Nov. 19, 2002

中性粒子と共存するプラズマの渦

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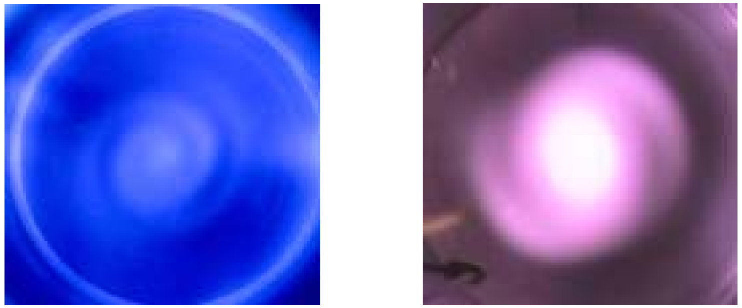
ＥＣＲプラズマ中に形成される渦構造

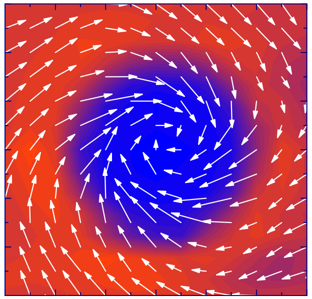


Spiral Pattern(Ar, H)

M. Kono and M.Y. Tanaka, Phys. Rev. Lett.
84, 4369 (2000)
M.Y. Tanaka and M. Kono, J. Plasma Fusion Res.
SERIES IV, 131(2001)

Multi-pole Vortex (Ar)

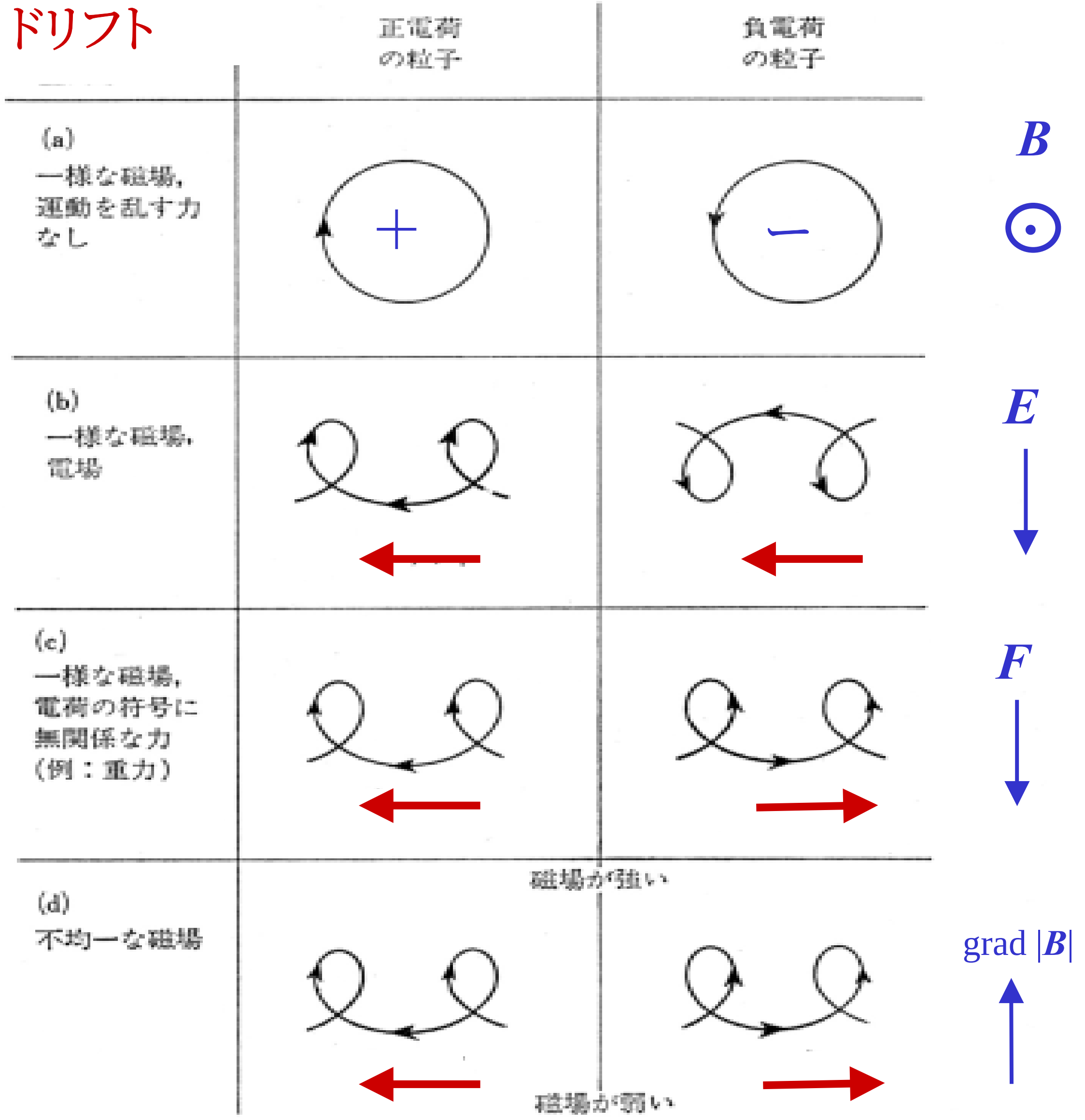
A. Okamoto et al., in submitted to Phys. Of Plasmas
A. Okamoto et al., J. Plasma Fusion Res.(2002)
in printing



Plasma Hole (He)

K. Nagaoka et al., Phys. Rev. Lett. **89**, 075001(2002)

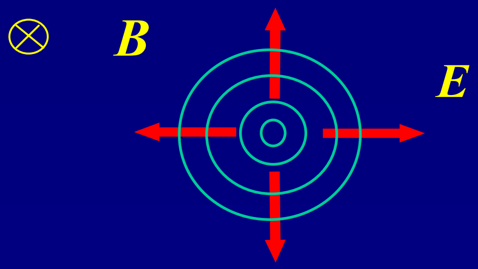
磁場中の荷電粒子のドリフト



プラズマは渦を作る！

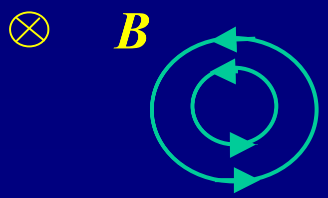
局所的密度不均一 $\frac{\delta n}{n} \approx \frac{e\phi}{T_e}$ → 電場の形成

→ $E \times B$ 回転 → 渦運動



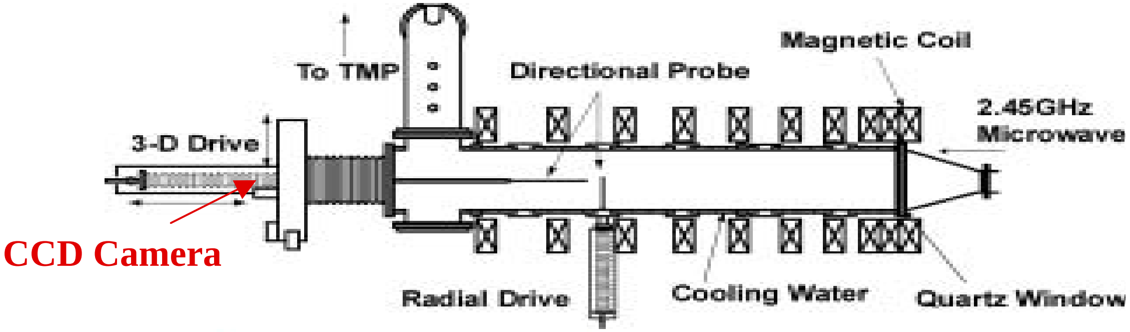
密度不均一

＝



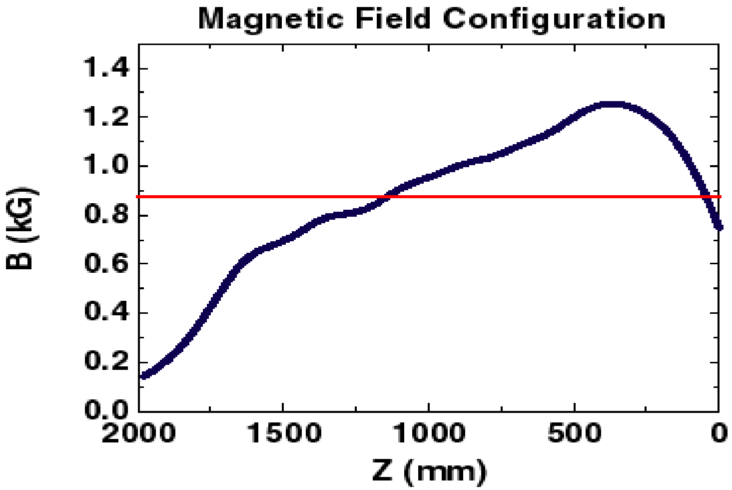
渦

Experimental Apparatus (HYPER-I)



