m^3
40 cm I.D.
Axial Length *L*: 9.5 – 126 cm



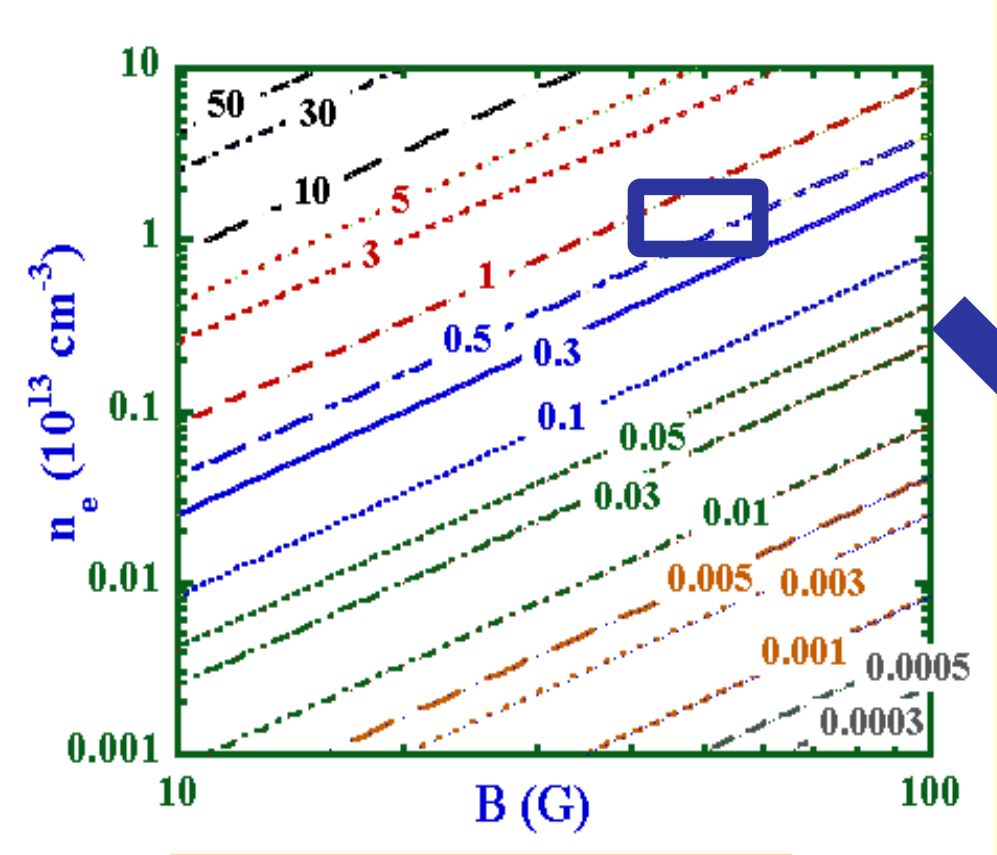


Flat Spiral Antenna:
18 cm$^{\phi}$, 4 Turns

RF System & Results
S. Shinohara *et al.*,
Jpn. J. Appl. Phys.
35 (1996) 4503.
Plasma Sources Sci.
Technol. 10 (2010) 052313.

Ar: 3 mTorr – 10 mTorr
RF Frequency: 7 MHz
RF Power: 5 kW
Discharge Duration:
~ 12 ms (10 pps)

Beta and Density in (P_{Ar}, B) Space



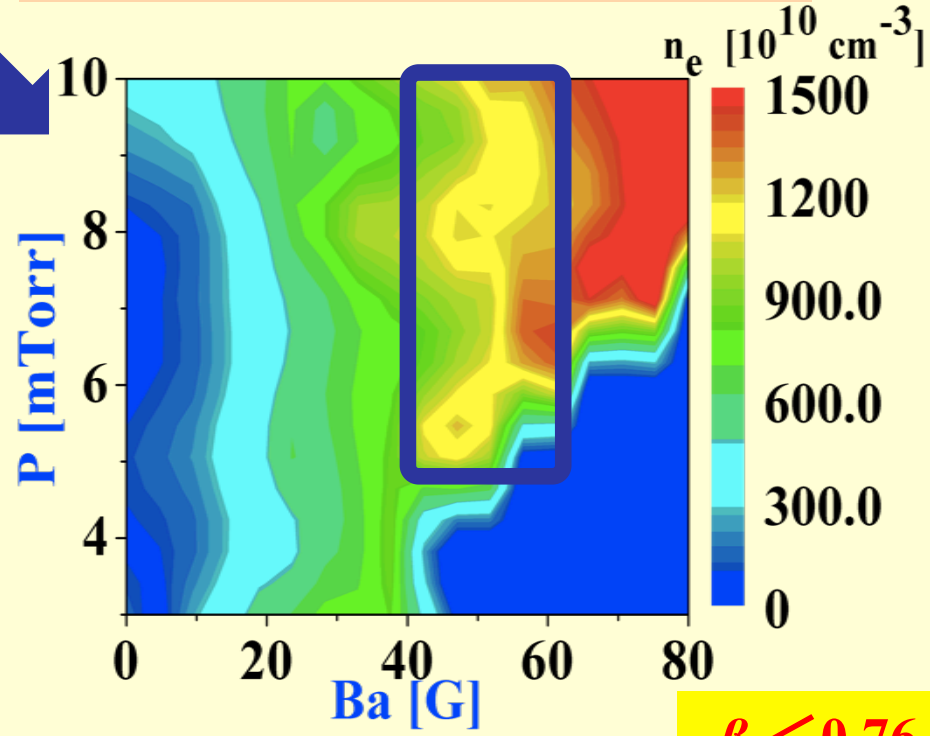
[Contour of Beta]

(Ratio of Plasma Pressure to Mag. One)

MHD Conditions:

Larmor Radius, $\Omega_c \tau$, Skin Time

High Density > 10^{13} cm^{-3}



$\beta_0 < 0.76$

[Contour of Electron Density]

High Beta: Structure and Instabilities

(Fusion, Space Plasma etc.)

Outline

広域ヘリコン高密度プラズマ科学の進展

~ MHz, kW ⇒ 10^{13} cm^{-3} : 幅広い運転領域と応用

新規スタート : ガンマ 10 対象
関係者との議論と方向性の決定

1. ヘリコン波とは？

プラズマ源の重要性　cf. 高周波プラズマ生成法

分散関係、励起アンテナと応用研究例

2. ヘリコン波プラズマ源の開発と応用 : 我々の研究例

構造形成、密度分布とプラズマ流分布制御

3. 大容量高密度ヘリコンプラズマ : 短軸長化、高ベータ

4 . 今後の展望 : ヘリコンプラズマによる貢献

プラズマ端での高密度
プラズマ流生成・制御の基礎研究

4. 今後の展望：ヘリコンプラズマによる貢献

広域ヘリコン高密度プラズマ科学の進展

~ MHz, kW ⇒ 10^{13} cm^{-3}：幅広い運転領域と応用

⇨ 新規スタート：ガンマ 10 対象
関係者との議論と方向性の決定

I. 高密度プラズマ源

初期プラズマ生成　cf. 分布制御

壁洗浄

プラズマ―壁相互作用　cf. APSEDAS (Helicon)

II. 高密度プラズマ流制御

周・軸方向　cf. 平衡と安定性制御

III. 高ベータプラズマ

構造形成、安定性：動的変化　cf. AIC (GAMMA 10)

★ 理論・シミュレーション
研究との比較

➡ プラズマ端での高密度
プラズマ流生成・制御の基礎研究

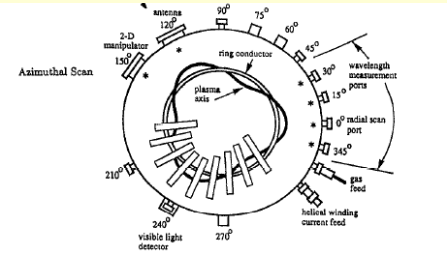
I. 高密度プラズマ源

初期プラズマ生成

cf. 分布制御

開放端系 OK

ガス種



環状系 SHEILA

＋ TJ-K, Heliotron DR …

壁洗浄

環状系 ?

開放端系 OK

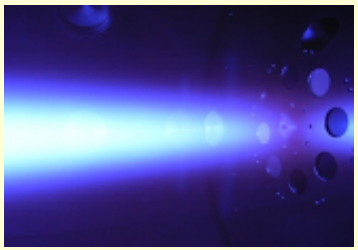
ガス種

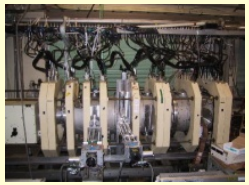
cf. TDC, GD, Baking

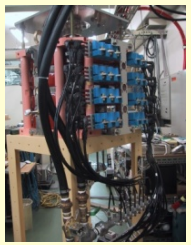
プラズマー壁相互作用

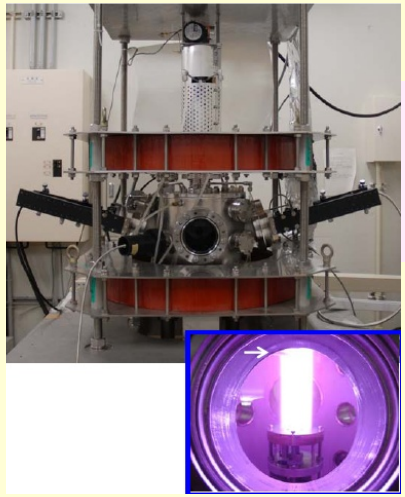
LMD, SMD, HFD

cf. Ceramics







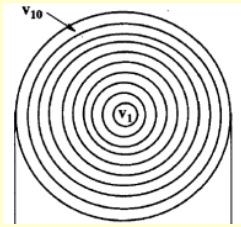


cf. APSEDAS (Helicon)

II. 高密度プラズマ流制御

周方向プラズマ流

e.g., 多重極電圧バイアス法

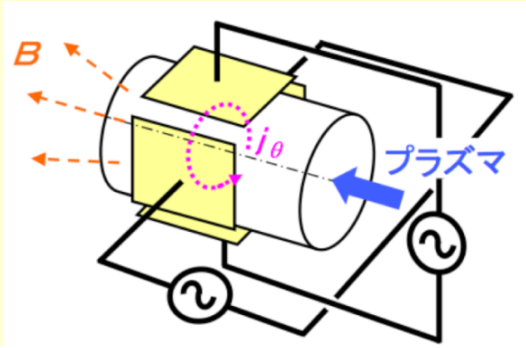


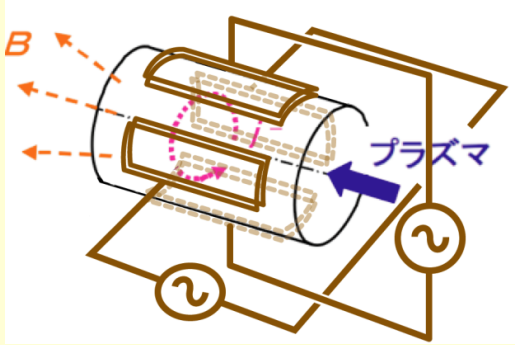
開放端系 OK

軸方向プラズマ流

開放端系 OK

e.g., 新プラズマ推進法
（プロジェクト）





平衡と安定性制御

e.g., 分布制御、乱流制御

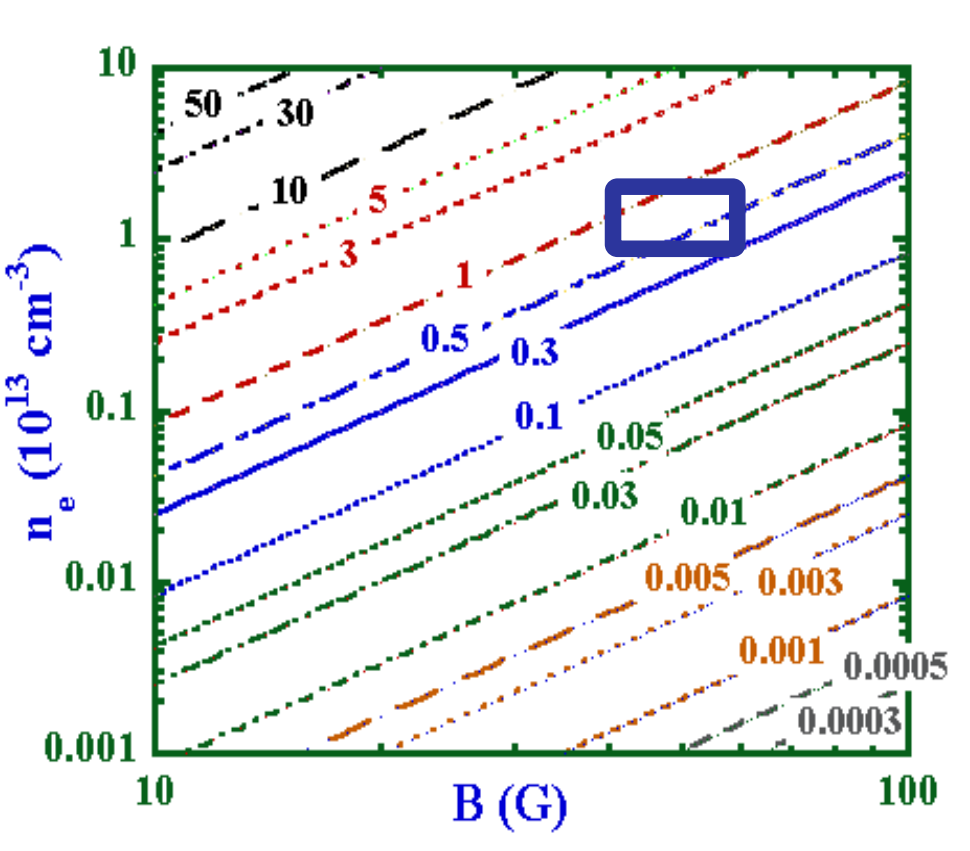
不純物排出
プラズマ粒子補給

e.g., $n_e \sim 10^{19}$ m^{-3}
$v >> 10^3$ m/s
(定常可能)

c.f. ICR

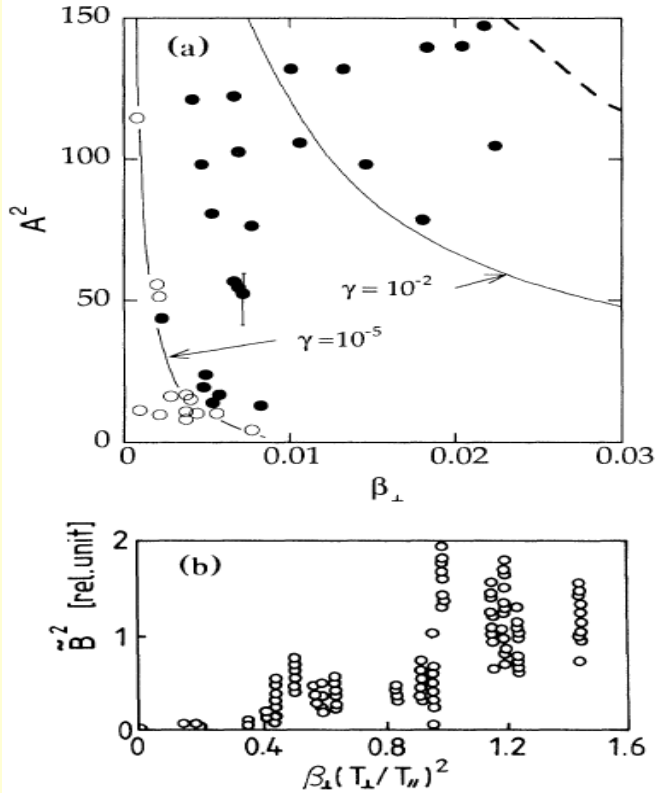
III. 高ベータプラズマ

無電流
低磁場・高密度



密度ー磁場空間での
ベータ値

$\beta = p_e / (B_0^2/2\mu_0)$



βと磁場揺動の関係

cf. AIC (GAMMA 10)

○：揺動なし
●：揺動あり

★$B^2/2\mu_0 + p_e > B_0^2/2\mu_0$

Larmor Radius < Plasma Radius
$\Omega_c \tau < 1$ (Ion), >1 (Electron)
★ $\tau = \mu_0 \sigma a^2$ < Discharge Duration

共通性:リニア装置

まとめ

ヘリコンプラズマによる貢献

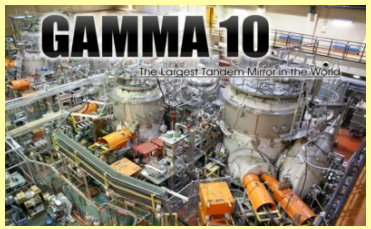
広域ヘリコン高密度プラズマ科学の応用

★ 関連研究者

~ MHz, kW ⇒ 10^{13} cm^{-3} : 周辺制御、輸送制御

★ 基礎

⇨ 新規スタート：ガンマ 10 対象
関係者との議論と方向性の決定

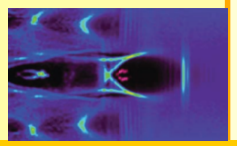


I. 高密度プラズマ源

初期プラズマ生成　cf. 分布制御

壁洗浄

プラズマ―壁相互作用　cf. APSEDAS (Helicon)



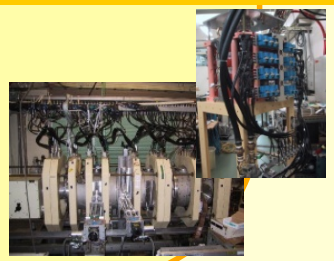
II. 高密度プラズマ流制御

周・軸方向　cf. 平衡と安定性制御

★ 理論・シミュレーション研究との比較

III. 高ベータプラズマ

構造形成、安定性:動的変化　cf. AIC (GAMMA 10)



➡ プラズマ端での高密度
プラズマ流生成・制御の基礎研究

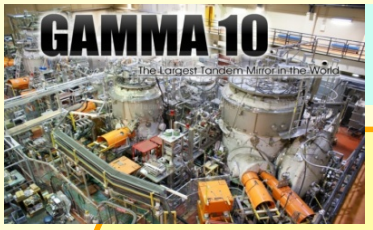
共通性:リニア装置

測 定 系

ヘリコンプラズマによる貢献

広域ヘリコン高密度プラズマ科学の応用

★ 関連研究者



~ MHz, kW ⇒ 10^{13} cm^{-3} : 周辺制御、輸送制御

I. 静電、磁気計測 (1D, 2D, 3D : マルチ) 機動性

静電プローブ (SP, DP, TP: MP)

磁気プローブ

IEA

ロゴスキーコイル

2 次元駆動

48 チャンネル

II. 光計測

高速度カメラ

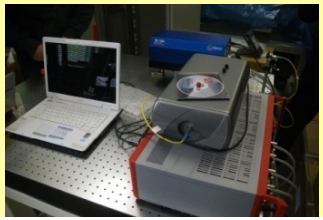
分光器 1.5 m

LIF

IR カメラ

フォトロン
FASTCAM SA : 1 MFPS

1.5 m 分光器



ダイオードレーザー
(TOPTICA) : 0.5 W
668.6 nm (蛍光442 nm)

III. その他

[波動を用いた主なプラズマ生成法の比較]

(プラズマプロセス分野)　cf. NLD(磁気中性線放電)

	CCP (容量性結合)	ICP (誘導性結合)	電子サイクロトロン波	ヘリコン波	表面波
周波数 (MHz)	0.05−13.56↑	1 − 20↑	2450↓	5 − 30	1 − 10000
圧力 (mTorr)	100 − 5000	0.5 − 200	0.1 − 10	0.3 − 30	5↓ − 3000
磁場 (G)	0	0	~ 875↓ (固定)	50 − 1000	0
励起法	平行平板	コイル	導波管 スロット	コイル	スロット 導波管 誘電板
電子密度 (cm^{-3})	$10^{9} - 10^{11}$	$10^{11} - 10^{13}$	$10^{11} - 10^{13}$	$10^{12} - 10^{13}$	$10^{10} - 10^{12}$
波動	非伝搬 (近接場)	非伝搬 (近接場)	伝搬	伝搬	伝搬
逆アスペクト比	3 − 10	2 − 5	0.5 − 2↑	0.5 − 2↑	0.1 − 2↑
生成機構	統計加熱 衝突減衰 二次電子加速	衝突減衰 無衝突電子加熱	電子サイクロトロン減衰 衝突減衰	衝突減衰 電子ランダウ減衰？ TG誤？	衝突減衰 無衝突電子加熱？

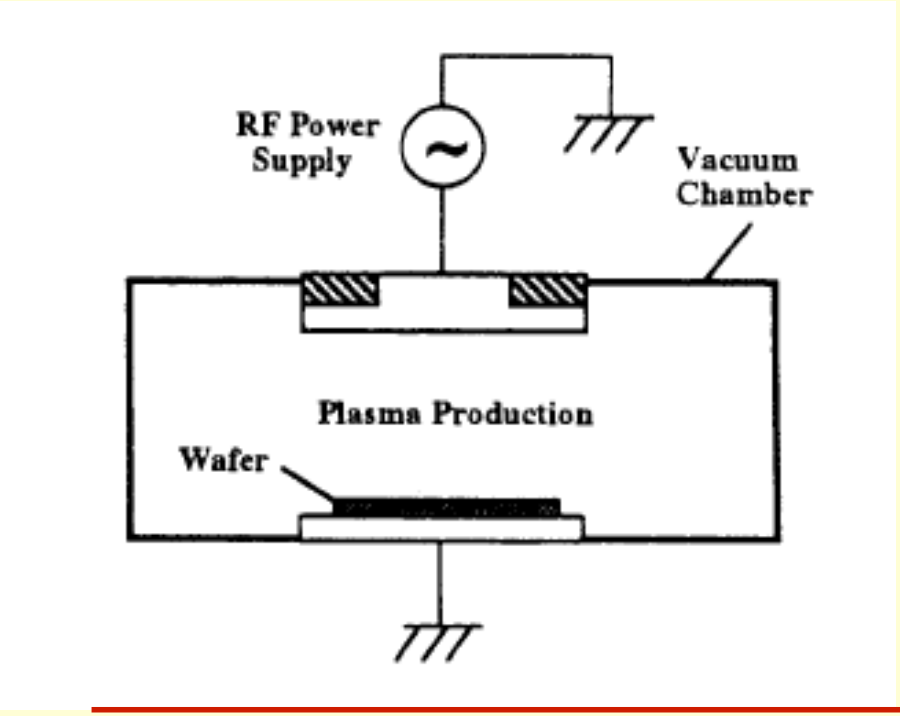
(核融合分野)

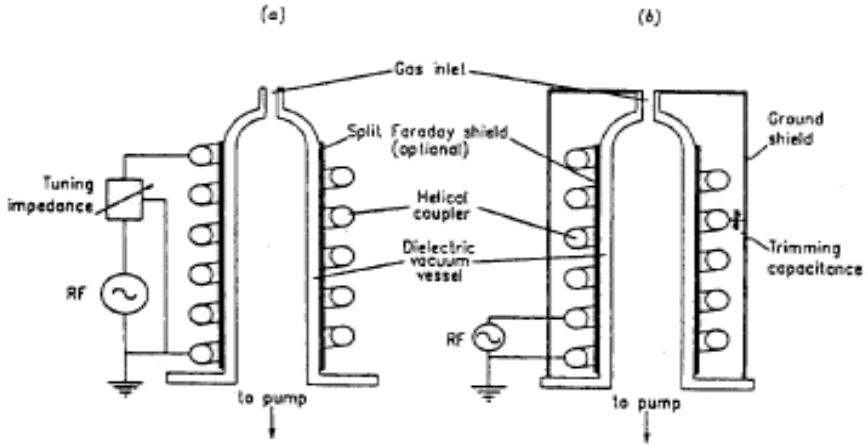
生成、加熱、電流駆動

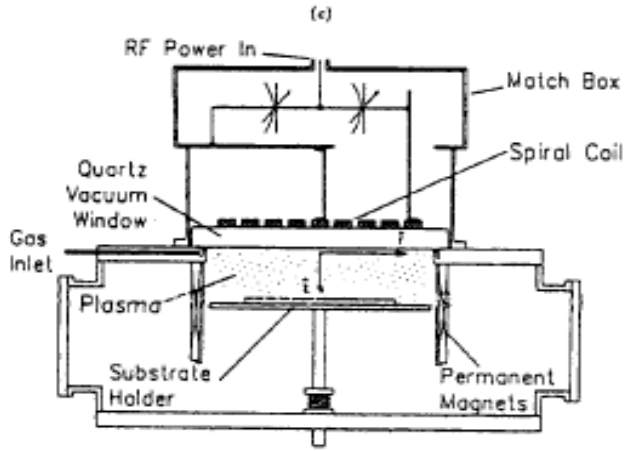
電子サイクロトロン及びイオンサイクロトロン周波数領域の波、
低域混成波、アルフヴェン波　(EBW, HHFW)

典型的な容量性結合型プラズマ(CCP)：平行平板型

低電離度：シース近傍統計加熱、衝突減衰、二次電子加速

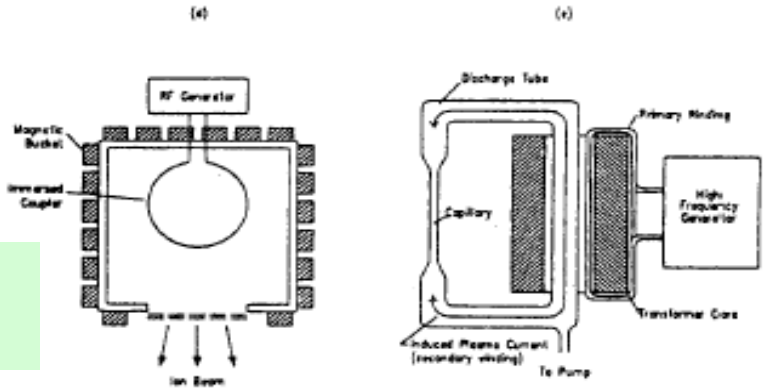




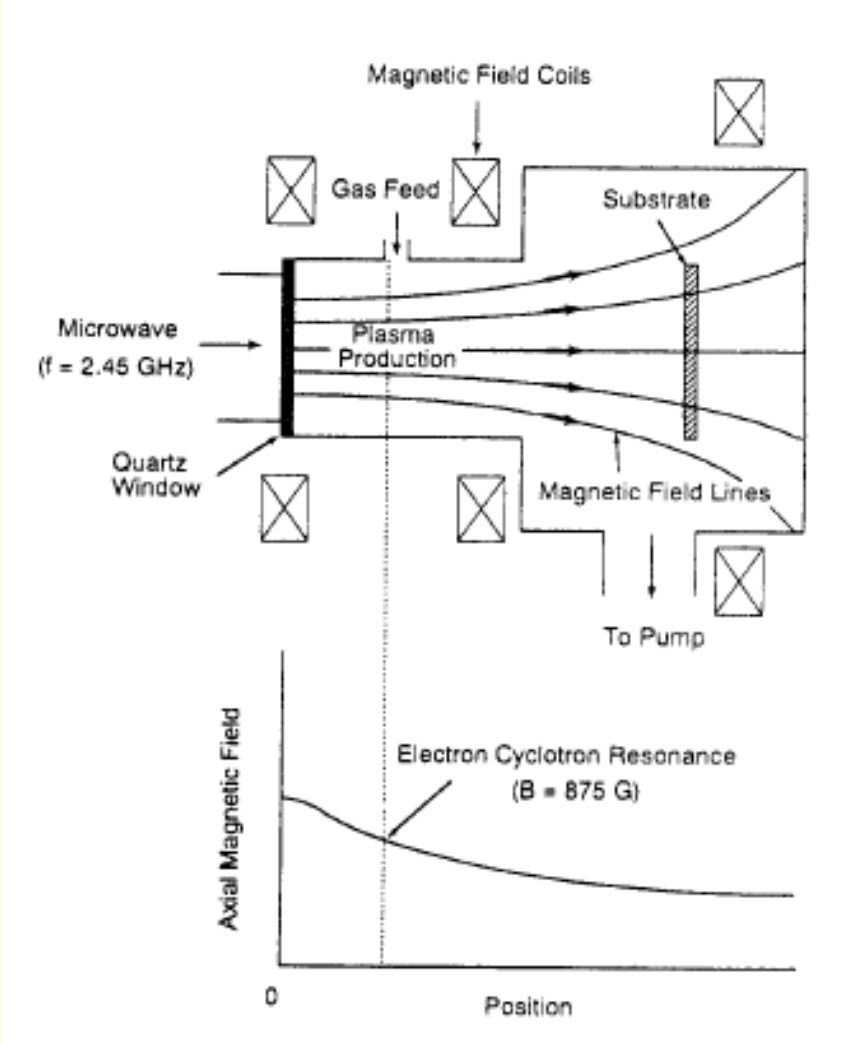


様々な誘導性性結合型プラズ(ICP)

高周波電場誘導：シース（衝突の有無、電子熱運動)、密度ジャンプ



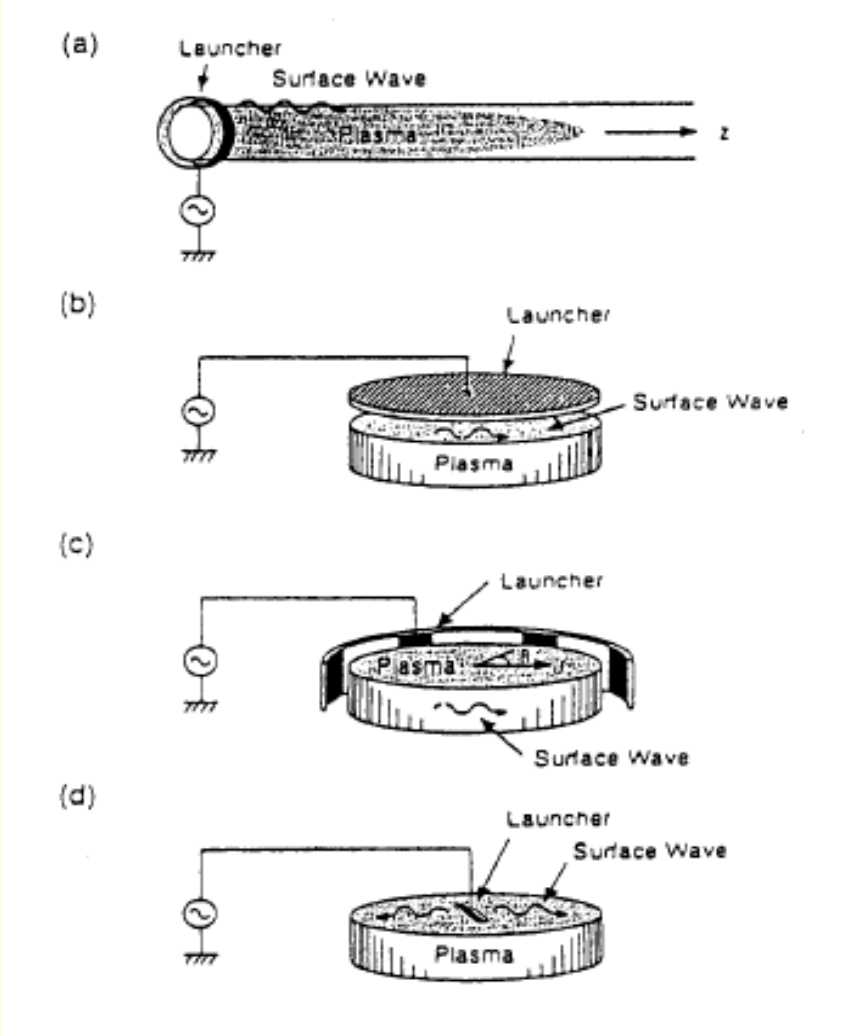
J. Hopwood, Plasma Sources. Sci. Technol. 1 (1992) 109.



典型的な電子サイクロトロン共鳴プラズマ(ECR)：発散磁場型

左右偏波、磁気ビーチ

S. Shinohara: Jpn. J. Appl. Phys. **36** (1997) 4695.



様々な表面波プラズマ源 (SW)

表面電荷波

小特集「表面波プラズマの生成とその応用」
プラズマ・核融合学会誌 **72** (1996) 621.

[ホイッスラー波の性質]

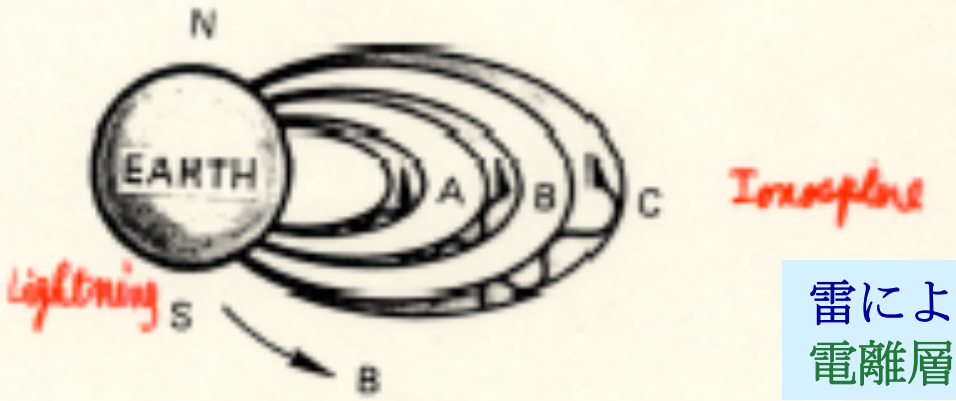
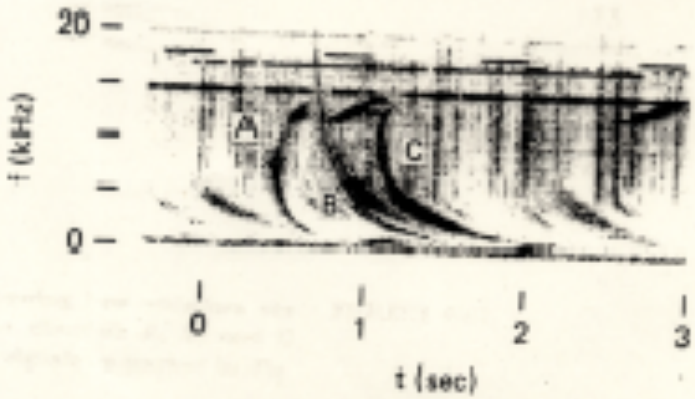


Diagram showing how whistlers are created. The channels A, B, and C refer to the signals so marked in Fig. 4-40.

FIGURE 4-41

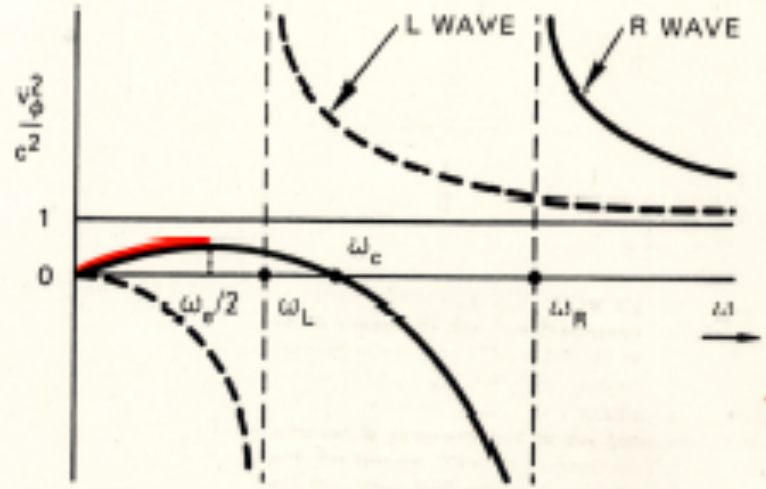
雷による生成：
電離層での伝搬



Actual spectrograms of whistler signals, showing the curvature caused by the low-frequency branch of the *R*-wave dispersion relation (Fig. 4-39). At each time t the receiver rapidly scans the frequency range between 0 and 20 kHz, tracing a vertical line. The recorder makes a spot whose darkness is proportional to the intensity of the signal at each frequency. The downward motion of the dark spot with time then indicates a descending glide tone. [Courtesy of D. L. Carpenter, *J. Geophys. Res.* 71, 695 (1966).]

高音から低音へ

F. F. Chen : Introduction to Plasma Physics (Plenum Press, NY, 1984)



$$\left(\frac{R}{L}\right)\quad n^2 = \frac{c^2k^2}{\omega^2} = 1 - \frac{\omega_p^2/\omega^2}{1 \mp (\omega_c/\omega)}$$

v_{ph} ↗ if ω ↗ $\left(\omega < \frac{\omega_c}{2}\right)$

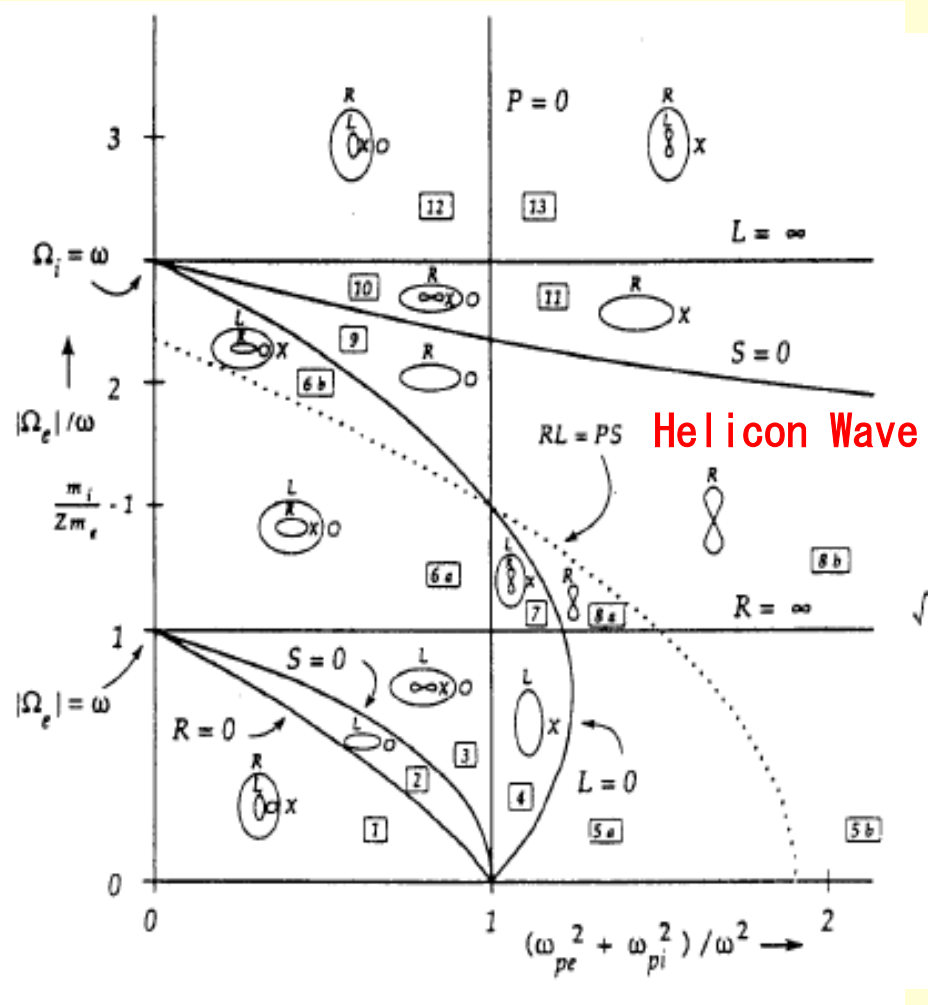
The v_ϕ^2/c^2 vs. ω diagrams for the *L* and *R* waves. The regions of nonpropagation ($v_\phi^2/c^2 < 0$) have not been shaded, since they are different for the two waves.