Parameters

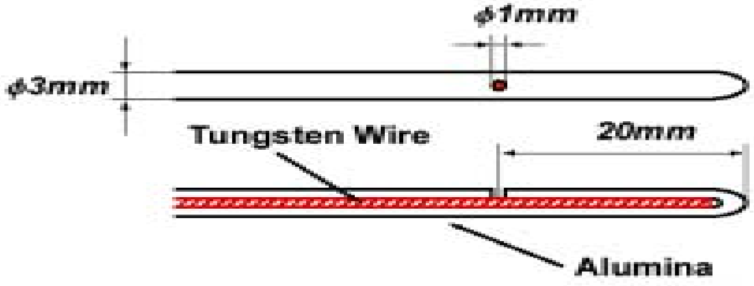
Power	4-15	kW
Frequency	2.45	GHz
Magnetic Field	1	kG
Gas (He)	6×10^{-4}	Torr
El. Temp.	20	eV
El Density	10^{12}	cm^{-3}

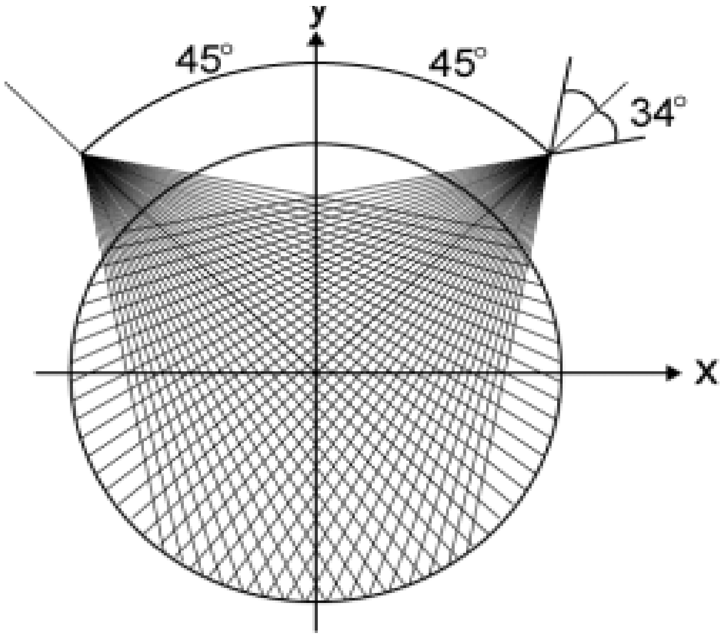


The experiments have been performed with the High Density Plasma Experiment (HYPER-I) device at National Institute for Fusion Science. The plasmas are produced by electron cyclotron resonance heating. The magnetic field configuration is a so-called magnetic beach structure. The plasma discharge time is ~60s and a helium gas is used with the operation pressures 6 ~ 8 x 10^{-4} Torr.

磁場に垂直な平面内の速度ベクトル場の測定

Directional Langmuir Probe

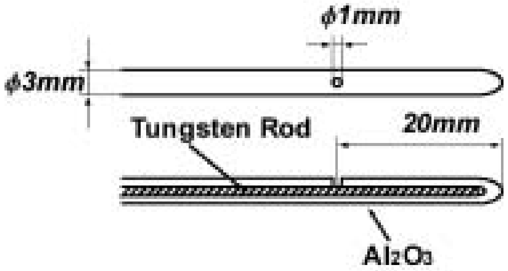




A set of Directional Langumuir Probes

プローブ信号と流速の一般関係式

$$I_s(\boldsymbol{n}) = I_s^{(0)} \underbrace{\left(1 + F_{\mathbf{V}}(\boldsymbol{V},\boldsymbol{n})\right)}_{\text{イオン流速による補正項}} \cdot \underbrace{\left(1 + F_{\mathbf{B}}(\boldsymbol{B},\boldsymbol{n})\right)}_{\text{磁場による補正項}}$$

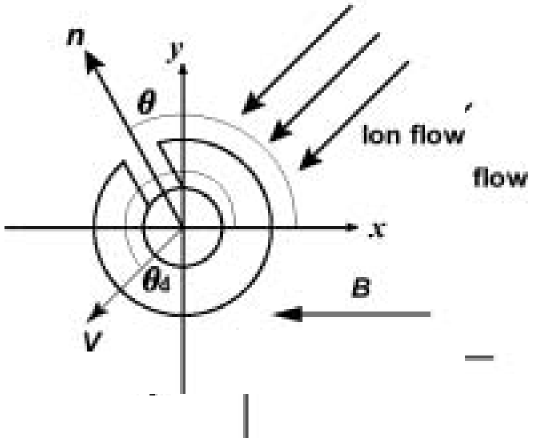


流れによる補正項は、流速V の反転に対して符号を変える性質。

$$F_V(\boldsymbol{V},\boldsymbol{n}) = -F_V(-\boldsymbol{V},\boldsymbol{n}) = -F_V(\boldsymbol{V},-\boldsymbol{n})$$

イオン流速による補正項は、$\boldsymbol{V}\cdot\boldsymbol{n}$ の奇関数で展開できる。

$$F_V = -\alpha_1(\boldsymbol{V}\cdot\boldsymbol{n})^1 - \alpha_3(\boldsymbol{V}\cdot\boldsymbol{n})^3 - \cdots$$



磁場による補正項は、磁場B の反転に対して符号を変えない性質。

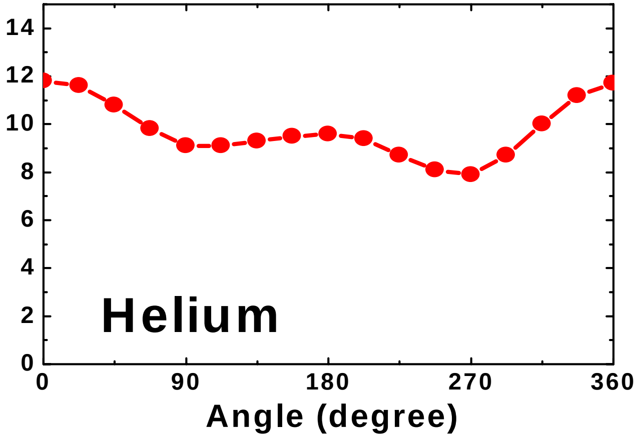
$$F_{\mathbf{B}}(\boldsymbol{B},\boldsymbol{n}) = F_{\mathbf{B}}(-\boldsymbol{B},\boldsymbol{n}) = F_{\mathbf{B}}(\boldsymbol{B},-\boldsymbol{n})$$

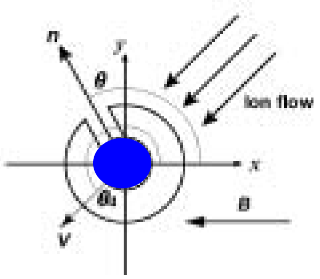
イオン流速による補正項は、$\boldsymbol{B}\cdot\boldsymbol{n}$ の遇関数で展開できる。

$$F_V = -\alpha_1(\boldsymbol{V}\cdot\boldsymbol{n})^1 - \alpha_3(\boldsymbol{V}\cdot\boldsymbol{n})^3 - \cdots$$

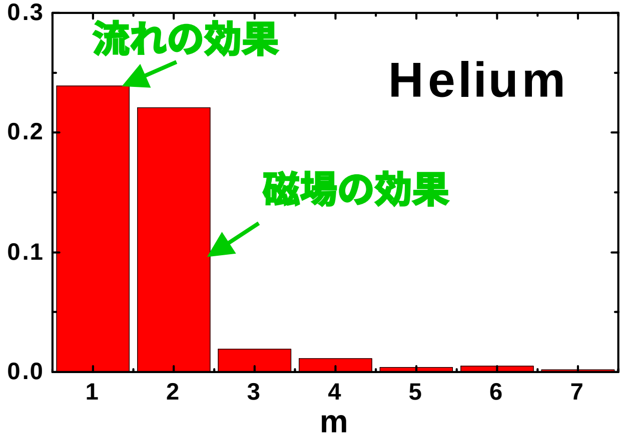
$$\frac{\boldsymbol{V}\cdot\boldsymbol{n}}{C_S} = \frac{V\cos(\theta-\theta_{\mathbf{d}})}{C_S} = \frac{1}{\alpha}\cdot\frac{I_S(\theta+\pi)-I_S(\theta)}{I_S(\theta+\pi)+I_S(\theta)}$$

方向性プローブ信号の角度依存性



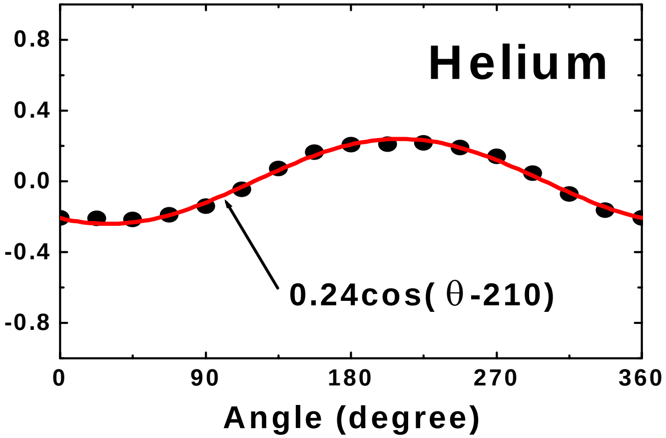


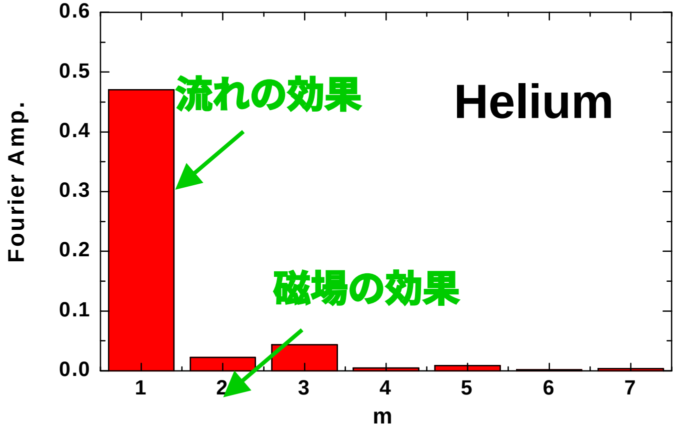
フーリエ成分



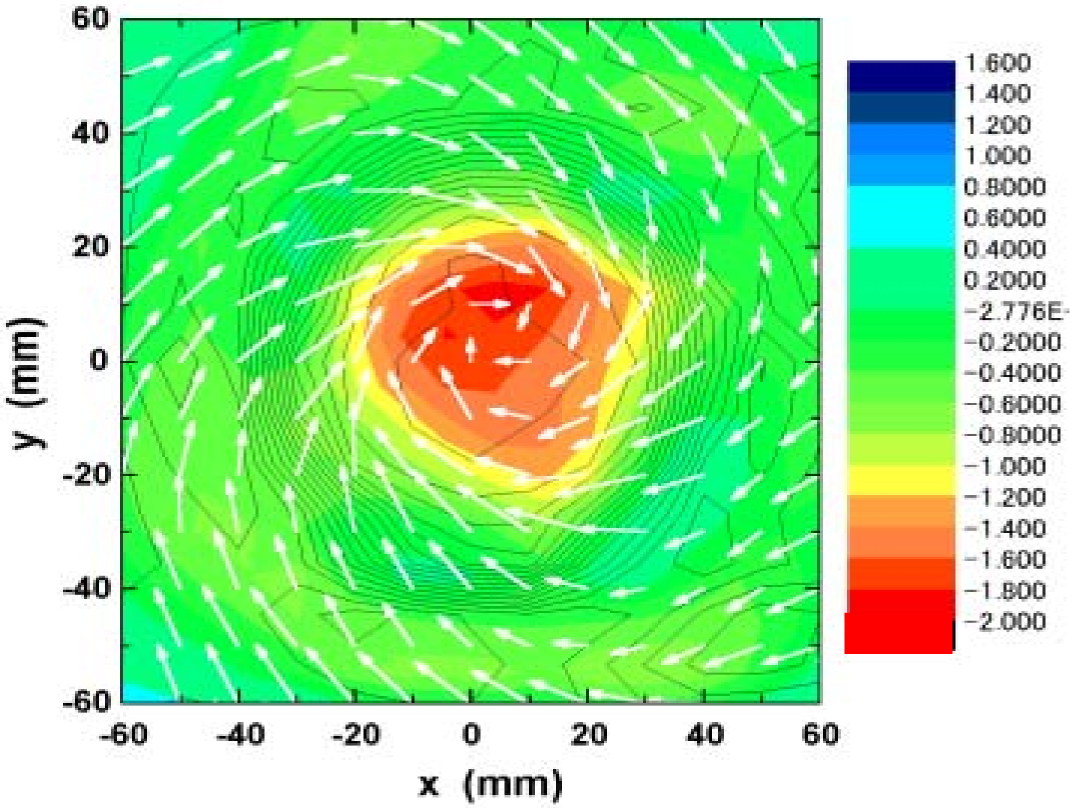
$$\frac{I_S(\vartheta)}{I_S(\vartheta+\pi)} = \frac{I_S^0\left(1+F_V(\boldsymbol{n},V)\right)}{I_S^0\left(1+F_V(-\boldsymbol{n},V)\right)}\frac{\left(1+F_B(\boldsymbol{n},\boldsymbol{B})\right)}{\left(1+F_B(-\boldsymbol{n},\boldsymbol{B})\right)}$$