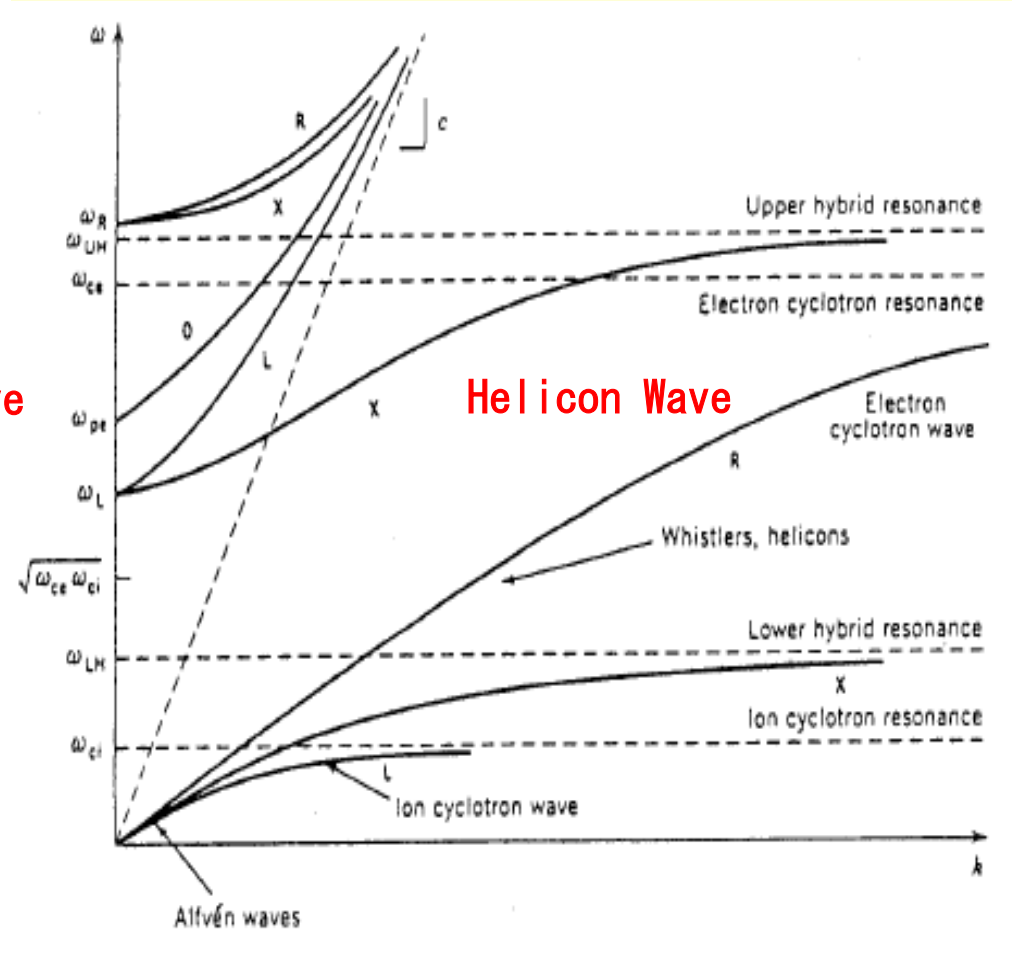
FIGURE 4-39

分散関係

ヘリコン波の性質

[Propagating Region of Helicon Wave]





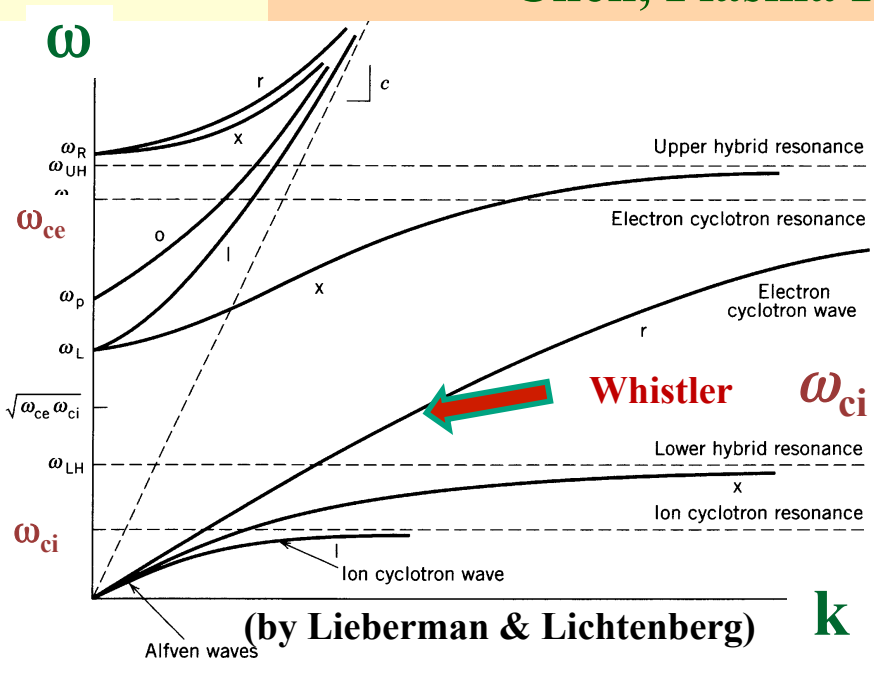
by Stix

by Lieberman & Lichtenberg

⇒ **Bounded Whistler Wave**

History & References

1962-: Lehne & Thoneman, Proc. Phys. Scr. 85 (1965) 301.
1970-: Boswell, Phys. Lett. 7 (1970) 457.
Plasma Phys. Control. Fusion 26 (1984) 1147.
Chen, Plasma Phys. Control. Fusion 33 (1991) 339…..



(by Lieberman & Lichtenberg)

$\omega_{ci} << \omega << \omega_{ce}$

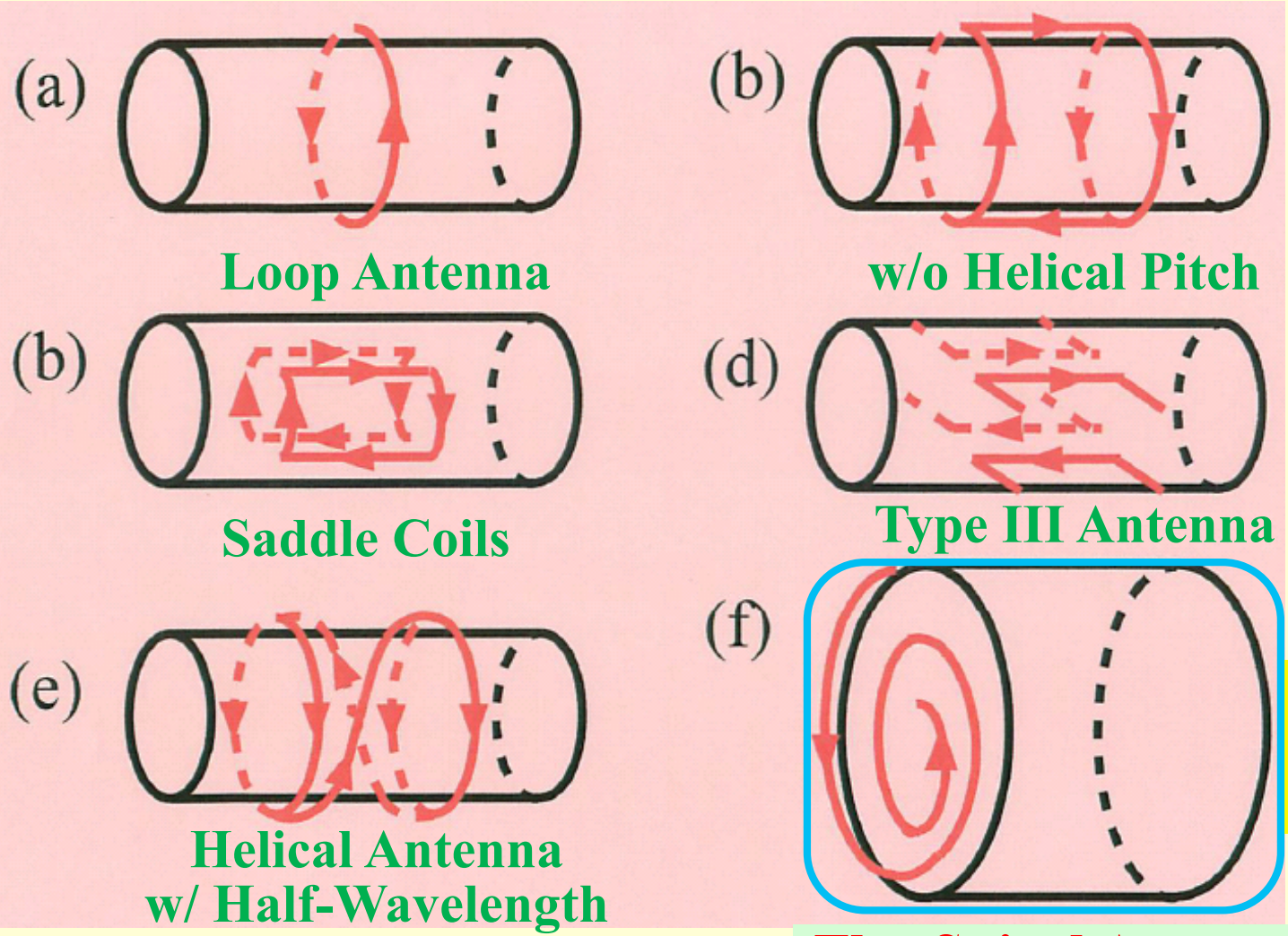
Boundary

Now, More Than 50 Papers Per Year !

Basic Study ⇒Application

Review Papers e.g.,
Chen, Phys. Plasmas 3 (1996) 1783.
Shinohara, Jpn. J. Appl. Phys. 36 (1997) 4395, J. Plasma Fus. Res. 78 (2002) 5.
Memoir in Physical Society of Japan 64 (2009) 519.
Shoji & Sakawa, J. Plasma Fus. Res. 74 (1998) 29.
Boswell & Chen, IEEE Trans. Plasma Sci. 25 (1997) 1229.
Chen & Boswell, IEEE Trans. Plasma Sci. 25 (1997) 1245.

Various Types of Helicon Antenna



Flat Spiral Antenna

cf. Internal Antenna

Mostly (a) – (e): around the Small Insulation Tube (Side Wall)

For Large Plasma Diameter

(End of Chamber)

$D < 15$ cm $\Rightarrow$ 74 cm, $V < 0.1$ m^3 $\Rightarrow$ 2.1 m^3

S. Shinohara: Jpn. J. Appl. Phys. 36 (1997) 4695.

Dispersion Relation

F. F. Chen, Plasma Phys. Control. Fusion 33 (1991) 339.

$\omega_{ci} << \omega << \omega_{ce}$

マクスウェルの方程式 ＋一般化されたオームの式

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$$
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j}$$
$$\mathbf{E} = \mathbf{j} \times \mathbf{B}_0 / e n_e$$

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}$$

$\exp[i(k_{//} z + m\theta - \omega t)]$

$\alpha = (\omega / k_{//})(\omega_{pe}^2 / \omega_{ce} c^2)$

$$B = B_0 \hat{z}, \quad k_{//}^2 + k_\perp^2 = \alpha^2$$

$$i\omega \mathbf{B} = \nabla \times \mathbf{E} = \nabla \times (\mathbf{j} \times \mathbf{B}_0)/e n_0$$
$$= (\mathbf{B}_0 \cdot \nabla)\mathbf{j}/e n_0 = (i k B_0 / e n_0)\mathbf{j}$$

プラズマの抵抗（衝突項）は無視

電流は電子が担う（$\mathbf{E} \times \mathbf{B}_0$ドリフト）

$j // B$: Force Free（無力磁場配位）

Bessel Function の解 ⇒ 磁気再結合：逆転磁場ピンチ、太陽表面等

★ 衝突項導入：ヘリコン波 (長波) と TG波(短波)

ダブルベルトラミ　渦と流れが平行

S. M. Mahajan & Z. Yoshida, Phys. Rev. Lett. 81 (1998) 4863.

高効率ヘリコンプラズマ生成機構

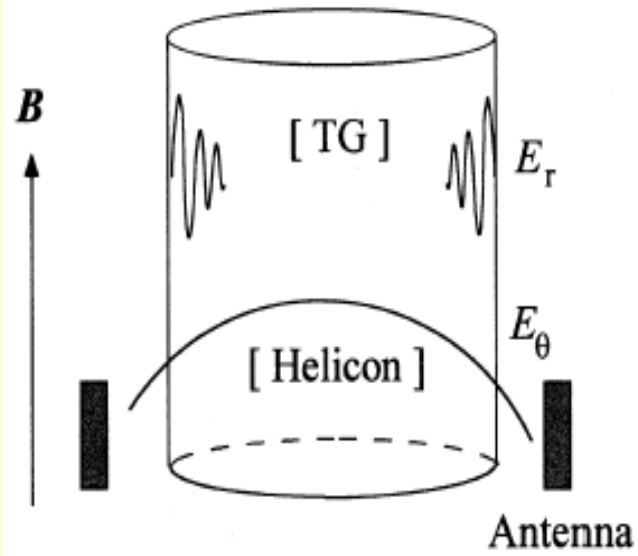
衝突減衰とランダウ減衰が候補
統一的に説明できず長年の懸案
↓
励起されたヘリコン波から静電波である
Trivelpiece-Gould 波へモード変換

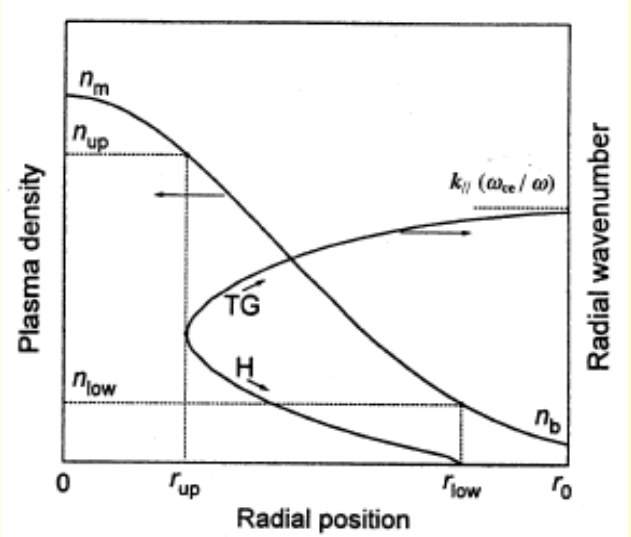
理論： Dr. Shamrai

静電波の高減衰によるプラズマ生成モデル
プラズマ中の波動現象：基礎物理学的に興味深い

実験と理論の一致：
波動構造
アンテナ抵抗のパラメータ依存性

モード変換の概念図



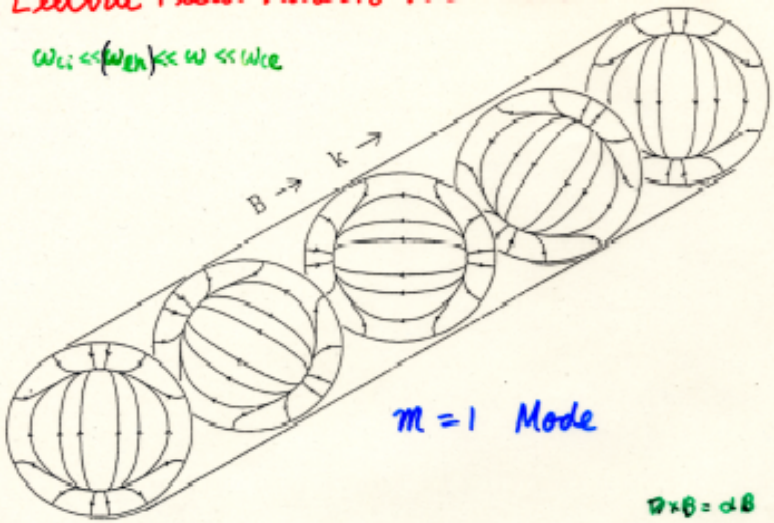


S. Shinohara & K. P. Shamrai, Plasma Phys. Control. Fusion 42 (2000) 865.
K. P. Shamrai & S. Shinohara, Phys. Plasmas 8 (2001) 4659.

[ヘリコン波の電場のパターン]

[Electric Field Pattern for Helicon Wave]

$\omega_{ci} \ll (\omega_{ex}) \ll \omega \ll \omega_{ce}$

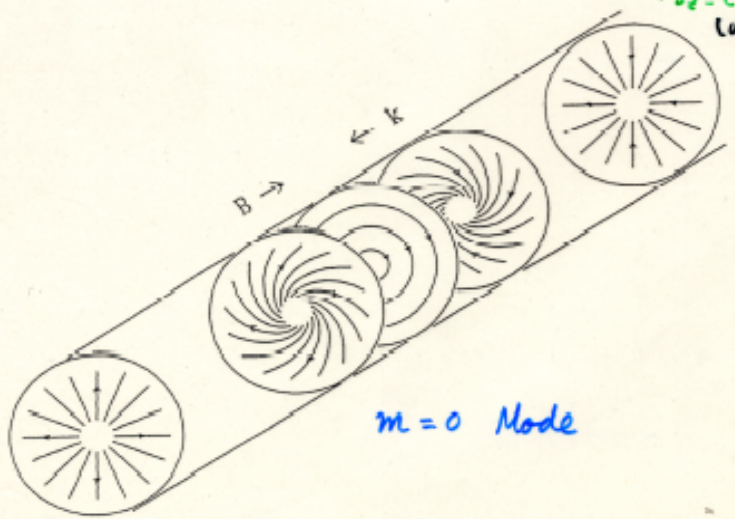


Instantaneous electric field pattern for an m = +1 helicon wave in space

$\nabla \times B = \alpha B$

$$\begin{cases} B_r = C_1 J_{m-1} + C_2 J_{m+1} \\ B_\theta = i(C_1 J_{m-1} - C_2 J_{m+1}) \\ B_z = C_3 J_m \end{cases}$$

(Uniform Density)

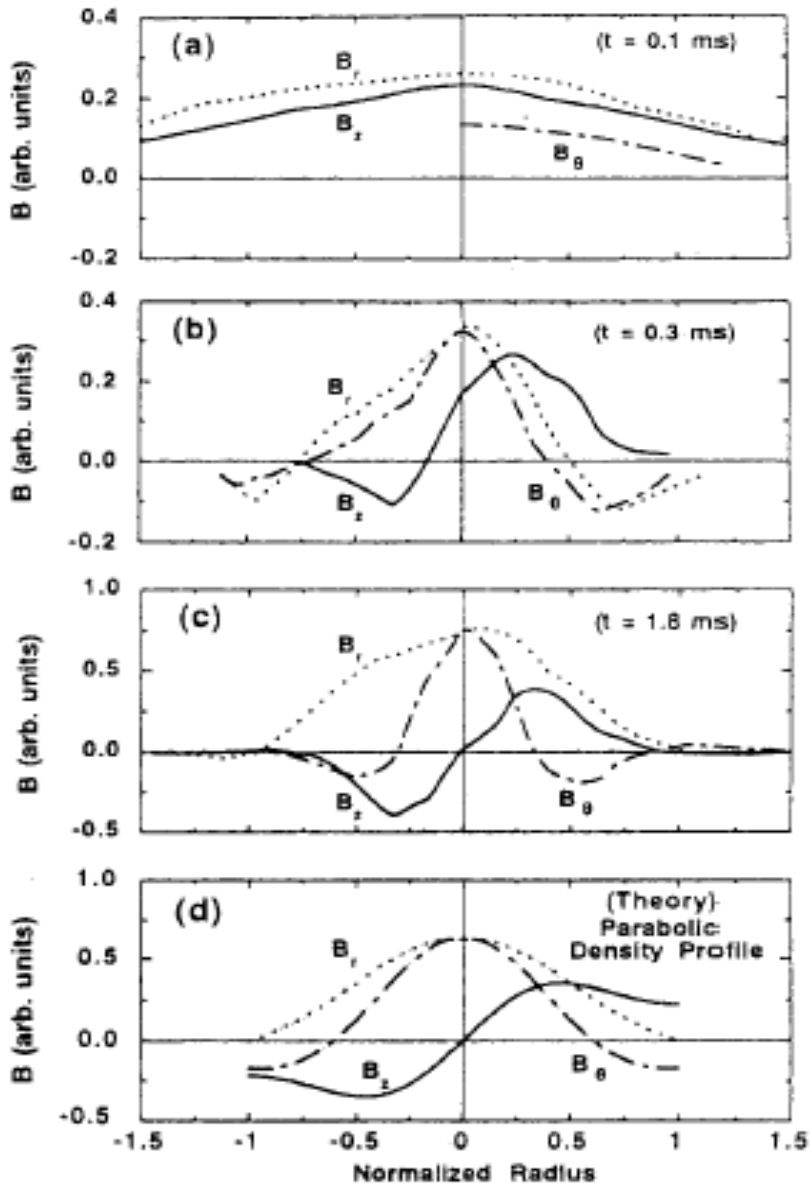


cf. Boswell

Instantaneous electric field pattern for an m = 0 helicon wave in space

F. F. Chen, Plasma Phys. Control Fusion 33 (1991) 339.

[ヘリコン波の励起磁場分布の時間変化]



S. Shinohara, Y. Miyauchi and Y. Kawai: Jpn. J. Appl. Phys. **35** (1996) L731.

理論と実験：
ベッセル関数

境界条件と励起波動

境界が絶縁体：$j_r = 0\ (r = a) \Rightarrow B_r = 0$

境界が導体：$E_\theta = 0 \Rightarrow B_r = 0$

$$m\alpha J_m(k_\perp a) + k_{||} a J'_m(k_\perp a) = B_r = 0$$

$$J_1(k_\perp a) = 0 \qquad (m = 0)$$

$$J_1(k_\perp a) = (k_{||}\, a\, k_\perp / 2\alpha)\,(J_2 - J_1) \qquad (m = 1)$$

$$B_r = (-k/\omega)E_\theta = (2A/T)[(m\alpha/r)J_m(k_\perp r) + kJ'_m(k_\perp r)]\cos(m\theta + kz - \omega t)$$

$$B_\theta = (k/\omega)E_r = -(2A/T)[\alpha J'_m(k_\perp r) + (mk/r)J_m(k_\perp r)]\sin(m\theta + kz - \omega t)$$

$$B_z = 2ATJ_m(k_\perp r)\sin(m\theta + kz - \omega t),\ E_z = 0$$

$m = 0$

$$B_r = -AkJ_1(k_\perp r)\cos(kz - \omega t)$$

$$B_\theta = -A\alpha J_1(k_\perp r)\sin(kz - \omega t)$$

$$B_z = Ak_\perp J_0(k_\perp r)\sin(kz - \omega t)$$

$$E_r = A\omega(\alpha/k)J_1(k_\perp r)\sin(kz - \omega t)$$

$$E_\theta = A\omega J_1(k_\perp r)\cos(kz - \omega t)$$

$$E_z = 0$$

[高効率プラズマ生成機構解明]

初期：衝突減衰とランダウ減衰が候補 → 統一的に説明できず長年の懸案

↓

励起されたヘリコン波から静電波である Trivelpiece-Gould 波へモード変換

静電波の高減衰によるプラズマ生成モデル

プラズマ中の波動現象として基礎物理学的に興味深い内容

by Dr. Shamrai

波数の虚数部

衝突減衰（ヘリコン）　$k_{iH} = \nu_e k_\perp / \omega_{ce} \sim \nu_e \omega^2 / k_{//}^3 \delta^4 \omega_{ce}^3$ (ヘリコン波伝搬領域)

ランダウ減衰（ヘリコン）　$k_{iL} = [2\pi^{0.5} \omega k_\perp \zeta^3 \exp(-\zeta^2)] / \omega_{ce}$

衝突減衰（TG）　$k_{iTG} \sim k_{//} \nu_e \omega_{ce} / (\omega^2 + \nu_e^2)$

(但しスキン長 $\delta = c / \omega_{pe}$ 、$\zeta = \omega / k_{//} V_{Te}$)

減衰

ヘリコン波　$W_B >> T >> W_E$ ：全エネルギー $W (= W_B + T + W_E)$ の減衰を、T だけでの説明は無理

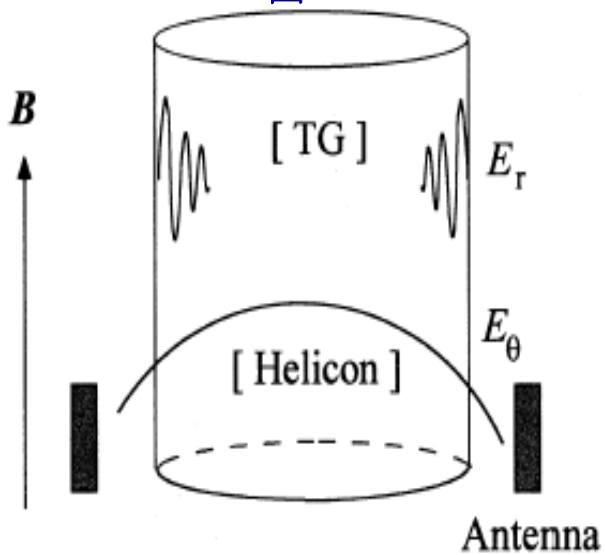
TG 波は $T >> W_B >> W_E$ であり短波長のこの波の衝突減衰は大きい

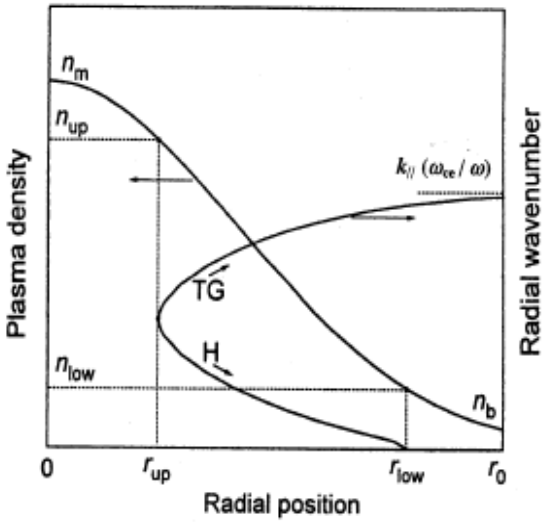
(波動磁場と電場のエネルギー W_B、W_E、粒子のエネルギー T)

モード変換

共鳴 (分散関係) と非共鳴過程　$(j_r \sim E_r + i(\omega_{ce} / \omega) E_\theta \sim 0)$

モード変換の概念図





Double Beltrami

$$\nabla \times \mathbf{B} = \alpha\, \mathbf{B}$$

j // B : Force Free（無力磁場配位）

Bessel Function : 磁気再結合 : 逆転磁場ピンチ、太陽表面など

★ 衝突項導入 : ヘリコン (TG波) : 長波 (短波)

ダブルベルトラミ

S. M. Mahajan & Z. Yoshida, Phys. Rev. Lett. 81 (1998) 4863.
Z. Yoshida, S. M. Mahajan & S. Osaki, Phys. Plasmas 11 (2004) 3660.

Two Fluids: Hall MHD (Macro & Micro scales)

(Ion Skin Depth, Cyclotron Motion)

$$\boldsymbol{E} + \boldsymbol{V}_e \times \boldsymbol{B} + \frac{1}{en}\nabla p_e = 0, \qquad \frac{\partial}{\partial t}\boldsymbol{V} + (\boldsymbol{V}\cdot\nabla)\boldsymbol{V} = \frac{e}{M}(\boldsymbol{E} + \boldsymbol{V}\times\boldsymbol{B}) - \frac{1}{Mn}\nabla p_i$$

$$\partial_t \boldsymbol{\Omega}_j - \nabla \times (\boldsymbol{U}_j \times \boldsymbol{\Omega}_j) = 0 \quad (j = 1,2)$$

$$\begin{cases} \boldsymbol{\Omega}_1 = \boldsymbol{B}, \\ \boldsymbol{U}_1 = \boldsymbol{V} - \varepsilon \nabla \times \boldsymbol{B}, \end{cases} \qquad \begin{cases} \boldsymbol{\Omega}_2 = \boldsymbol{B} + \varepsilon \nabla \times \boldsymbol{V}, \\ \boldsymbol{U}_2 = \boldsymbol{V}. \end{cases}$$

$$\boldsymbol{U}_j = \mu_j \boldsymbol{\Omega}_j \quad (j = 1,2)$$

$$\nabla \times \boldsymbol{G}_\pm = \lambda_\pm \boldsymbol{G}_\pm,$$

$$\lambda_\pm = \frac{1}{2\varepsilon}\left[(b - a^{-1}) \pm \sqrt{(b - a^{-1})^2 - 4(1 - b/a)}\right]$$

$$\boldsymbol{B} = C_+ \boldsymbol{G}_+ + C_- \boldsymbol{G}_-,$$

$$\boldsymbol{V} = (a^{-1} + \varepsilon\lambda_+) C_+ \boldsymbol{G}_+ + (a^{-1} + \varepsilon\lambda_-) C_- \boldsymbol{G}_-$$

Comparison of Helicon Source Size

- **Large Diameter/Large Volume**

  JAXA(ISAS): (75 cm$^{\phi}$, 486 cm^{l}) (New) (Spiral Antenna)
  Kyushu Univ.: (45 cm$^{\phi}$, 170 cm^{l}) (Spiral Antenna)
  NM Tech.: (43 cm$^{\phi}$, 400 cm^{l}) ALPHA (Antenna Array) Small Plasma Radius
  MPI: (40 cm$^{\phi}$, 400 cm^{l}) VINETA Small Plasma Radius
  UCSD: (20 cm$^{\phi}$, 250 cm^{l}) CSDX
  Australian Nat'l Univ.: (20 cm$^{\phi}$, 50 cm^{l}) + (90 cm$^{\phi}$, 250 cm^{l}) WOMBAT
  Auburn Univ.: (15 cm$^{\phi}$, 250 cm^{l}) ALEPSI
  Ruhr Univ.: (15 cm$^{\phi}$, 200 cm^{l}) + (60 cm$^{\phi}$, 100 cm^{l}) (Multipole, Weak Field)
  WVU: (15 cm$^{\phi}$, 157 cm^{l}) HELIX + (200 cm$^{\phi}$, 450 cm^{l}) LEIA (Weak Field)

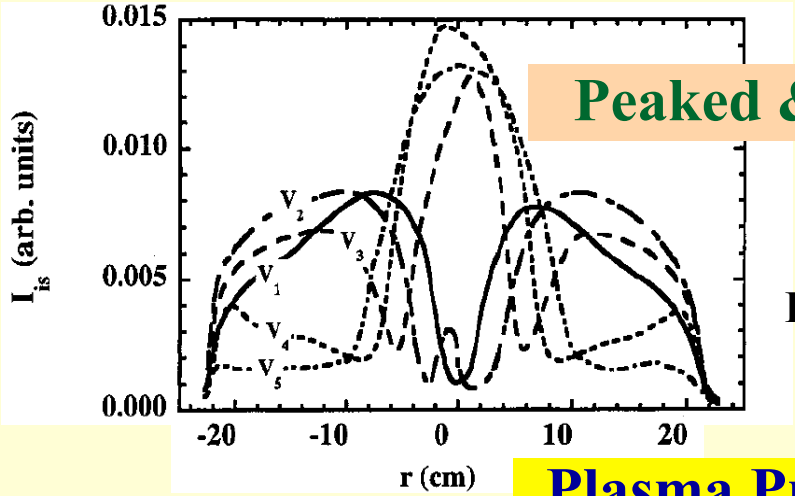
- **Small Diameter/Small Volume**

  JAXA (ISAS): (2.5 cm$^{\phi}$, 4.7 cm^{l}) (New) (10 - 100 MHz)
  Nagoya Univ.: (4.5 cm$^{\phi}$, 10 cm^{l})
  WVU (6 cm$^{\phi}$, 15 cm^{l}): CHEWIE (Low Density)
  KAIST: (5 cm$^{\phi}$, 30 cm^{l}) (98 MHz)

LMD Applications (No. 1)

Low Density (Voltage Biasing)

Profile Control

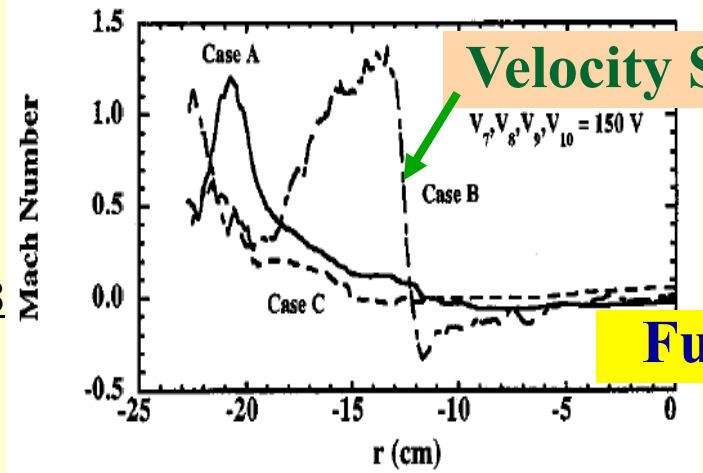


Peaked & Hollow

Phys. Plasmas 8 (2001)1154.

Plasma Processing

Plasma Flow Control

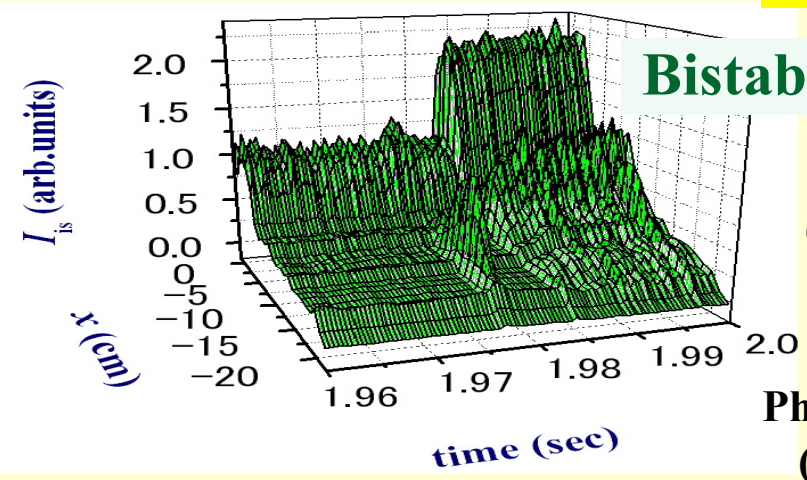


Velocity Shear

Fusion

Density Transition

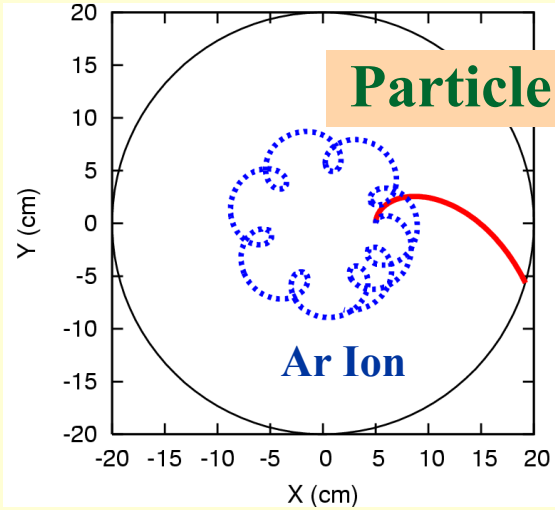
Fusion



Bistable

Hysteresis (Statistics)

Phys. Plasmas 9 (2002) 4540.



Particle Orbits

Jpn. J. Appl. Phys. 46 (2007) 4276.

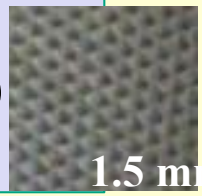
Mass Separation

$$v_\theta = \frac{\omega_{ci} r}{2}\left(-1 \pm \sqrt{1 - 4E_r/rB_z\omega_{ci}}\right)$$

The Largest Helicon Device (No. 1)

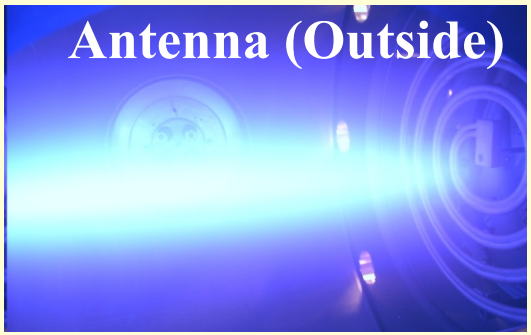
Up to 2.1 m^3
73.8 (75) cm I.D. (O.D.)
5.5 – 486 cm Axial Length: *L*

Ar: 0.75 mTorr – 7.5 mTorr
RF Frequency: 7 MHz
RF Power: 5 kW
Discharge Duration: 12～40 ms (1 pps)
End Plate: Transparency ～35 %
(SUS: Punching Plate 0.5 cm^t)
(or Plate w/o Holes or Mica Plate w/o Holes)



JAXA 宇宙航空研究開発機構
Japan Aerospace Exploration Agency

Refs.
Rev. Sci. Instrum. 75 (2004) 1941.
Phys. Plasmas 12 (2005) 044502 & 16 (2009) 057104.
Thin Solid Films 506-507 (2006) 564.
J. Plasma Fus. Res. 8 (2008) 00006.
Plasma Sources Sci. Technol. 19 (2010) 034018.
Memoir in Physical Society of Japan 64 (2009) 519.



Helicon Plasma
(Blue Mode)

cf. Archimedes Technol. G.

LHPD Very Large Diameter Objectives

Large Volume

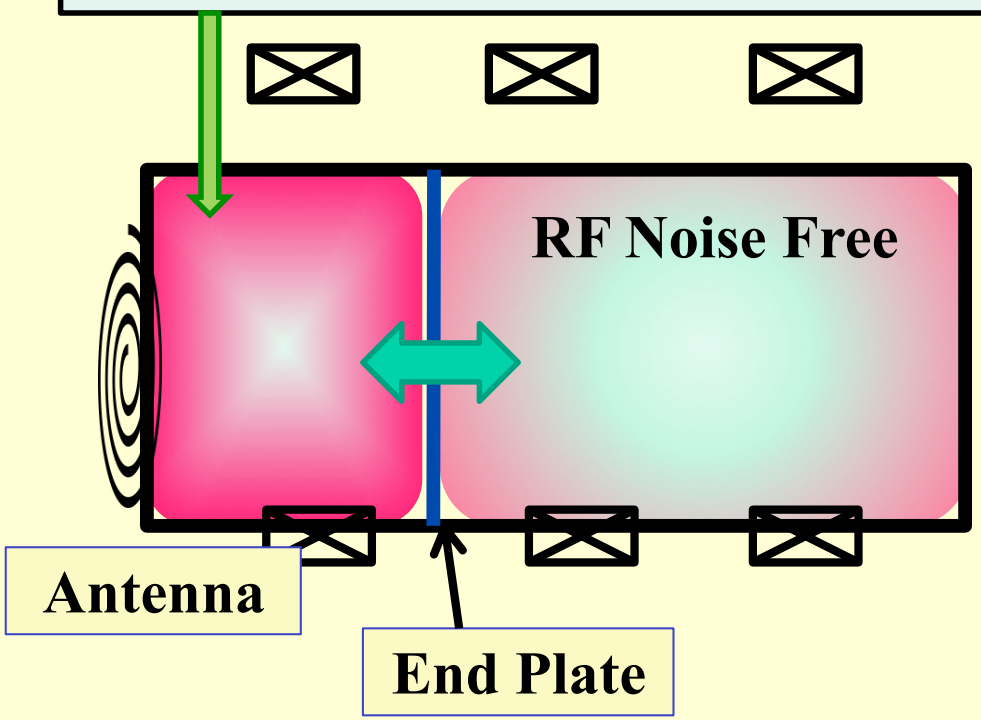
⇒ Fusion, Basic Study (Space Plasma Simulation), Application

Low Aspect Ratio A (So far $A = L/D > 0.5$)

⇒ Plasma Propulsion & Processing

cf. Boundary Condition (Axial Direction)

cf. $A = R / a$



★ Development

Profile Control

Production Scaling

Wave Structures

LHPD: Large Helicon Plasma Device

- Excellent Production Efficiency
- A as low as 0.075 (5.5 cm Length)

Particle Production Efficiency I (Calc.)