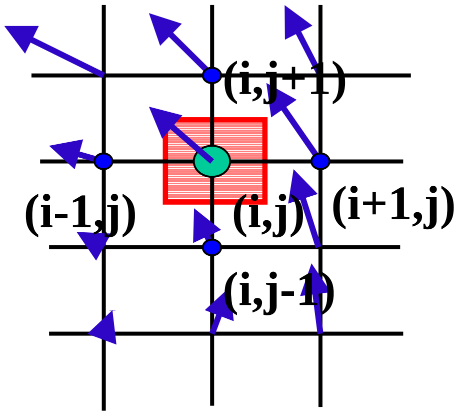
磁場の効果を相殺し、流れの効だけを求めることができる。





Evaluation of Vorticity

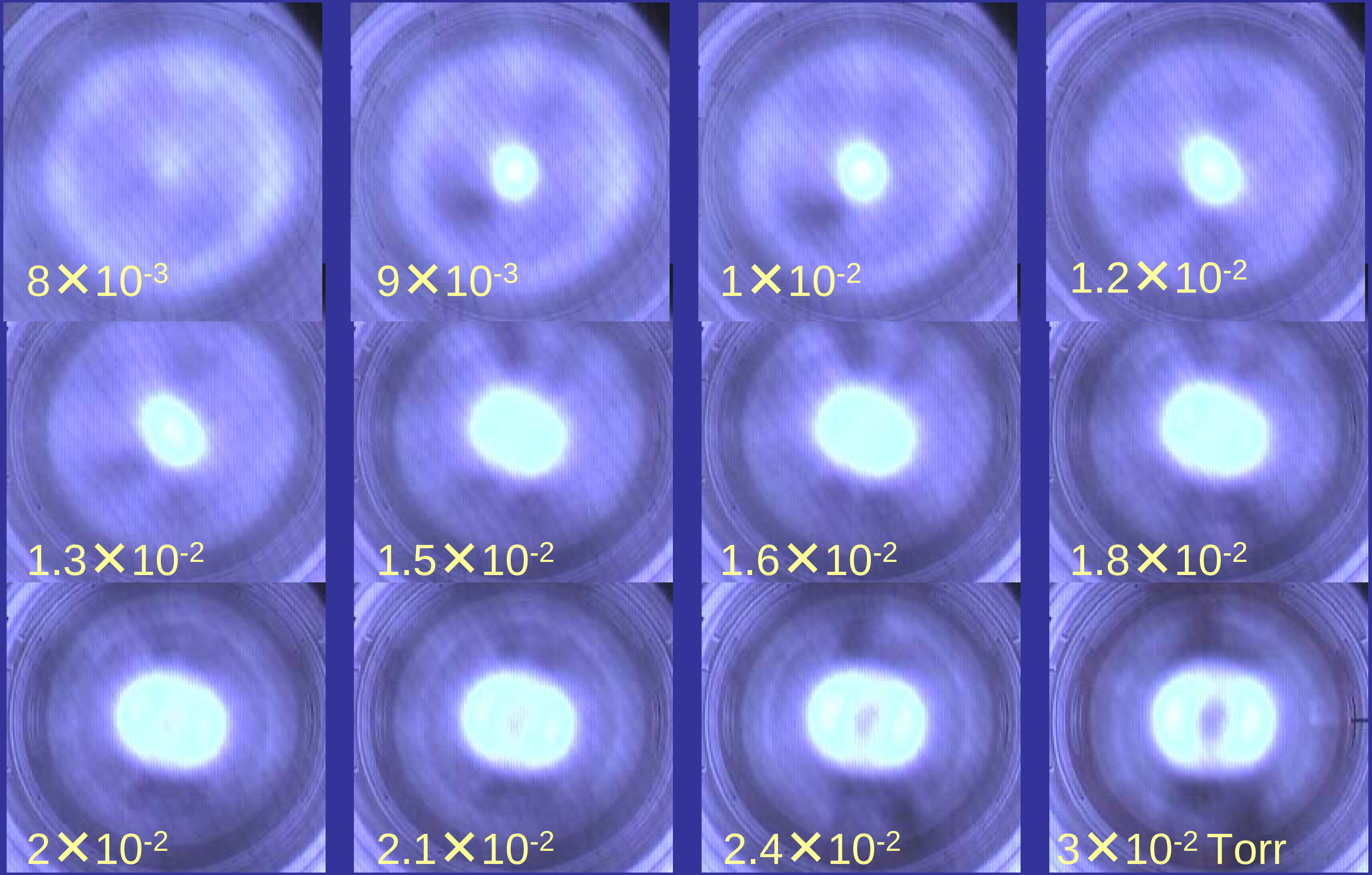




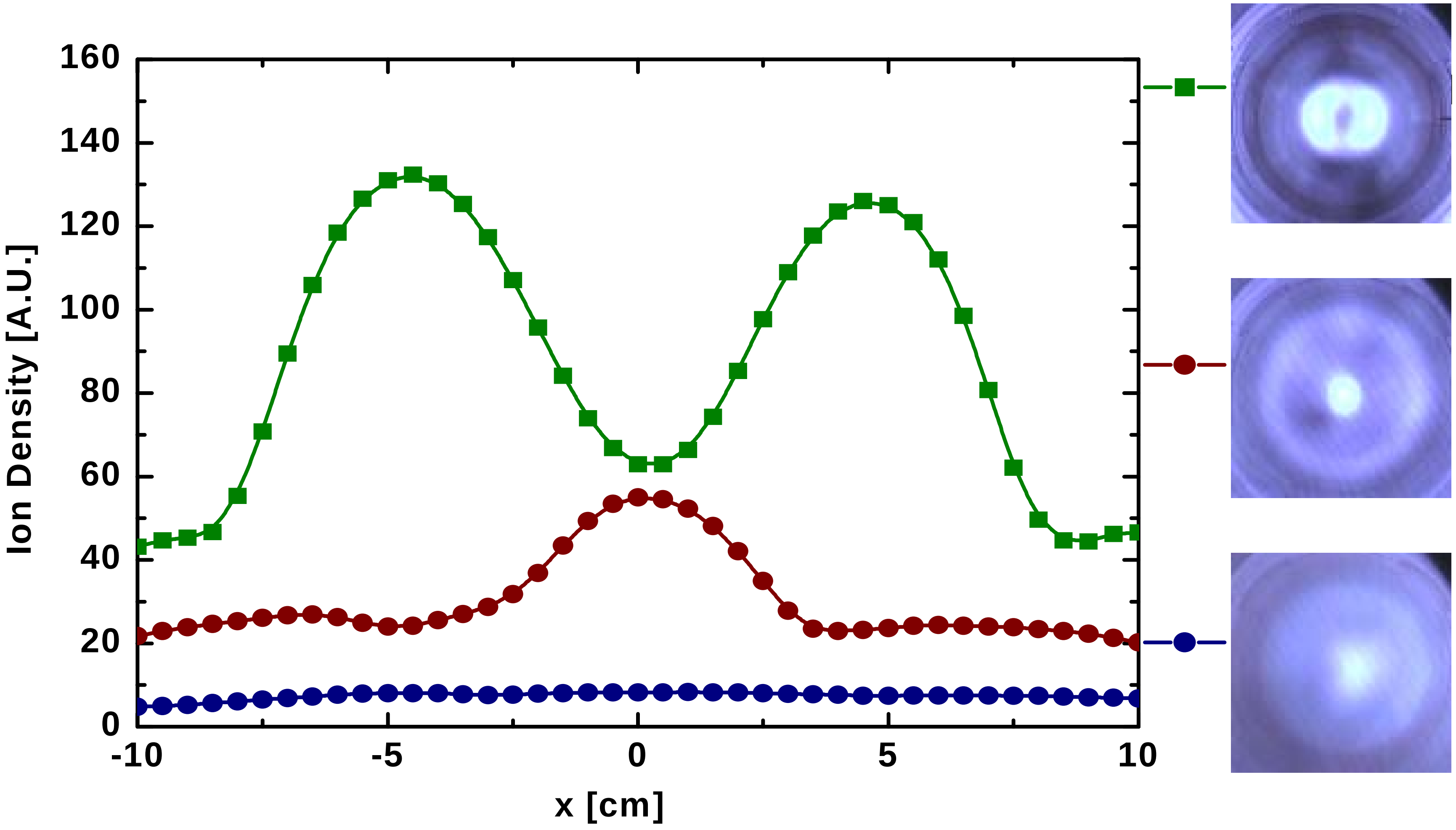
$$\omega_z = (\nabla \times \boldsymbol{v})_z \approx \int \boldsymbol{v} \cdot \boldsymbol{dl} / \Delta S$$

We calculate the z-component of vorticity at each point, by performing the line integration given above. The vorticity (color contour map) is localized in the center of the plasma hole. The solid lines indicate density contour.

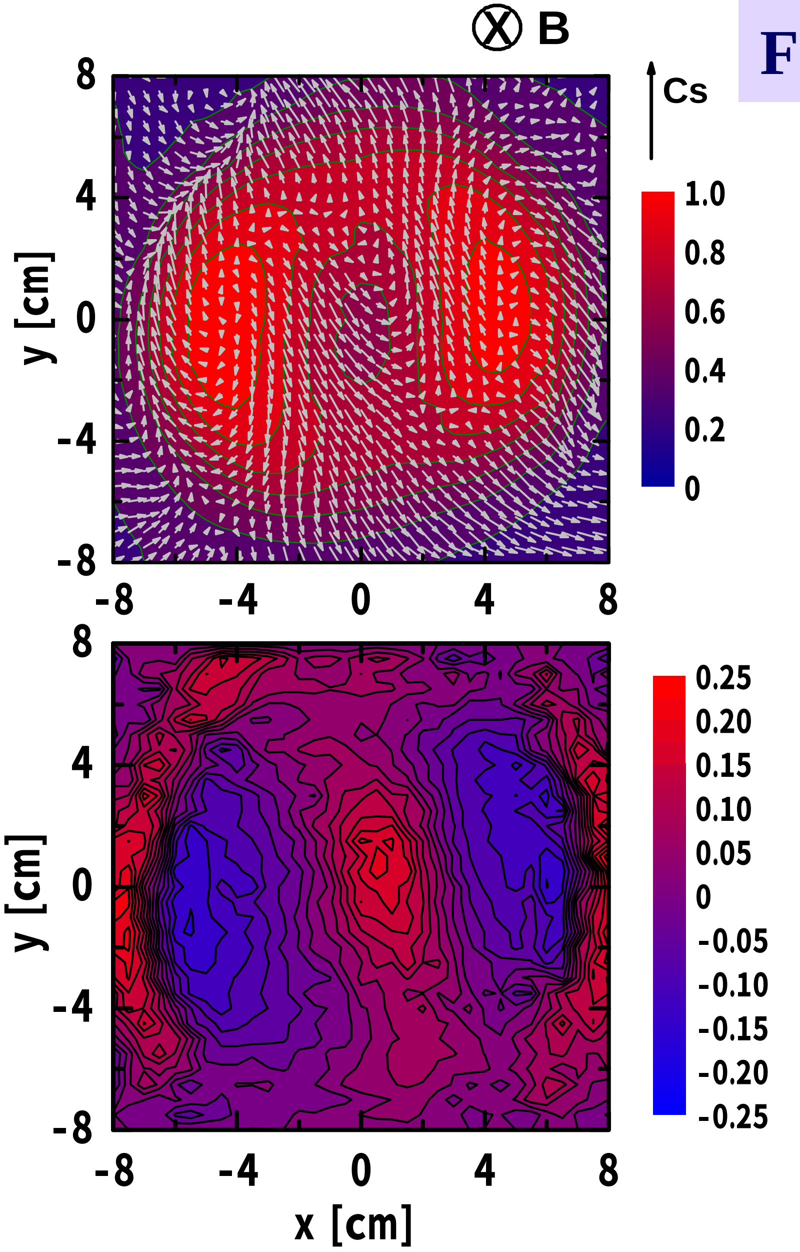
Formation of Tripolar Vortex (End View Image)



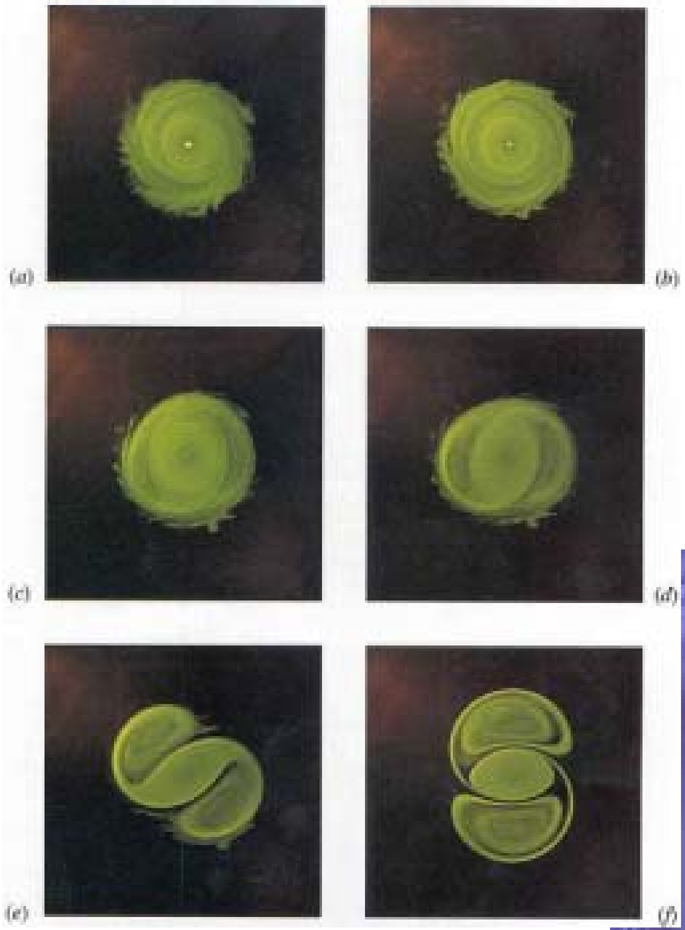
プラズマ密度の径方向分布



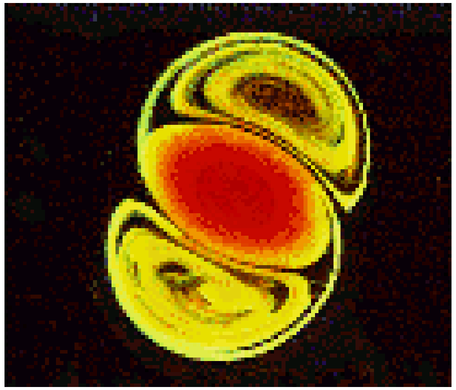
Flow Velocity Field and Vorticity Contour



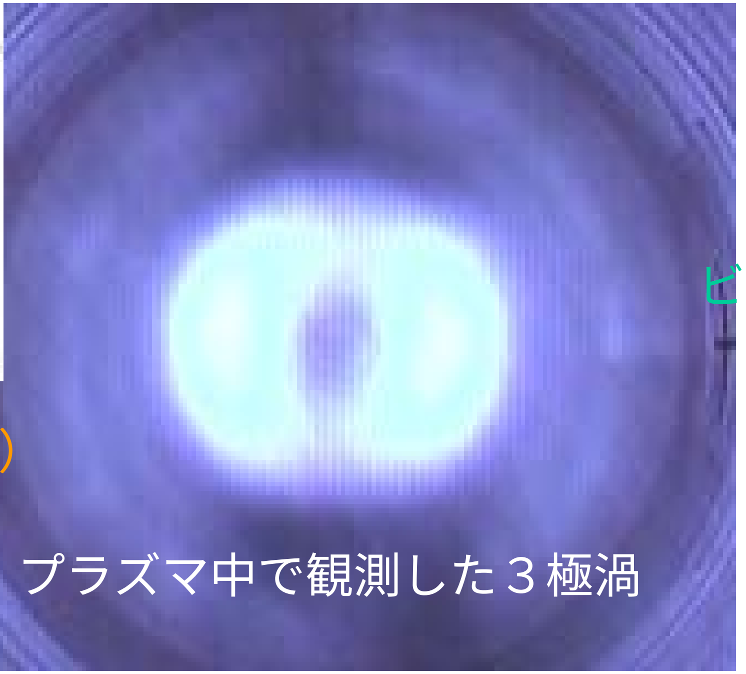
The vector field plot (Top) and the contour map of z-component of vorticity (Bottom) are shown. The vorticity is evaluating the line integration $(rot\, v)_z = \sum v \cdot dl / \Delta S$. There are two clockwise vortical motion In both side orresponding to ion density peaks. Between these vortices, there present a counter-clockwise motion in the center. The vorticity contour clearly indicates the existense of three vortices. Two of them have negative polarity (clockwise) and the central vortex has positive polarity (counter-clockwise). The observed structure is a tripolar vortex.



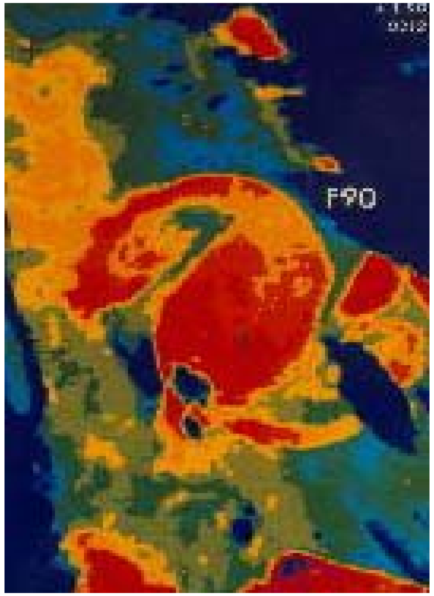
回転流体で発生する３極渦（2）



回転流体で発生する３極渦（1）



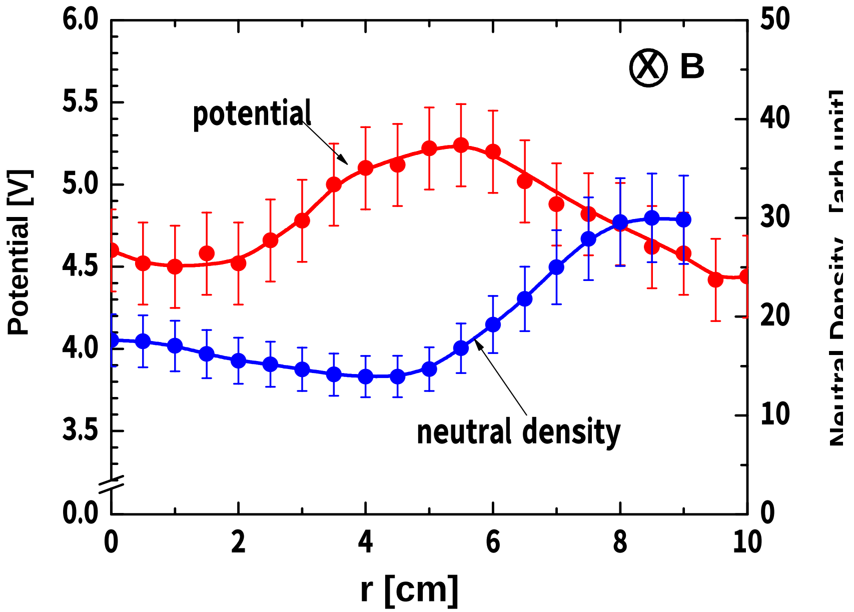
プラズマ中で観測した３極渦



ビスケー湾に発生した３極渦

Potential Profile and Neutral Density Profile

A remarkable characteristic of the tripolar vortex is that each vortex rotates in the opposite direction to the *ExB* drift. This results suggests that there should be an inward force acting on the ions.



The potential profile is a double peaked one, and the peak positions roughly coincide with the ion density peaks. The neutral density has double minimum, at which the potential becomes maximum. If there is a dynamical coupling between the ions and neutrals, the neutral density gradients may produce the inward force.

分光による中性粒子分布計測

$$I_{\mathrm{Ar\,I}} \propto n_{\mathrm{n}} n_{\mathrm{e}} \langle \sigma_{\mathrm{ex}} v \rangle \qquad (425.9\mathrm{nm}\ \ 5p\text{-}4s)$$