Scaling: *12th Int. Cong. on Plasma Physics* (2004) p. 179. hal-00002013

Loss Across the Field

Small Radius a
Long Axial Length L
Weak Magnetic Field B

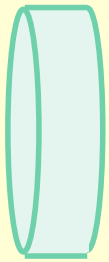
Ion: Weakly Magnetized

$$N_e / P_{inp} \propto a^2$$

$$n_e / P_{inp} \propto 1 / L$$

Loss Along the Field

Large a
Short L
Strong B



$$N_e / P_{inp} \propto L$$

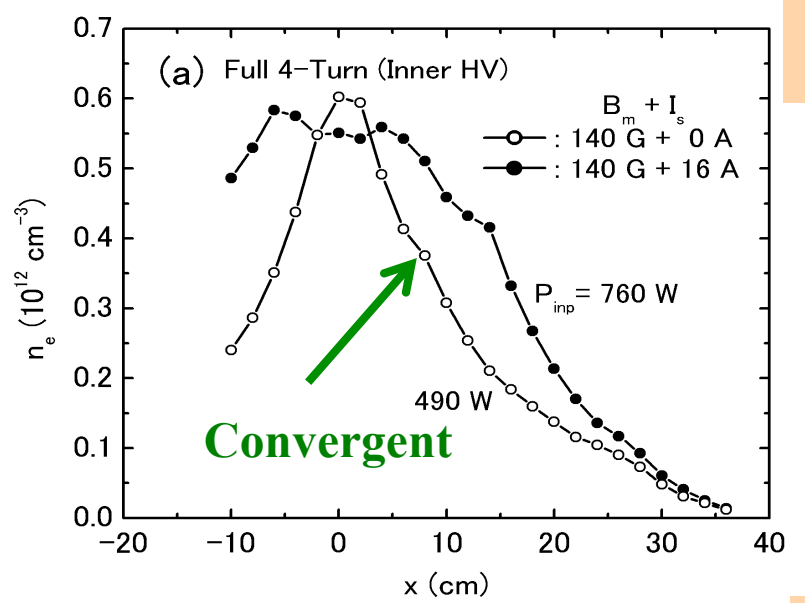
$$n_e / P_{inp} \propto 1 / a^2$$

$$P_{inp} = (2\pi a)(L)\ (D_{i\perp} \nabla n_s)\, E$$
$$\Rightarrow \quad N_e / P_{inp} = a^2 / 4.8\, D_i\, E\, f$$

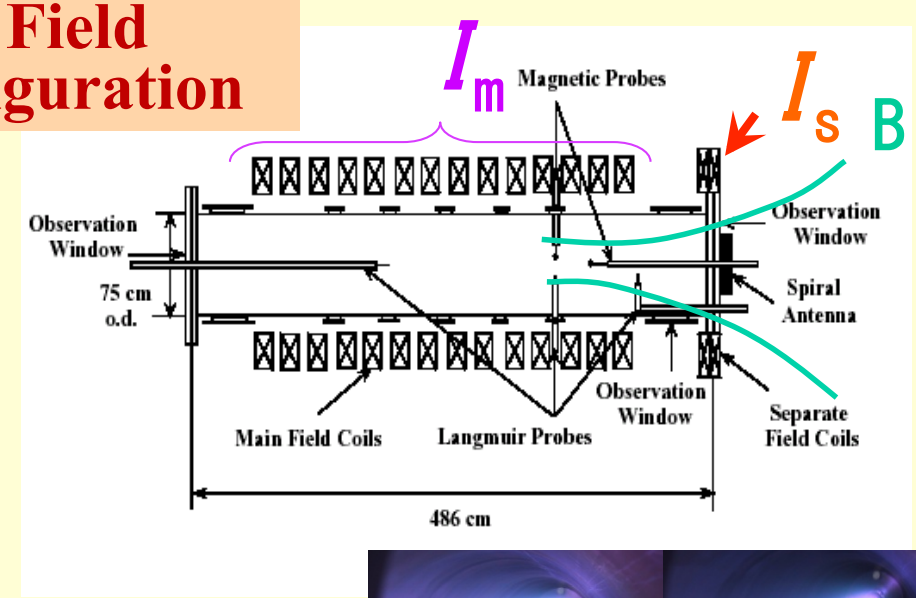
$$P_{inp} = n_s C_s E\, (2\pi a^2)$$
$$\Rightarrow \quad N_e / P_{inp} = L / 2\, C_s\, E\, f$$

N_e: Total Number of Electrons, n_s: Edge Electron Density
f: Form Factor ($n_s = f\, n_e$), ν_i : Ion Collision, C_s: Ion Sound Velocity
E: Energy to Produce Ion and Electron Pair, $D_{i\perp}$: Ion Diffusion $\sim k T_i / m_i \nu_i$

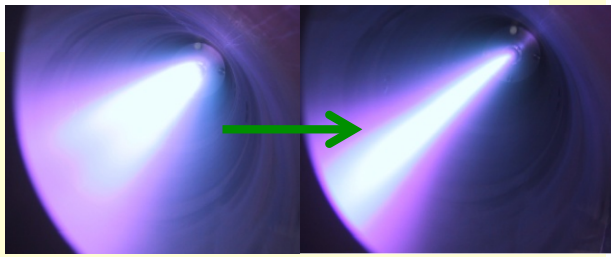
Radial Density Profile Control (L = 486 cm)



1. Field Configuration

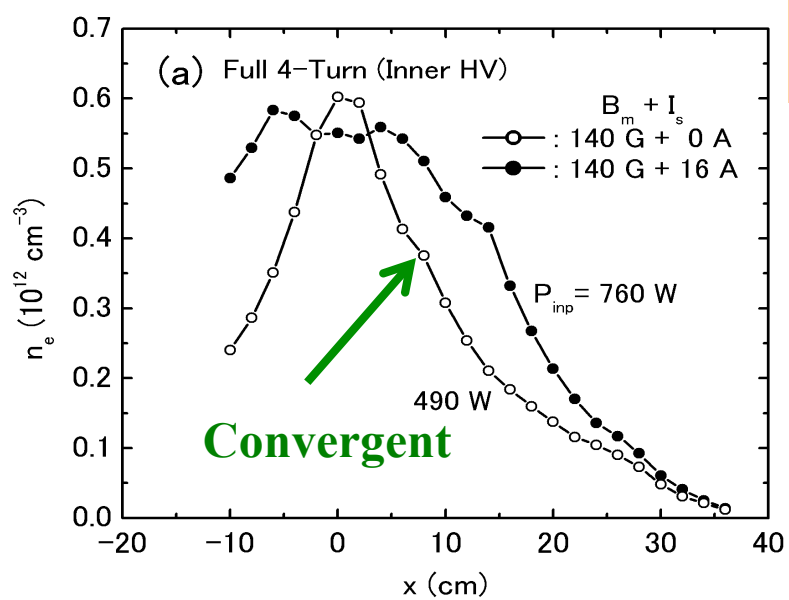


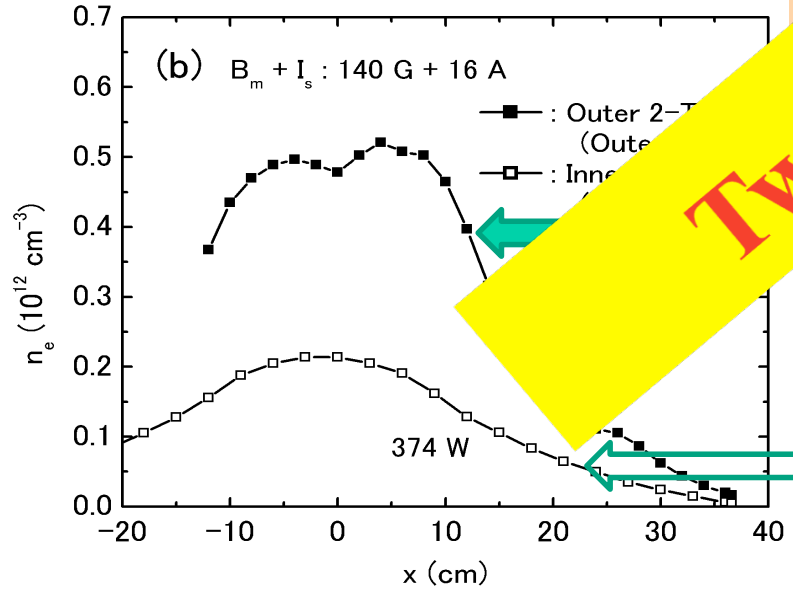
2. Antenna Configuration



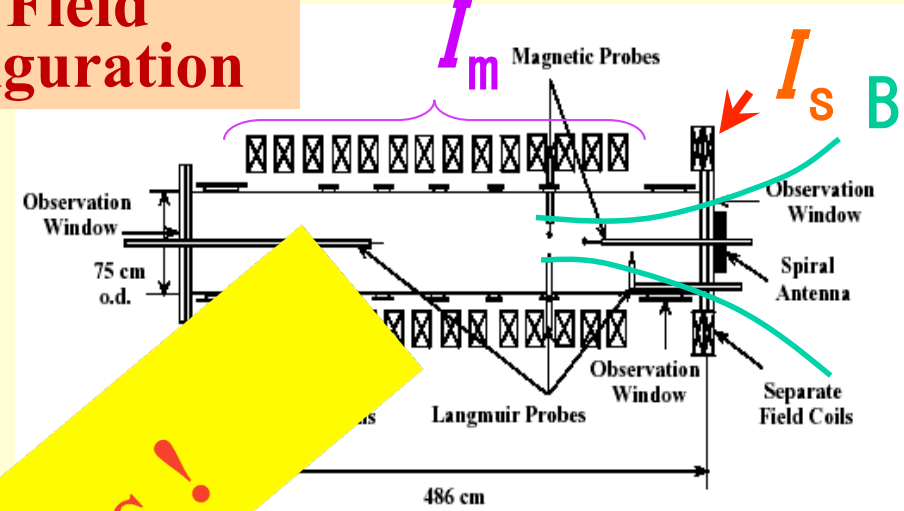
Importance: Processing, Fundamental Study ….

Radial Density Profile Control (L = 486 cm)



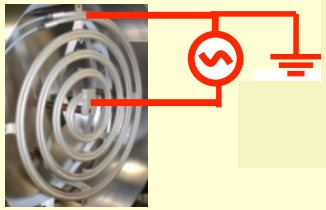


1. Field Configuration

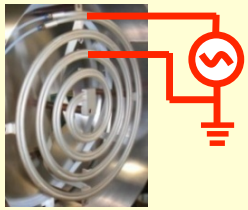


Two Patents !

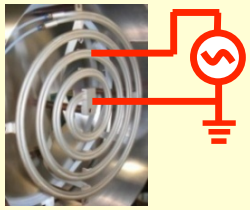
...nna ...guration



Full 4-Turn (Inner HV)



Outer 2-Turn (Outer HV)



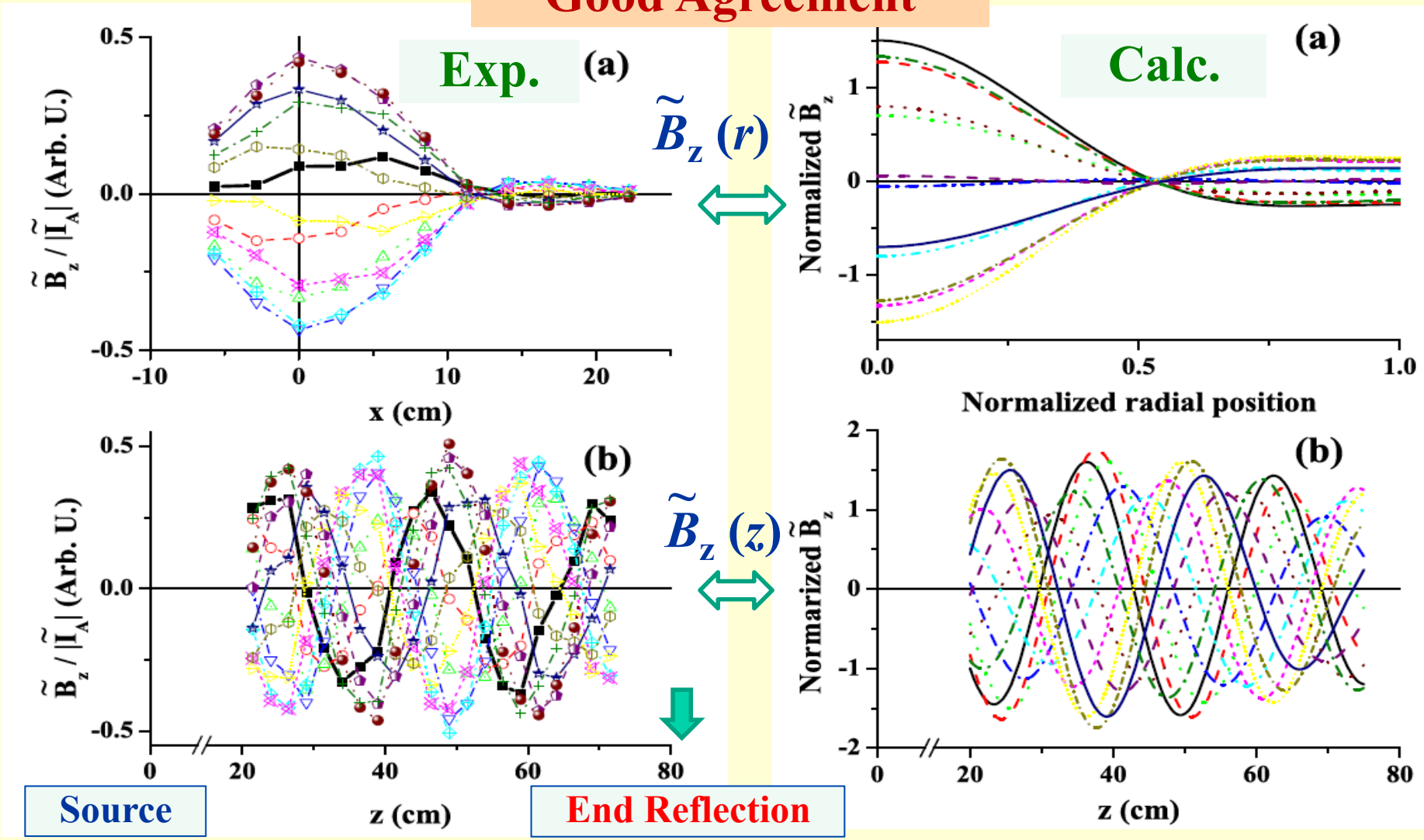
Inner 2-Turn (Outer HV)

- HV Point
- Connection Position

End Effect

Wave Structures I: $\tilde{B}_z(r,z)$ (L = 81 cm)

Good Agreement



1.9 kW, HV in, 2-Turn, I_s = 60 A

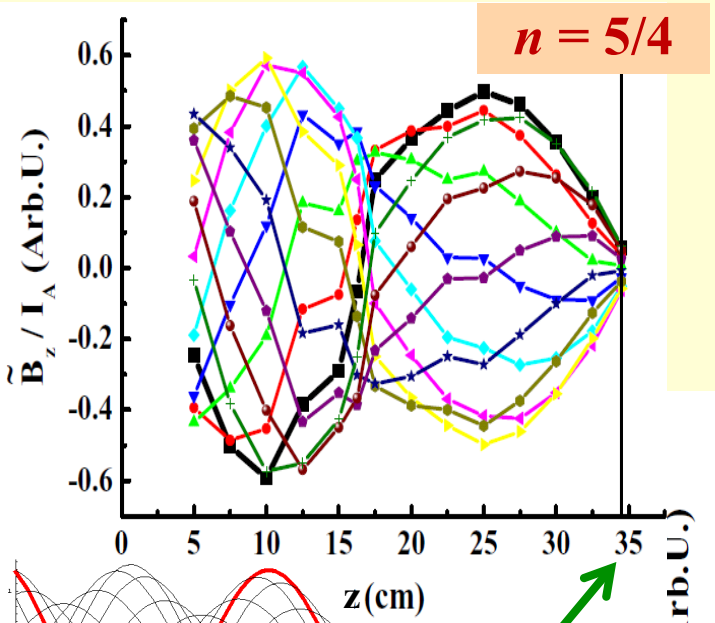
cf. High Radial Modes

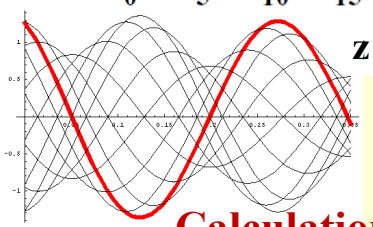
Amp. Ratio (2nd.)/(1st.) = 0.51 , Phase diff. = – 6.5 degs.