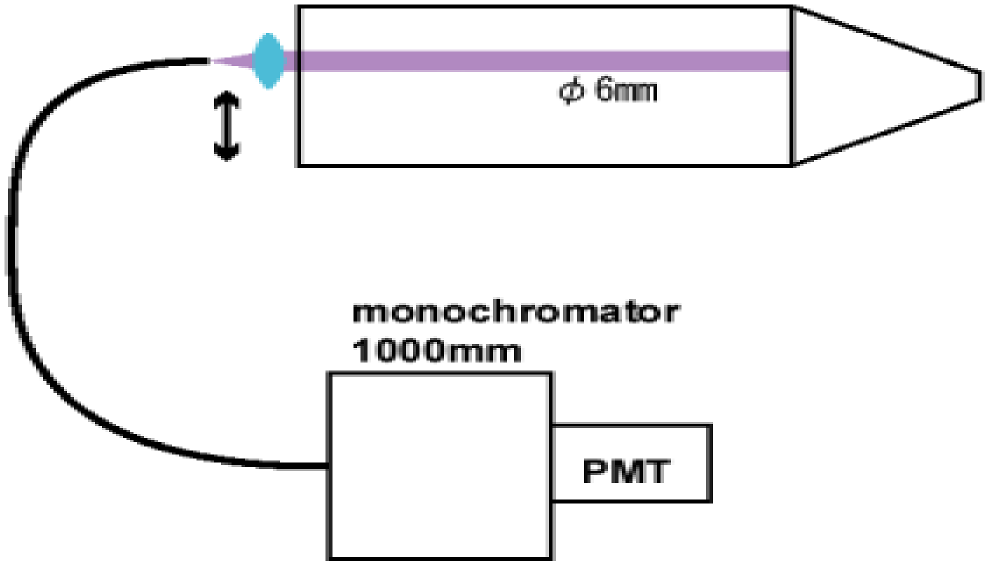
$$I_{\mathrm{Ar\,II}} \propto n_{\mathrm{i}} n_{\mathrm{e}} \langle \sigma_{\mathrm{ex}} v \rangle \qquad (488.0\mathrm{nm}\ \ 4p\text{-}4s)$$

- イオン密度

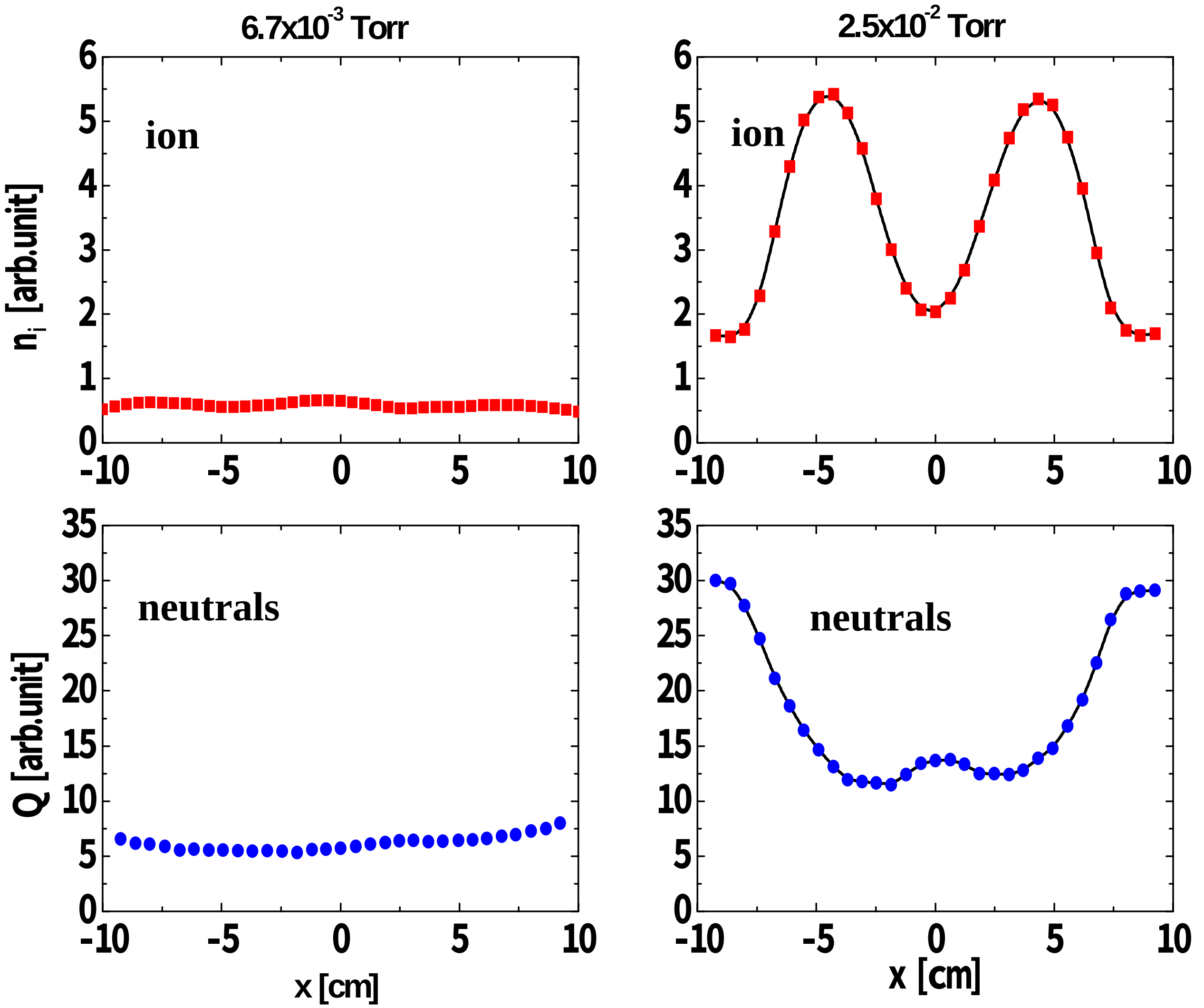
$$n_{\mathrm{i}} \propto \sqrt{I_{\mathrm{Ar\,II}}}$$

- 中性粒子密度

$$n_{\mathrm{n}} \propto I_{\mathrm{Ar\,I}} / \sqrt{I_{\mathrm{Ar\,II}}}$$



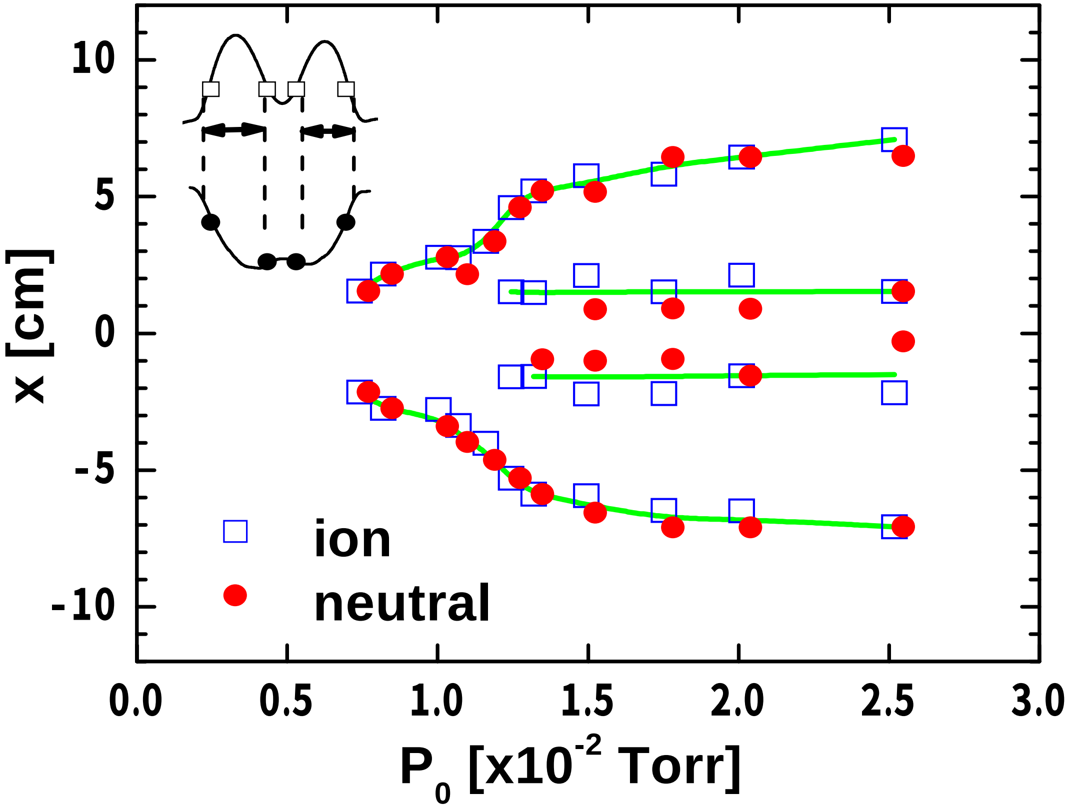
Ion Density and Neutral Density Profiles



The bean-shaped bright regions correspond to the ion density peaks (Top Right). There always exists a deep density depression in neutral particles (Bottom Right).

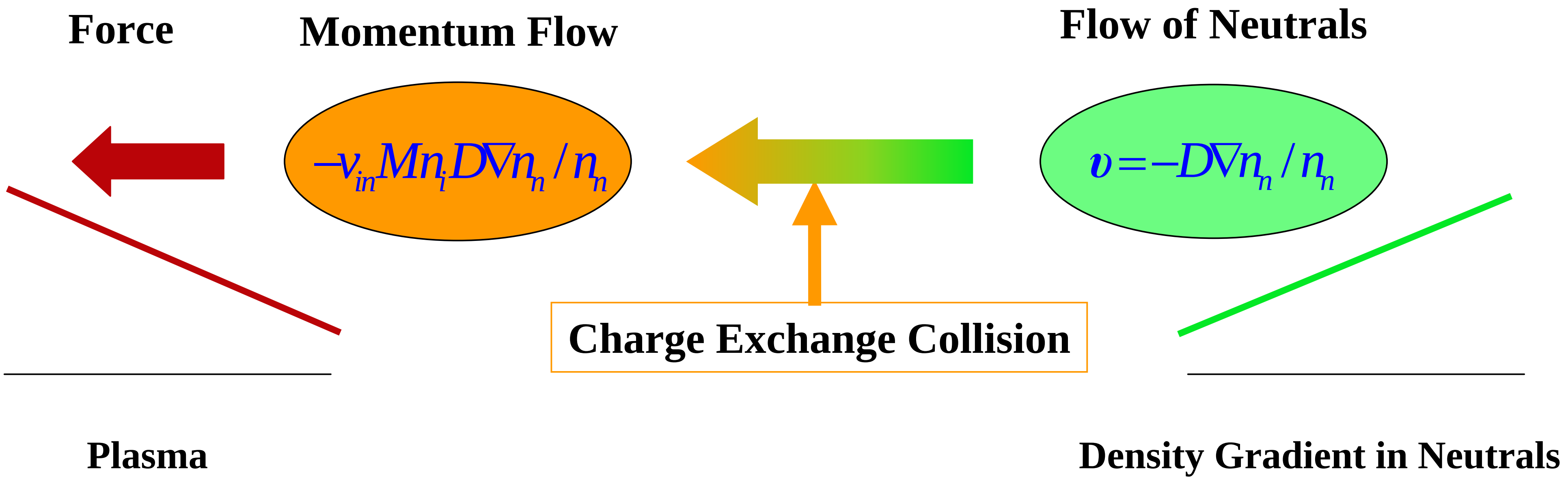
When the plasma is uniformly produced over the whole cross section, no density depression in neutrals was observed (Bottom Left).

三極渦構造と中性粒子密度分布の相関



三極渦の構造は中性粒子分布の穴に閉じ込められている。

Mechanism of Producing an Effective Force



Force

Momentum Flow

Flow of Neutrals

$-\nu_{in} M n_i D \nabla n_n / n_n$

$\upsilon = -D \nabla n_n / n_n$

Charge Exchange Collision

Plasma

Density Gradient in Neutrals

Generation of Inward Force due to Neutral Density Gradient

The equation of motion is then given by

$$Mn_i\left(\frac{\partial \boldsymbol{v}_i}{\partial t}+\boldsymbol{v}_i\cdot\nabla\boldsymbol{v}_i\right)=en_i(\boldsymbol{E}+\boldsymbol{v}_i\times\boldsymbol{B})-\nabla p_i-\nu_{in}Mn_i(\boldsymbol{v}_i+D\nabla\log n_n)$$

Where $\nu_{in}n_i=\nu_{ni}n_n$ **is used. The perpendicular velocity is**

$$\boldsymbol{v}_\perp=\frac{1}{\omega_{ci}^{2}+\nu_{in}^{2}}\Big[\frac{e}{m}(\omega_{ci}\boldsymbol{e}_z\times\nabla_\perp\phi-\nu_{in}\nabla_\perp\phi)+\upsilon^{2}_{Ti}(\omega_{ci}\boldsymbol{e}_z\times\nabla_\perp\ln n_i-\nu_{in}\nabla_\perp\ln n_i)$$

$$+(\omega_{ci}\nu_{in}D\,\boldsymbol{e}_z\times\nabla_\perp\ln n_n-\nu^{2}_{in}D\nabla_\perp\ln n_n)\Big]$$

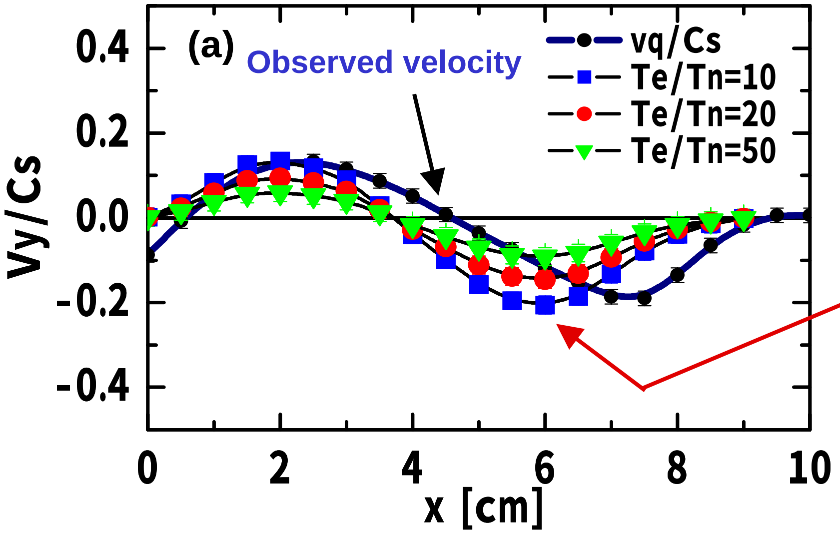
For y=0, $\partial/\partial r\gg\partial/\partial\theta$ **is hold, the above equation becomes simple,**

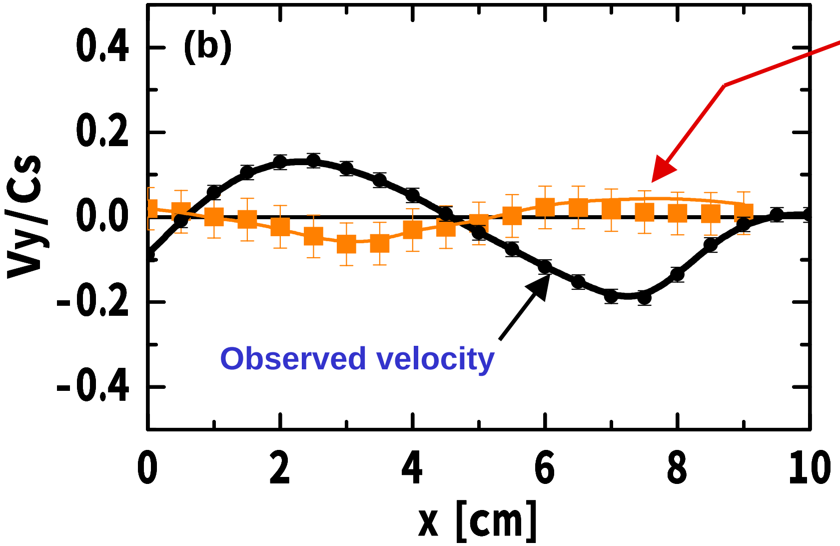
$$\frac{\upsilon_y}{C_S}=\frac{\omega_{ci}C_S}{\omega_{ci}^{2}+\nu^{2}_{in}}\left[\frac{\partial}{\partial r}\frac{e\phi}{T_e}+\frac{D}{C_s^2/\nu_{in}}\frac{\partial}{\partial r}(\ln n_n)\right]$$

***E*x*B* dift**

***F*x*B* dift due to neutrals**

Neutral-induced *F*x*B* drift and *E*x*B* drift velocity





Nuetral-induced *F*x*B* drift velocity

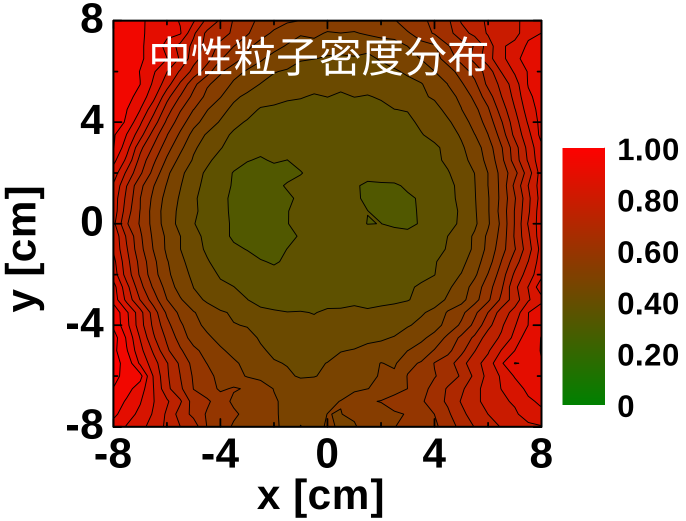
$$\frac{\upsilon_y}{C_S} = \frac{\omega_{ci} C_S}{\omega_{ci}^2 + \nu_{in}^2} \frac{D}{C_s^2 / \nu_{in}} \frac{\partial}{\partial r}(\ln n_n)$$

*E*x*B* drift velocity

$$\frac{\upsilon_y}{C_S} = \frac{\omega_{ci} C_S}{\omega_{ci}^2 + \nu_{in}^2} \frac{\partial}{\partial r}\left(\frac{e\phi}{T_e}\right)$$