@ z= 51.5 cm, Reflection: 50 %, Coll. & Landau Dampings

Standing Wave Like Pattern

Wave Structures II: $\tilde{B}_z(z)$ (Short L)

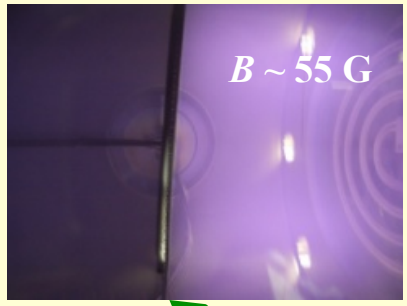




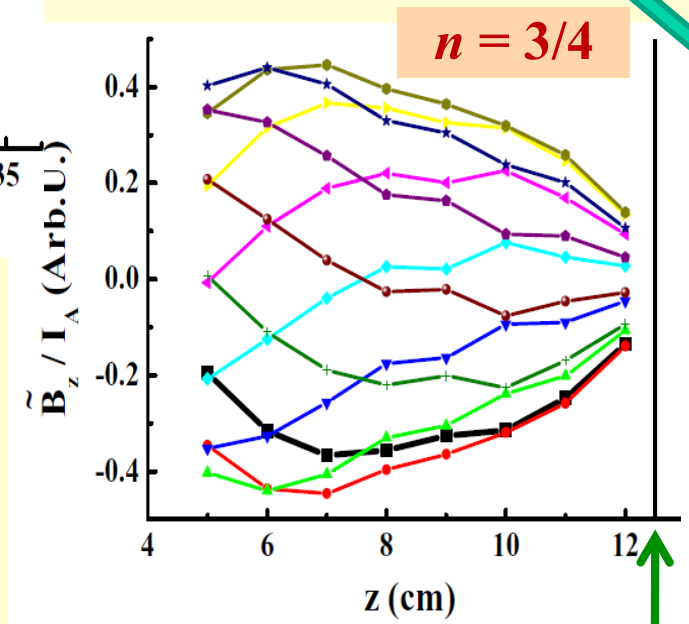
Calculation

End Plate 34.5 cm

Lower Axial Mode Number n, Decreasing Length

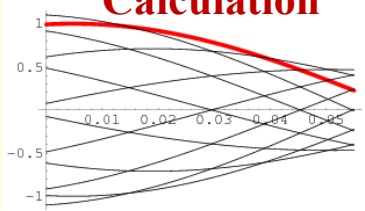


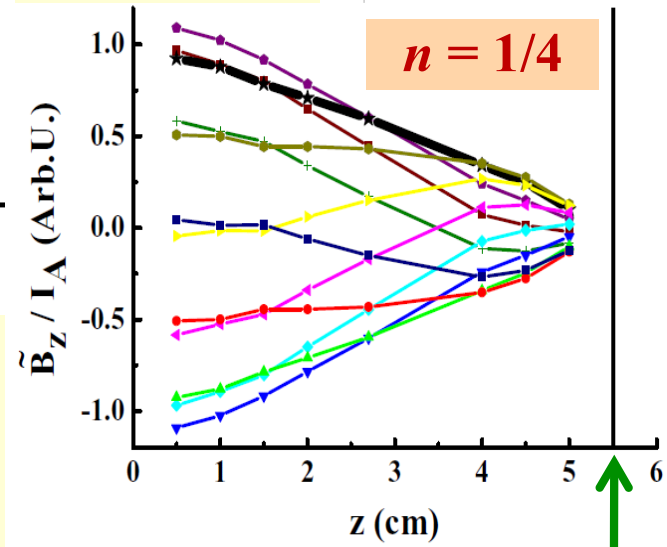
End Plate



12.5 cm

Calculation





(1.5 mTorr)

5.5 cm

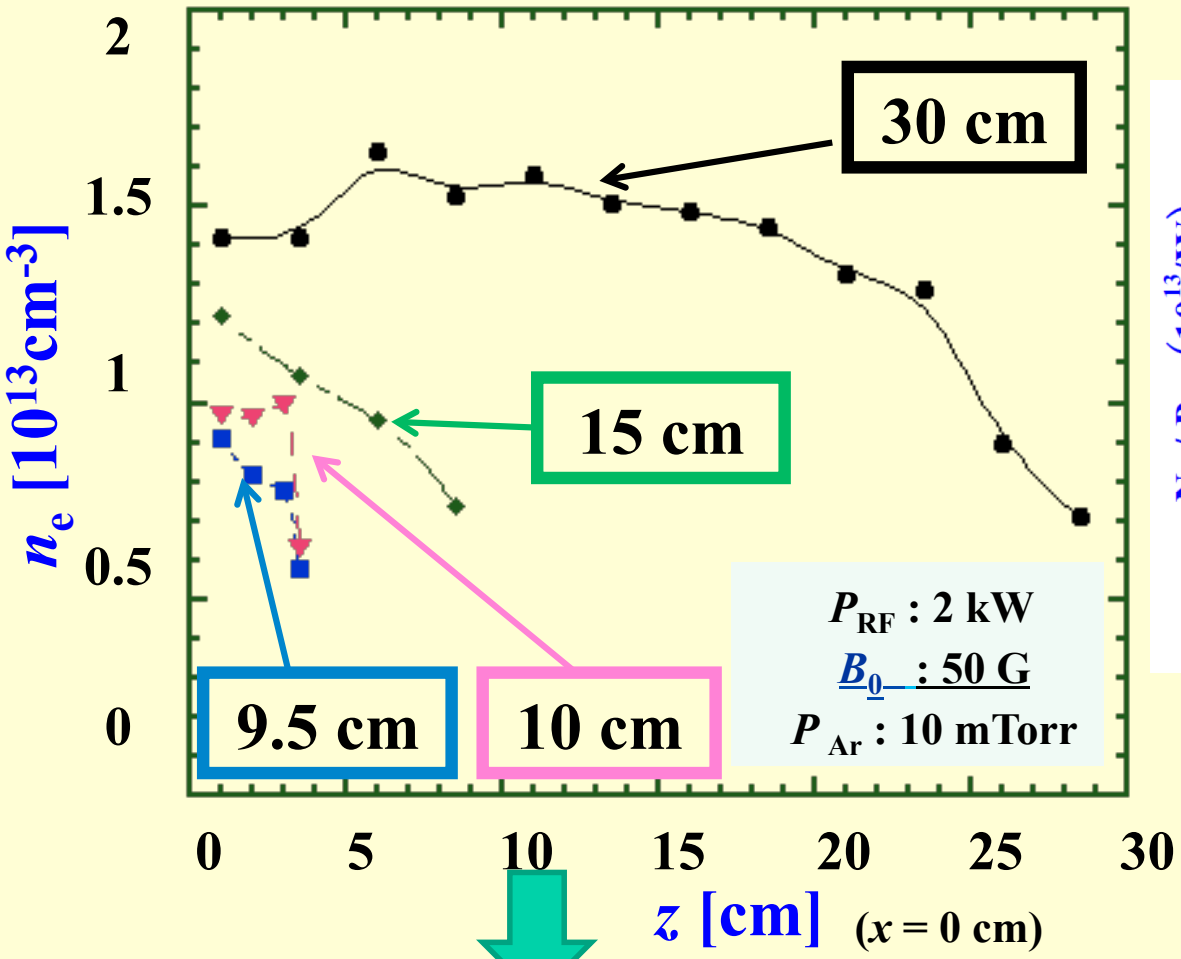
Antenna Side: Loop
End Plate Side: Node

- $n = 1/4 + p/2$ (p: Integer)
- Agreement with the Dispersion Relation

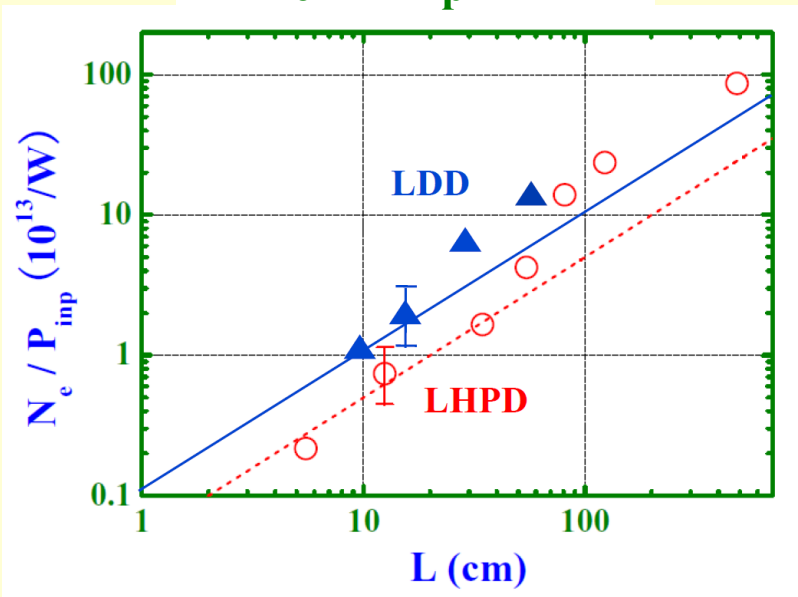
Axial Electron Density Profiles

Short Axial Length

Uniform Field



$N_e / P_{inp} \propto L$



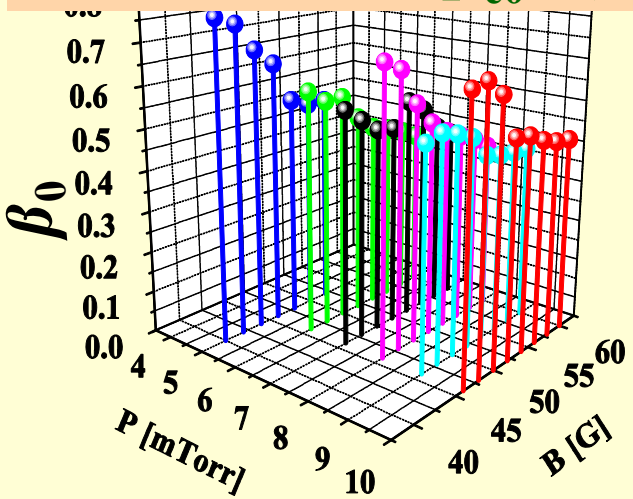
$n_e / P_{inp} \propto 1/a^2$

A as low as 0.25

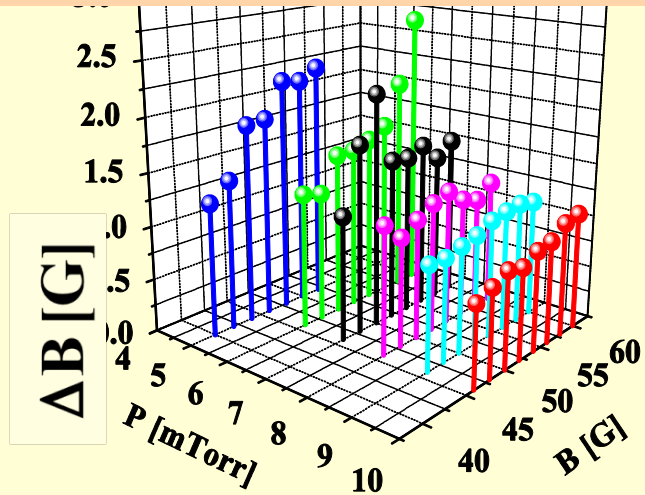
Even Though Short Length of L ~ 10 cm, High Density ~ 10^{13} cm^{-3}

Beta and Diamag. Effect in (P_{Ar}, B) Space

Central Beta: $p_{e0} / (B_0^2/2\mu_0)$



P_{RF} : 2 kW, L : 50 G (x = 0 cm, z = 30 cm)



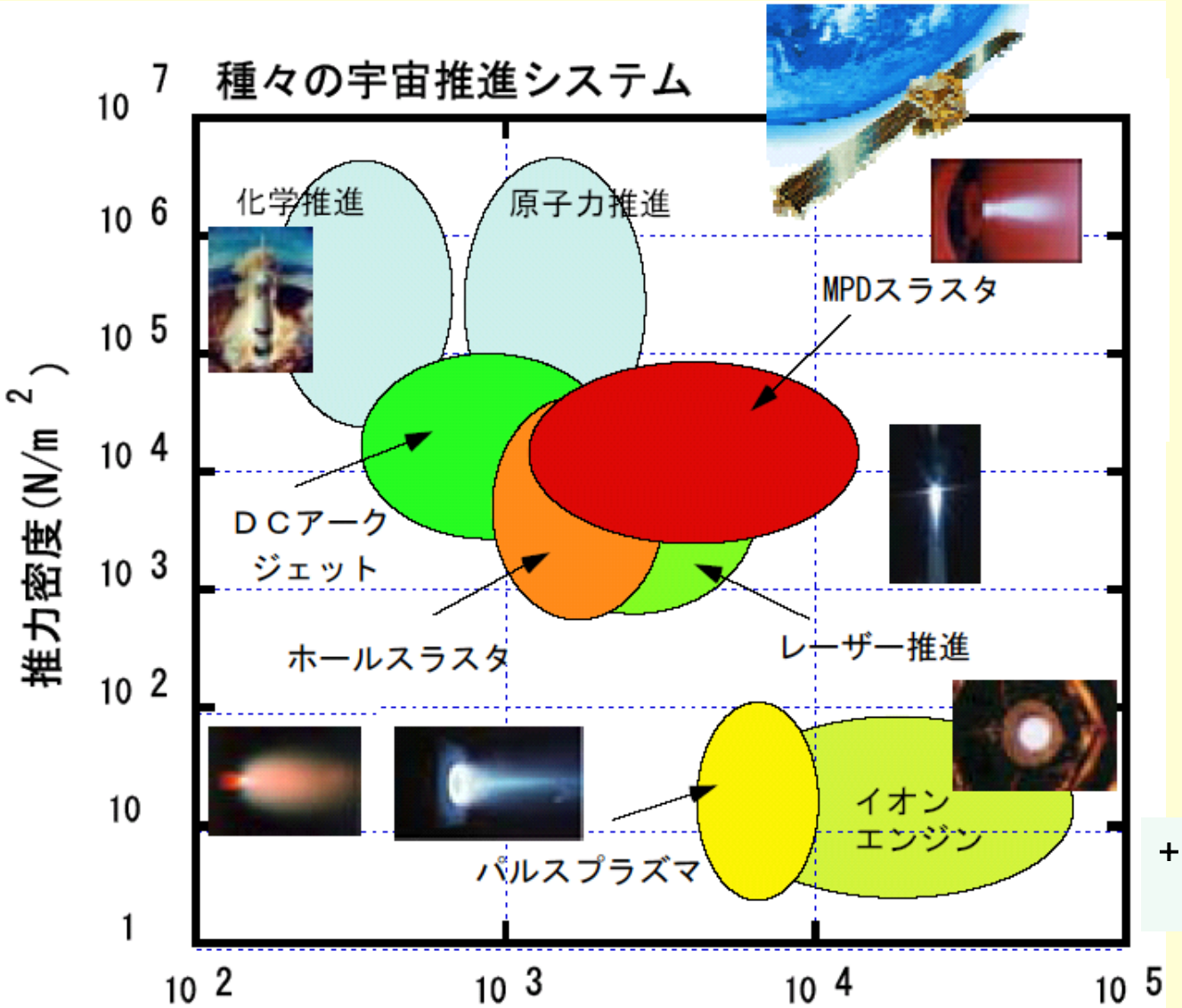
$\beta_0 < 0.76$

Small Diamag. Effect: $\Delta B/B$ < 4.5 % (cf. 50 %)

Larmor Radius < Plasma Radius
$\Omega_c \tau < 1$ (Ion), >1 (Electron)
★ $\tau = \mu_0 \sigma a^2$ < Discharge Duration

★ $B^2/2\mu_0 + p_e > B_0^2/2\mu_0$

比推力-推力空間での推進システム



（旧犬竹研資料より）

$I_{sp} = u_e / g$

ロケット公式

$$\Delta V = u_e \ln \frac{M_i}{M_f}$$

(ΔV, u_e: 増分速度、排出速度
M_i, M_f:初期、最終質量)

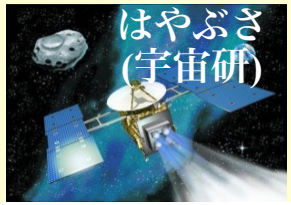
推力 F と比推力 I_{sp} の関係

$$F = \frac{2\eta_t P}{g I_{sp}}$$

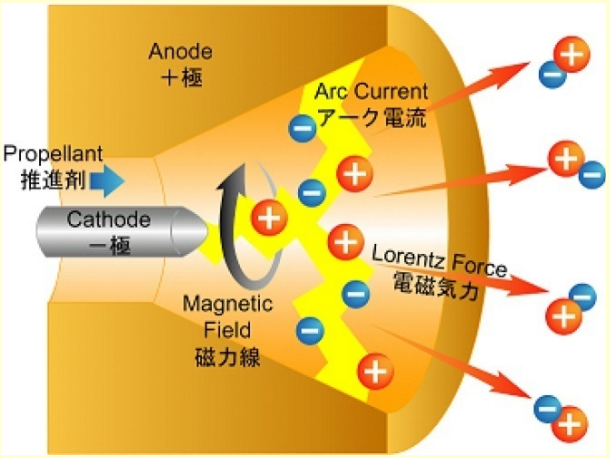
★ 電気推進法
静電加速
電熱・電磁加速

深宇宙探査

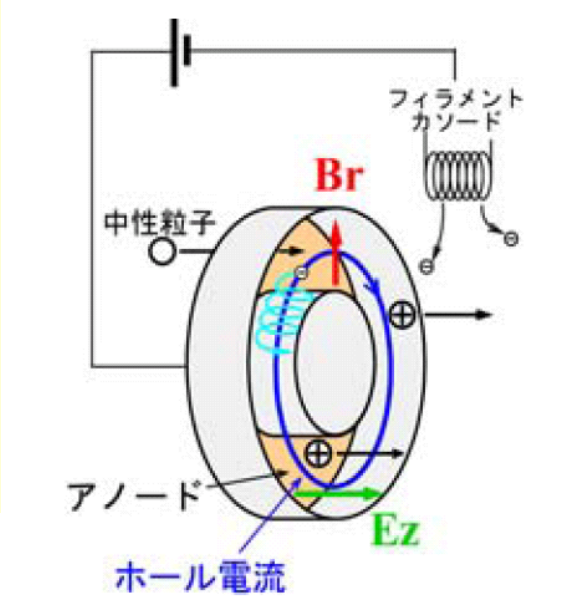
＋ 小型衛星（低高度/静止軌道）：
姿勢制御、デブリ除去等



プラズマ推進の例



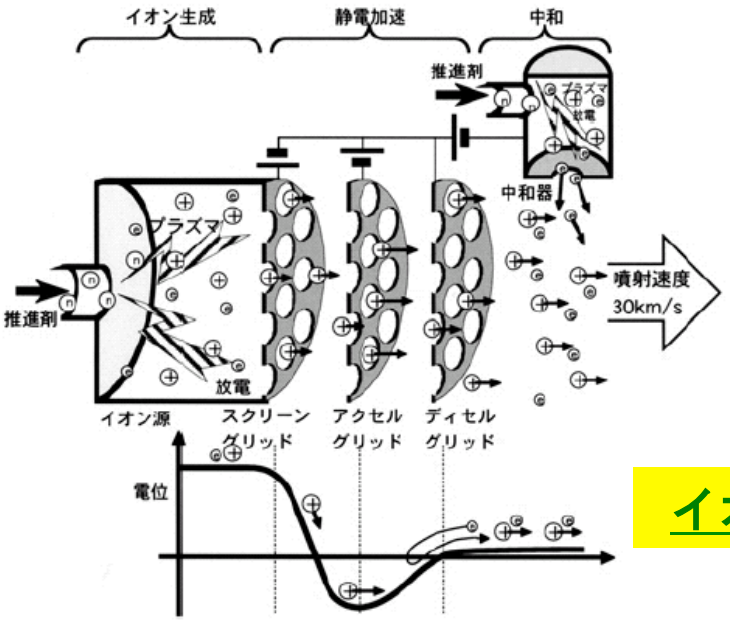
MPD　（宇宙研資料）



ホールスラスター

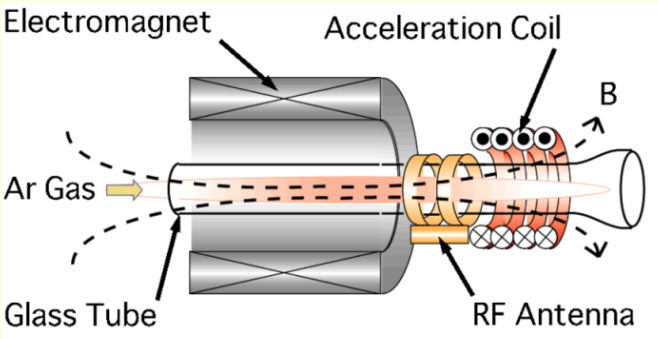
（犬竹研資料）

磁気セール　（ワシントン大）



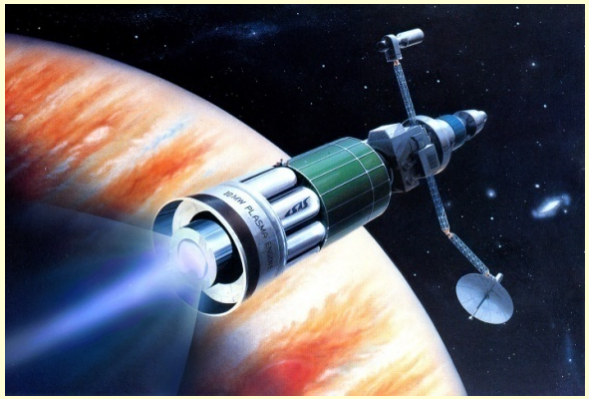
イオンエンジン

（国中資料）



電磁推進　（篠原）

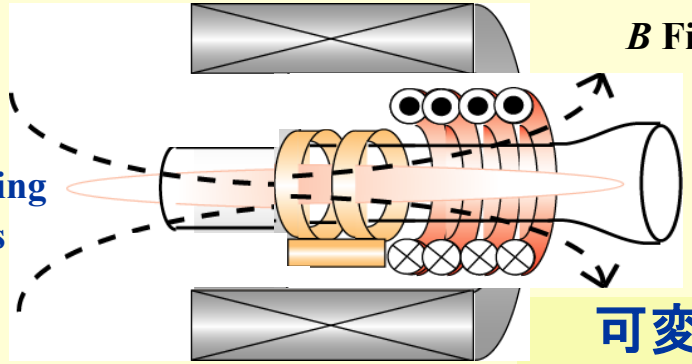
先進プラズマ推進プロジェクト (II)



プロジェクト研究

将来の 無電極 プラズマ推進

(プラズマと電極：直接接触なし)



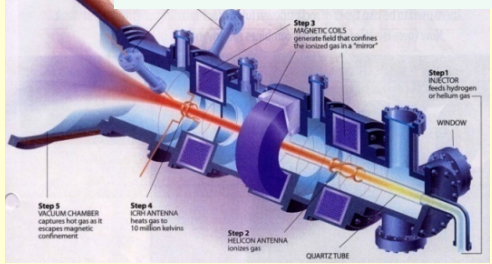
可変高比推力

先進アイデアと技術
(プラズマ物理学)

ヘリコン 高密度プラズマ生成　長寿命

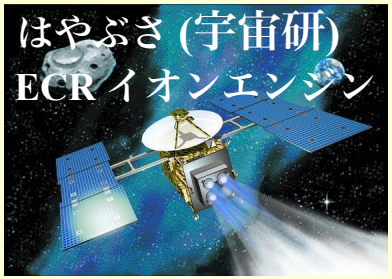
高効率　＋ 先進電磁推進

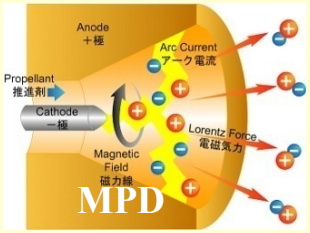
VASIMR (NASA)

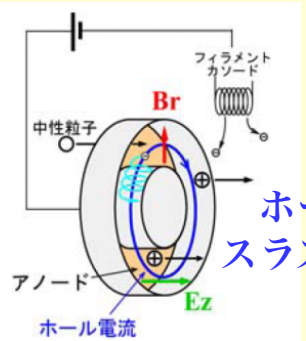


Helicon
+ICRF

強いプラズマー壁相互作用







ホール
スラスター

科学研究費：基盤研究 (S)

先進プラズマ推進

High-Density Helicon Plasma

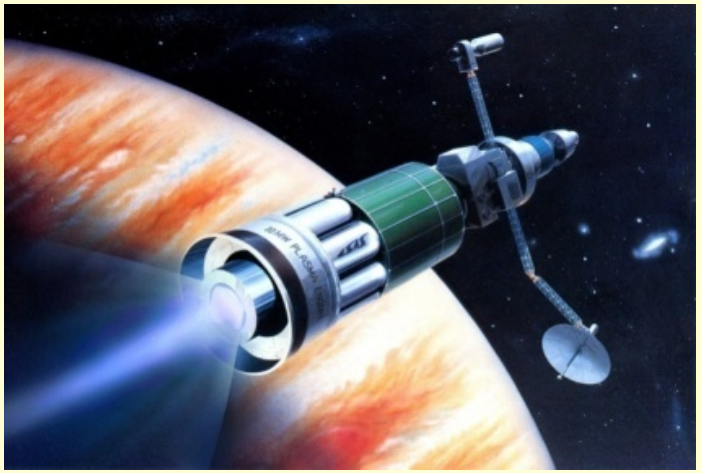
Initial Try of New Propulsion Scheme

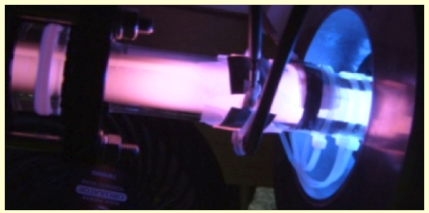
cf. NASA ”VASIMR”

ヘリコン波を用いた先進的無電極プラズマロケットエンジンの研究開発

基盤研究 (A)、(B)、(C) 等の蓄積

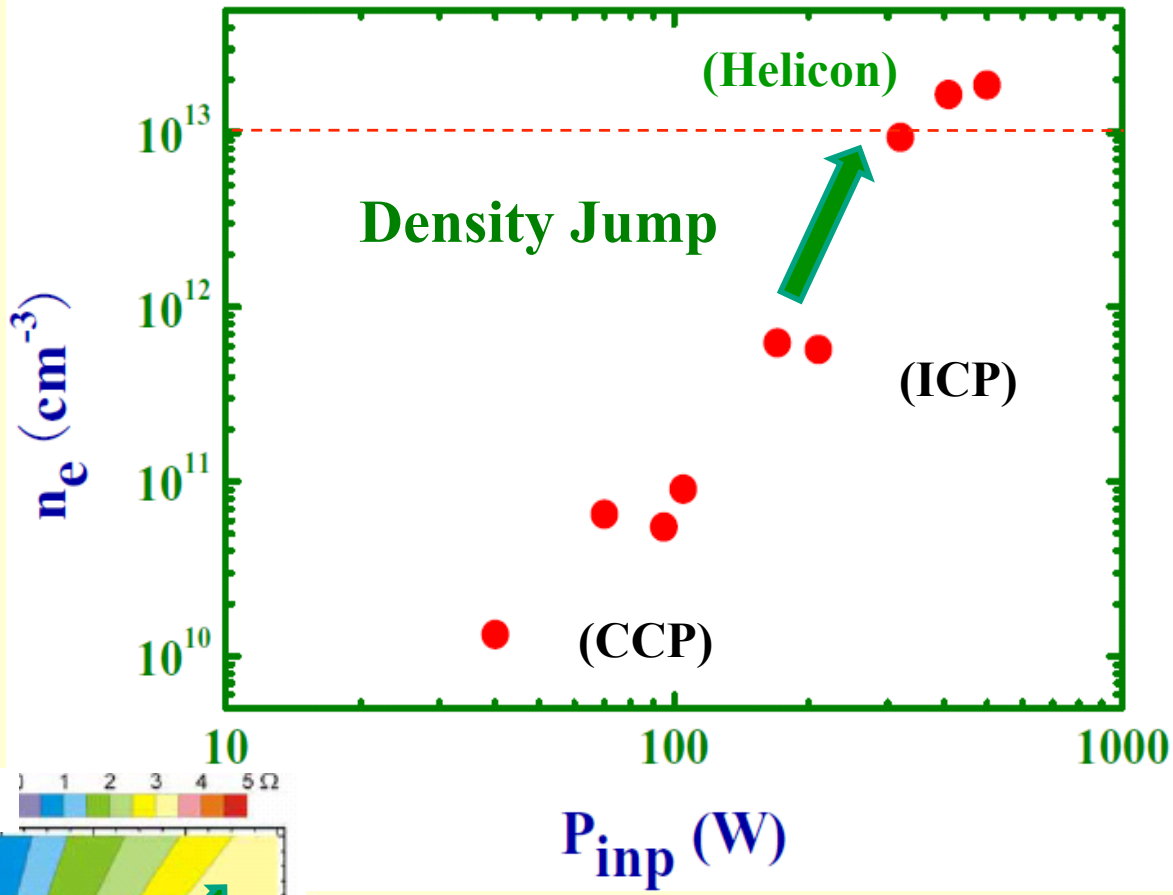
故都木教授、谷川教授、羽田准教授、船木准教授、西田准教授、
Shamrai博士 等と共同研究



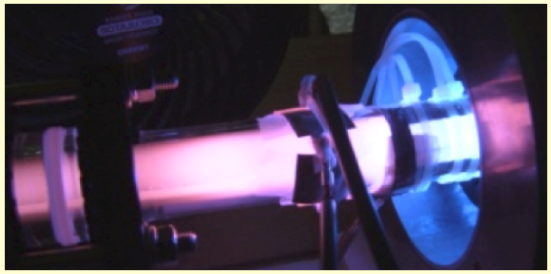


High-Density Plasma Production

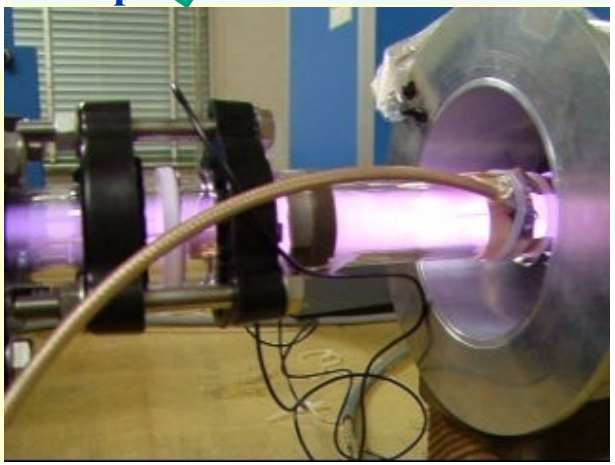
2.5 cm I.D.
(Smallest *D*)



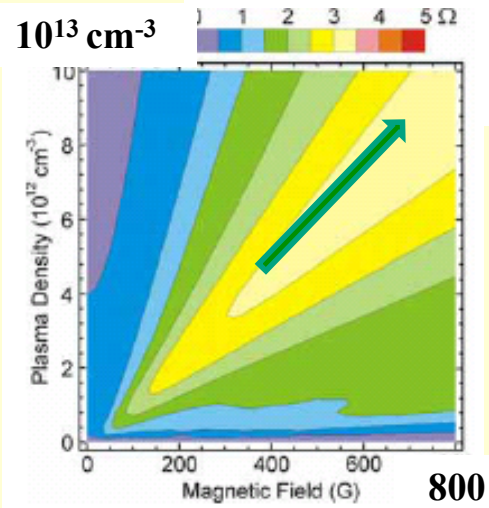
~ 2×10^{13} cm^{-3}
Achieved @ 500W



P_{inp} : Blue Mode



10^{13} cm^{-3}



800 G

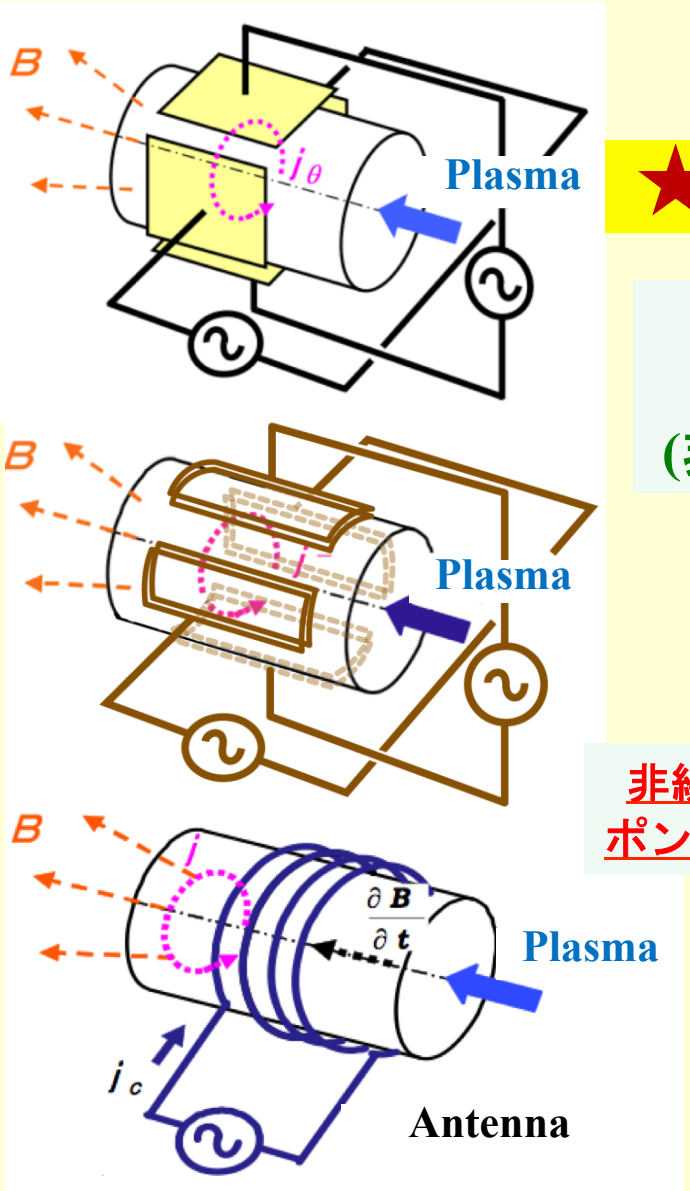
(27.12 MHz, 0.5 mg/s, 800 G)

Antenna Loading in (B, n_e) Space
(Calc. By Shamrai)

先進プラズマ推進プロジェクト

無電極MPD
スラスター

無電極 (アンテナがプラズマと無接触)



＋高密度ヘリコンプラズマ源

★ 原理実証実験 (進行中)

回転電場 (REF)
回転磁場 (RMF)
(非対称) 周方向電流

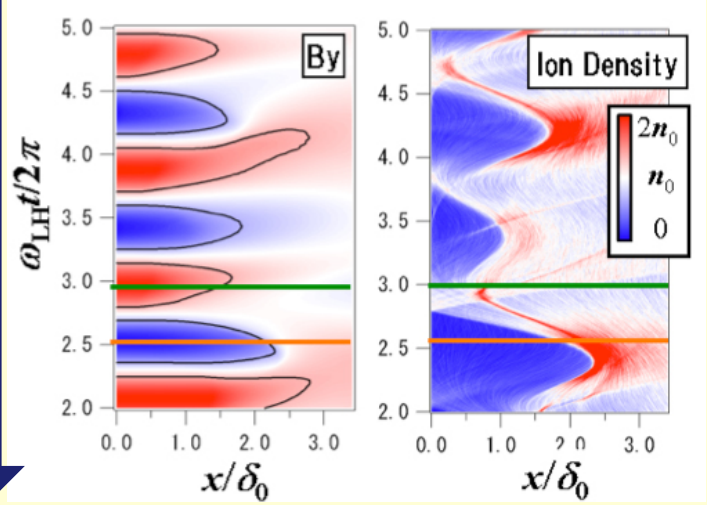
$F_z = j_\theta \times B_{r0}$

＋他の方法

非線形波動、ダブルレアー
ポンデロモーティブ力 ....

e.g., PIC、流体 ...

シミュレーション例



★ 理論＋ シミュレーション
粒子/流体/電磁場解析

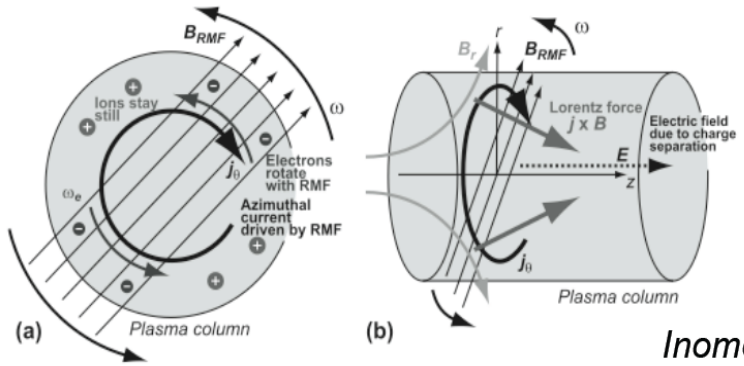
緊密な会合
データ共通化

RMF
25pQA2: Motomura *et al.*

Propulsion Scheme (I)

cf. FRC:
Nucl. Fusion

RMF: Rotating Magnetic Field

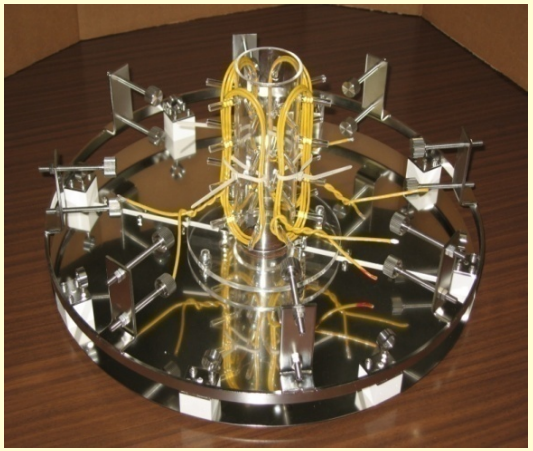


Inomoto, 2008

$$E - (j \times B)/e\, n_e = \eta j$$

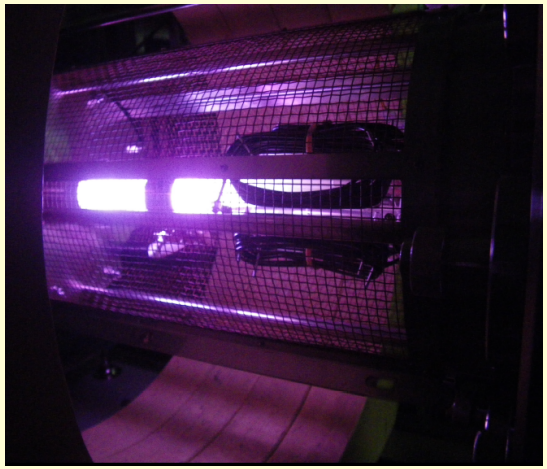
Rotating Magnetic Field (ω)	$\mathbf{B}_\perp \sim \exp(i\omega t)$	$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$
Inductive Electric Field (ω)	$\mathbf{E}_z \sim \exp(i\omega t)$	**Resistivity (Collision)**
Axial Ohmic current (ω)	$\mathbf{J}_z \sim \exp(i\omega t)$	nonlinearity
Azimuthal current (DC)	$\mathbf{J}_\theta \sim < \mathbf{J}_z \times \mathbf{B}_\perp >$	radial B field
Axial Lorentz force (DC)	$\mathbf{F}_z = \mathbf{J}_\theta \times \mathbf{B}_r$	

Rotating Magnetic Field: *Jones, 1979; Hugrass et al.,1980; Hoffman, 1998 etc*



Our Proto Type

(Inside of V.V)



Our Second Type

(Outside of V.V.)

Penetration Condition of the RMF into a Plasma

Axial Force $F \propto n\omega B_r R^3$

(非対称)
周方向電流

Propulsion Scheme (II)

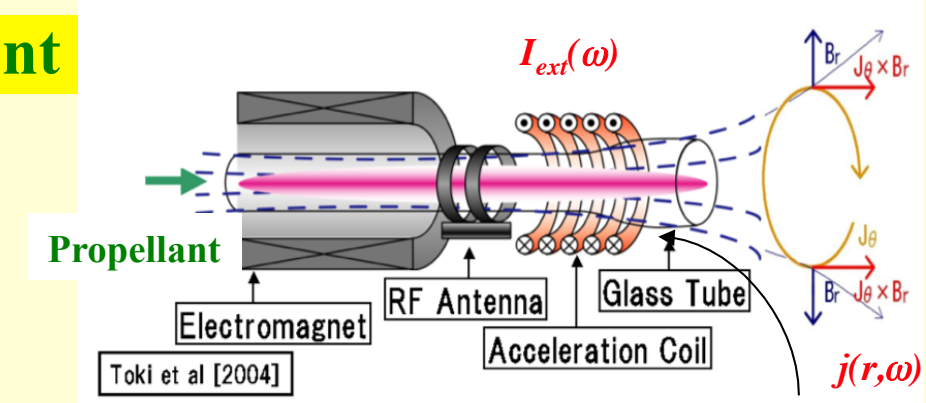
Cal. by Hada
PoP09 Shinohara

★ Multi Loops: Azimuthal Current

X Mode Disp. Relation
Boundary Condition

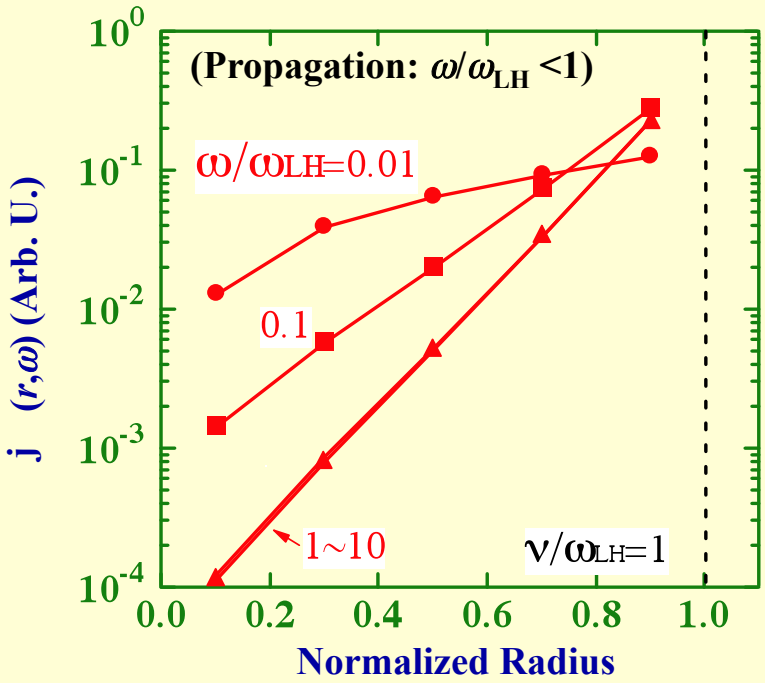
($k_z = 0$)

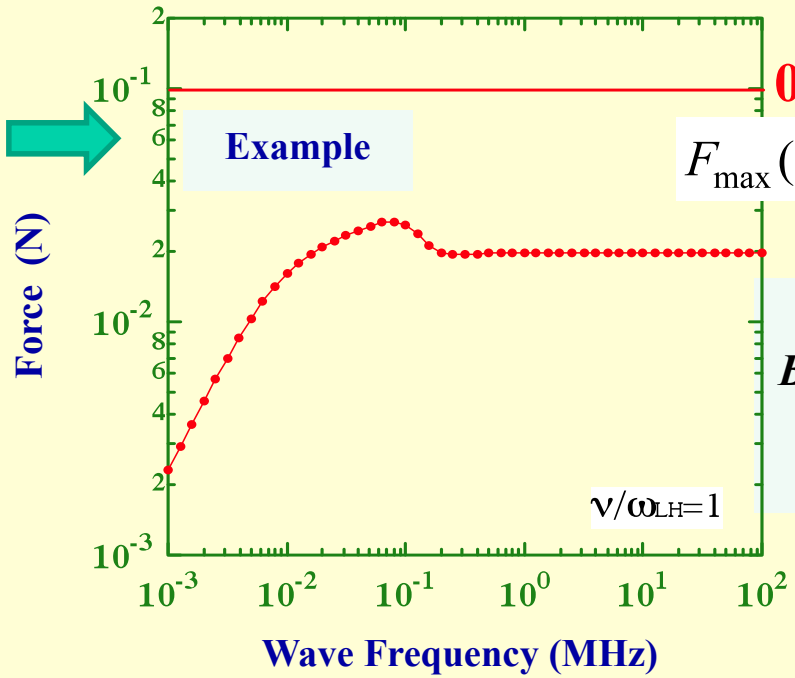
$I_{ext}(\omega)$: External Current
$j(r,\omega)$: Induced Current Density
$= C(r,\omega)\, I_{ext}(\omega)/\pi R^2$
$C(r,\omega)$: Response Function



$$F(\omega) = \int_0^L dz \int_0^R 2\pi r dr\, j(r,\omega) B_r(r)$$

Half Period



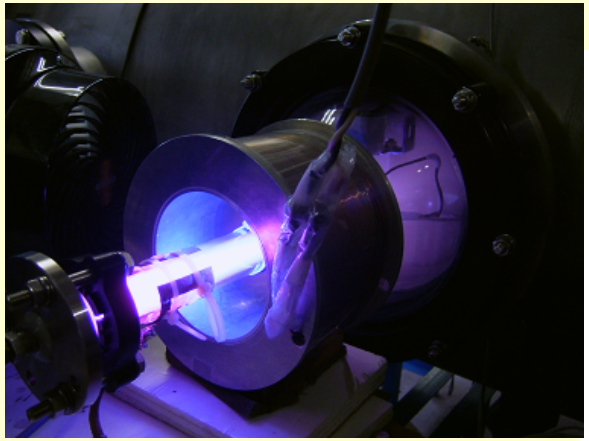


$n = 10^{12}$ (cm^{-3})
$B_{rm} = 100$(G) $\propto r$
$I_{ext} = 10$ (A)
f_{LH}=1 (MHz)

REF

Propulsion Scheme (III)

by Toki, Nishida *et al.*



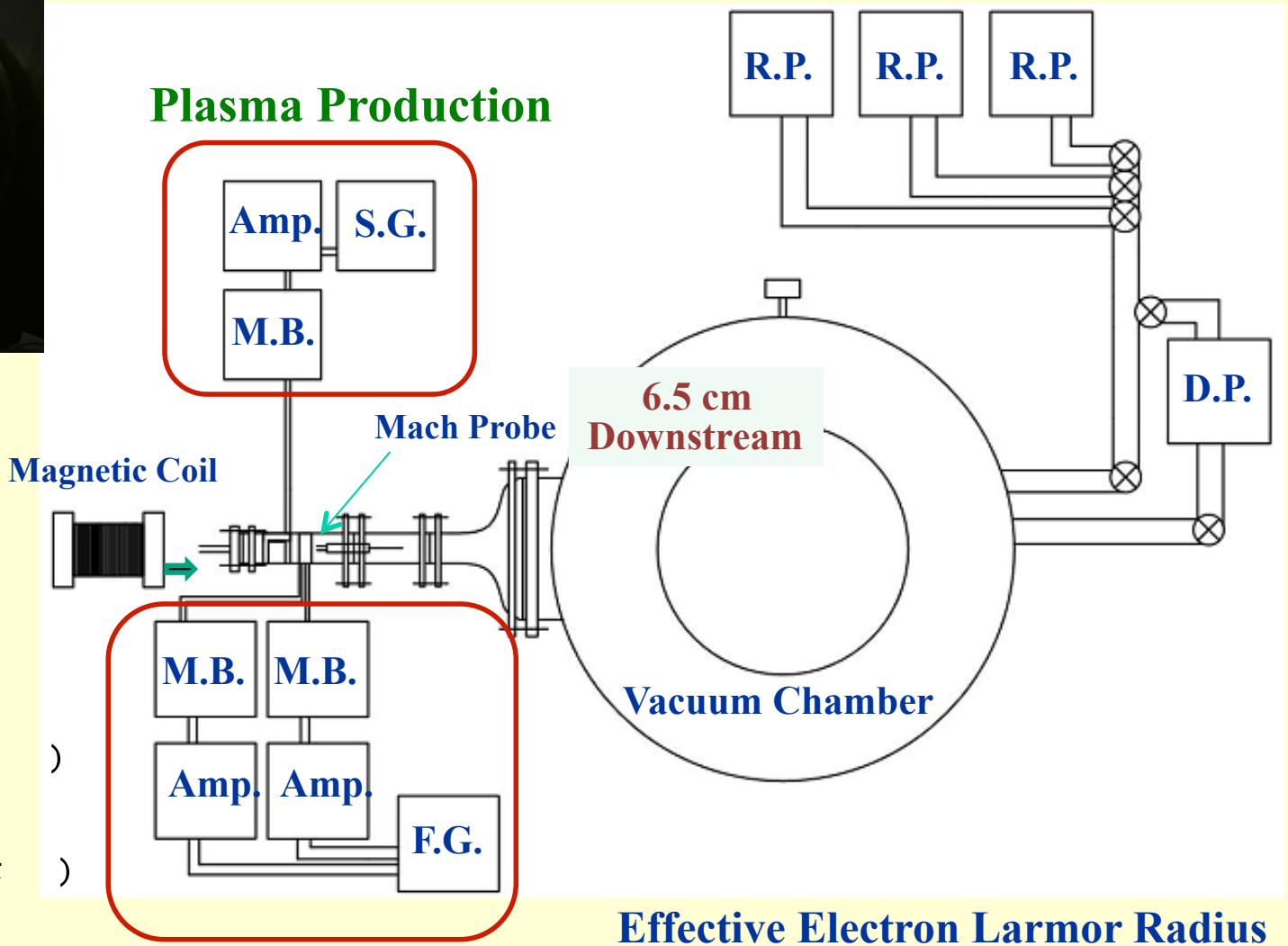
Rotating Electric Field (Lissajous)

Electron Motion

$$u_x \quad \frac{eE_0}{m}\frac{1}{\sqrt{(\quad_0 \quad)^2 \quad ^2}}\sin(\quad t \quad)$$

$$u_y \quad \frac{eE_0}{m}\frac{1}{\sqrt{(\quad_0 \quad)^2 \quad ^2}}\cos(\quad t \quad)$$

$$R_{L,eq.} = \frac{eE_0}{m_e\omega\sqrt{(\omega_0-\omega)^2+\nu^2}}$$



Effective Electron Larmor Radius

$$R_d = E/\omega B_{z0}$$

cf. Diamagnetic Current

推進効率

はやぶさ

比推力　3180[s]
推進効率　51 [%]
25 [mN/kW]

RMF

比推力　150[s]
推進効率　0.01 [%]
0.1 [mN/kW]

目標
$v(M) > 10$倍
$S \sim 4$倍(r~2倍)
$n > 5$~10倍

RMF

比推力　1500[s]
推進効率　20 % 以上
20 [mN/kW]　以上

Helicon: Future Potential Contribution

Nonlinearity－Complex/Structural Formation

Industrial Application

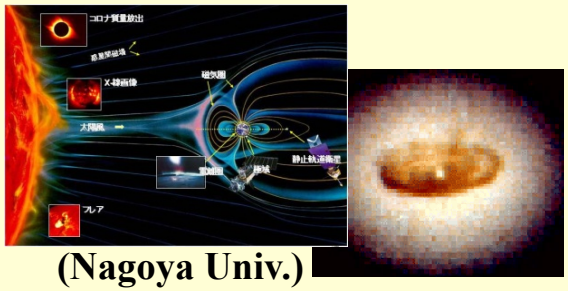
Nanotechnology/Materials, Environment,
Information/Telecommunication, Biotechnology …

Basic Physics

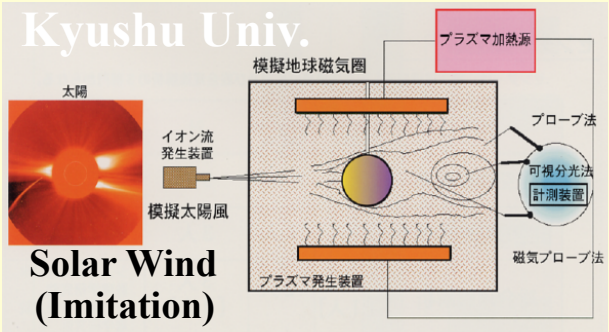
Self Organization
Density Transition
Velocity Shear
Turbulence
High-Beta, PWI
Boundary Layer
Magnetic Reconnection
Gas Laser…

Pre-ionization
Wall Conditioning
Neutron Source …

Fusion



(Nagoya Univ.)



Solar Wind
(Imitation)

Excitation of Various Waves
Magnetosphere

★ Propulsion

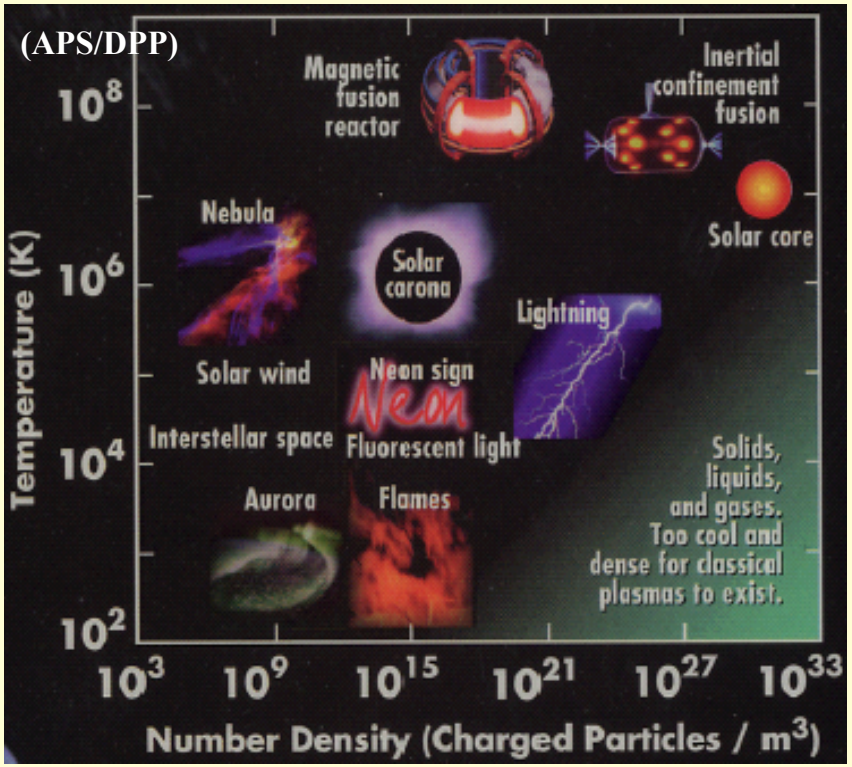
Dust (B, n_e …)
Astrobiology (Biopolesis)…

Space Physics

多 様 な プ ラ ズ マ　多くのシーズ/ニーズ

非常に広範な温度ー密度領域

複雑性/構造性



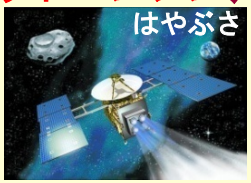
プラズマ基礎から応用への飛躍的展開

光　プラズマディスプレイ、光源、レーザー
リソグラフィー、マイクロプラズマ

熱　溶接/溶断、放電加工、精錬、ゴミ処理

電気　静電集塵機/塗装、空気清浄機、スイッチ素子
レーザー誘雷、MHD 発電

力学　レールガン、加速器、ロケットエンジン、異種イオン/遠心分離



化学反応　エッチング、CVD、フラーレン/ナノチューブ
フロン/PCB 分解、ダイアモンド合成、環境、バイオ/医療/生命誕生

核反応　核融合

→ 広域ヘリコンプラズマ科学

先進プラズマ研究へ貢献・展開

代表者　先進成果反映例　ヘリコンプラズマ科学

H22年度文部科学大臣表彰 科学技術賞

高密度ヘリコン波プラズマの物理現象と工学的応用の研究

表紙写真と解説

ヘリコンプラズマ源の開発と応用

プラズマ・核融合学会誌でも解説

特許 2件

高周波プラズマの発生方法

科学研究費

基盤研究(S)：代表
基盤研究(B)：代表
特別推進研究：分担
その他多数

査読論文

Nature Phys., Phys. Plasmas, Plasma Phys. Control. Fusion, Thin Solid Films, その他多数

国際会議等招待講演

電離気体現象に関する国際会議 (ICPIG)
マイクロエレクトロニクスとプラズマ技術に関する国際会議 (ICMAP)
アジア太平洋プラズマ科学技術に関する国際会議 (APCPST)
アメリカ物理学会 (APS)
ヨーロッパ物理学会 (EPS) ….

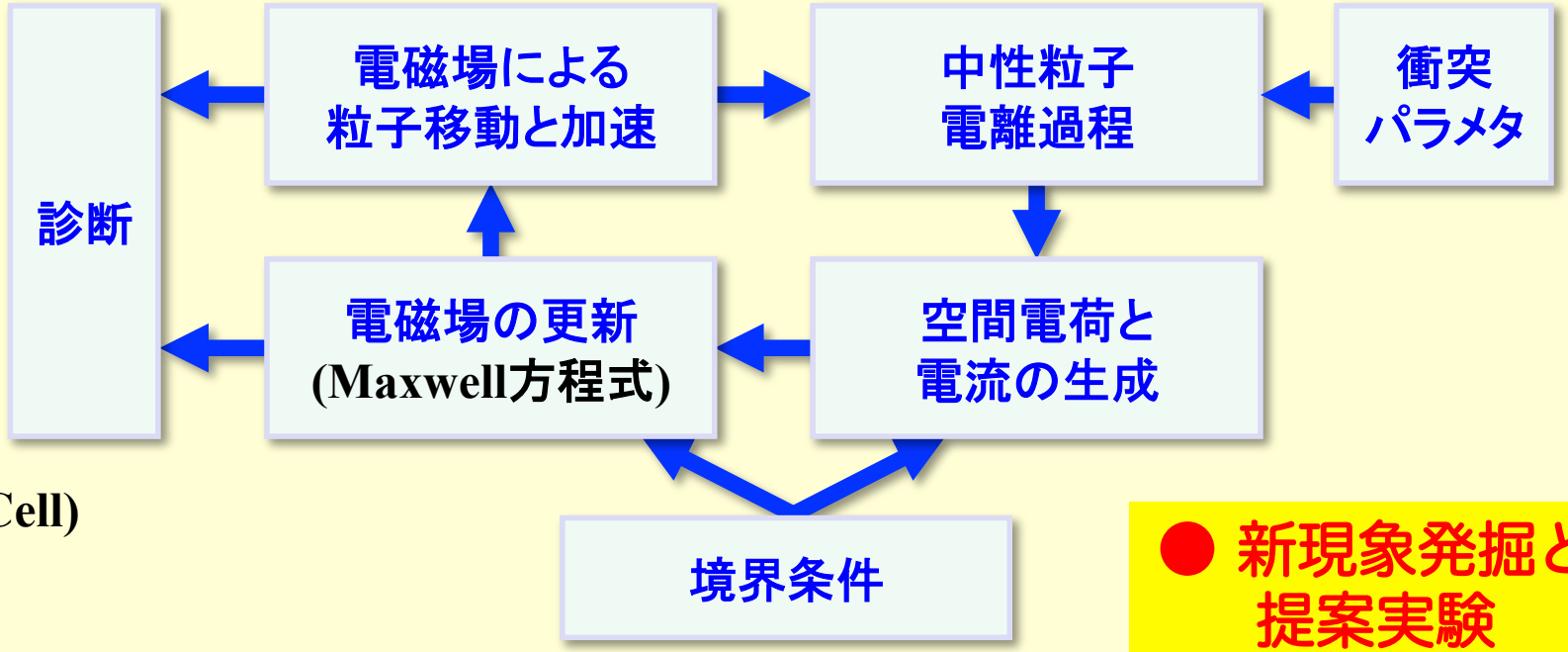
日本物理学会でも招待講演

羽田教授

H11年度
田中舘賞受賞他

高ベータプラズマの PIC 計算機実験

PIC計算の概念



(Particle-in-Cell)

● 新現象発掘と提案実験

今後の研究計画

円柱プラズマの理論モデル → 磁気流体モデルによる予備計算 → PICモデルによる計算機実験 → PICの3次元計算

- 分散関係の確認
- プラズマおよび電磁場パラメータ依存性確認

- 現実的密度分布での計算
- ヘリコン波とTG波とのカップリング確認

- プラズマ生成とロス評価
- 運動論的効果の考察
- 実験との比較検討

理論・シミュレーションによる支援研究

I. 高密度プラズマ源
- 初期プラズマ生成
- 壁洗浄
- プラズマ－壁相互作用

II. 高密度プラズマ流制御
- 周・軸方向

III. 高ベータプラズマ
- 構造形成、安定性：動的変化

ヘリコンプラズマ：波動と高密度プラズマ生成

高ベータ領域を伝播する波動の解析：磁場ヌル点通過など
GAMMA10 の IAC に関連：
円柱プラズマ系でイオンの非等方性による波動励起