The neutral-induced *F*x*B* drift velocity well agrees with the observed drift velocity, while the *E*x*B* drift velocity is small and opposite in direction. The vortex motion is considered to be induced by the density gradient of neutrals

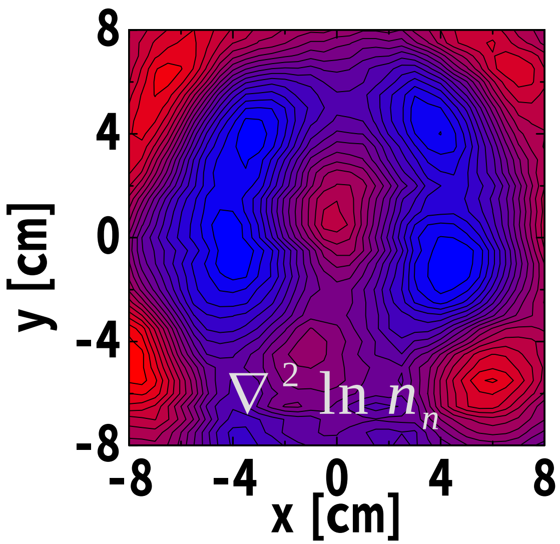
流線関数としての中性粒子密度分布

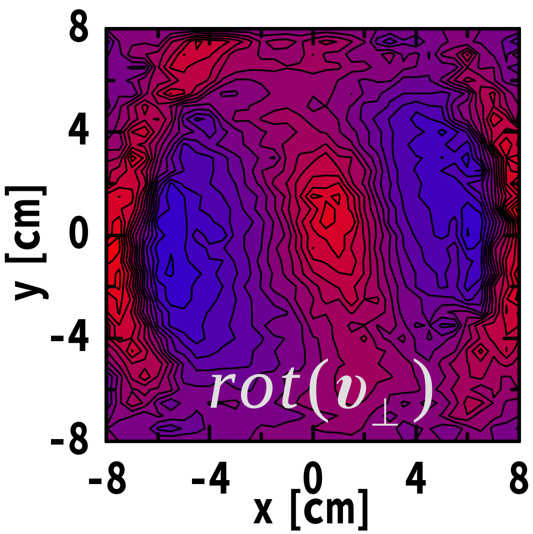


電荷交換反応が優勢であれば、中性粒子密度分布はイオンの流れ場の渦度分布を決定する。

$$\omega_z \approx \frac{\omega_{ci}}{\omega_{ci}^2 + v_{in}^2} v_{in} D \nabla_\perp^2 \ln n_n$$

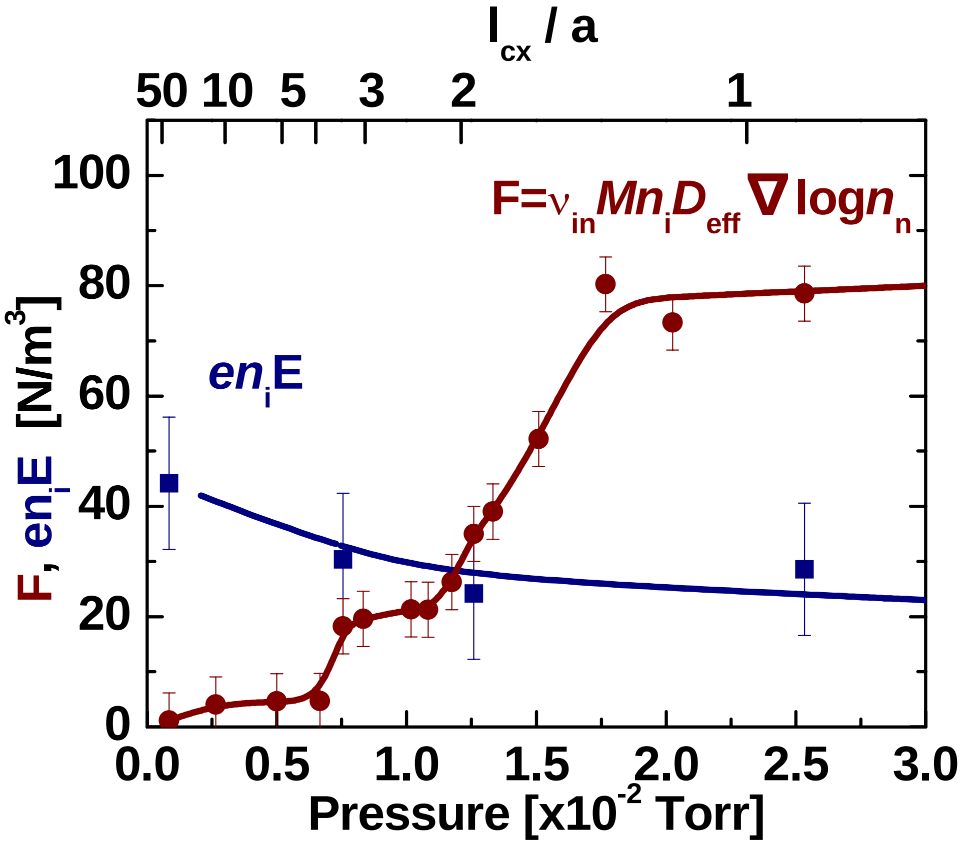
つまり、流線関数とみなすことができる





速度ベクトル場から決定した渦度分布は、中性粒子密度分布から求めた渦度分布と一致する

中性粒子の実効的な圧力と電場による力の比較



$$\frac{|en_i\mathbf{E}|}{|\nu_{in} M n_i D_{eff} \nabla \log n_n|} \le 1$$

$$\mathbf{E} \sim \phi / a, \quad \nabla \log n_n \sim l_{cx}^{-1}$$

a: プラズマ半径

l_{cx}: 中性粒子平均自由行程

$$\frac{l_{cx}}{a} \le \left(\frac{e\phi}{T_e}\right)^{-1} \frac{\sigma_{cx}}{\sigma_{nn}} \sqrt{\frac{T_n}{T_e}} \frac{D_c}{D_{eff}} \frac{C_s}{u_i} \approx 0.6-1.4$$

一方、実験結果から $\frac{l_{cx}}{a} \le 2$

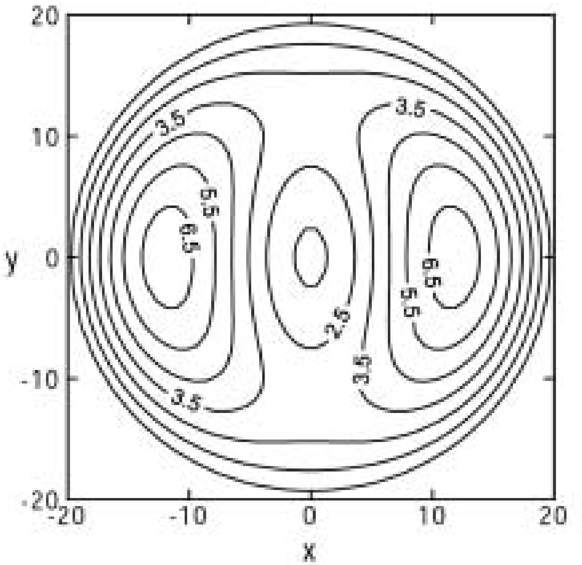
中性粒子の平均自由行程がプラズマ半径程度に短くなると、中性粒子の密度勾配による力が電場による力を上回る

Nonlinear Stationary Solution (Tripolar Vortex)

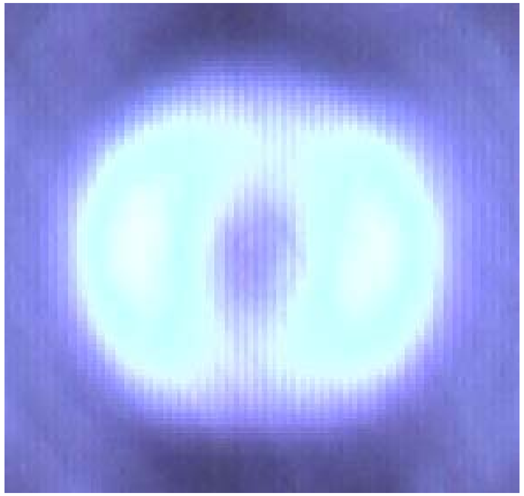
Nonlinear calculation shows the existence of stationary tripolar-vortex solution (J. Vranjes Phys. Rev. Lett. (2002) in printing) ,

$$\phi(r,\theta) = -\frac{G_0}{k^2} + br^2 + a_0 J_0(kr) + a_2 J(kr)\cos 2\theta$$

This solution well reproduces the tripolar structure observed in the experiments (Right).



Theory



Experiments

Summary

1) A tripolar vortex has been found in a plasma.

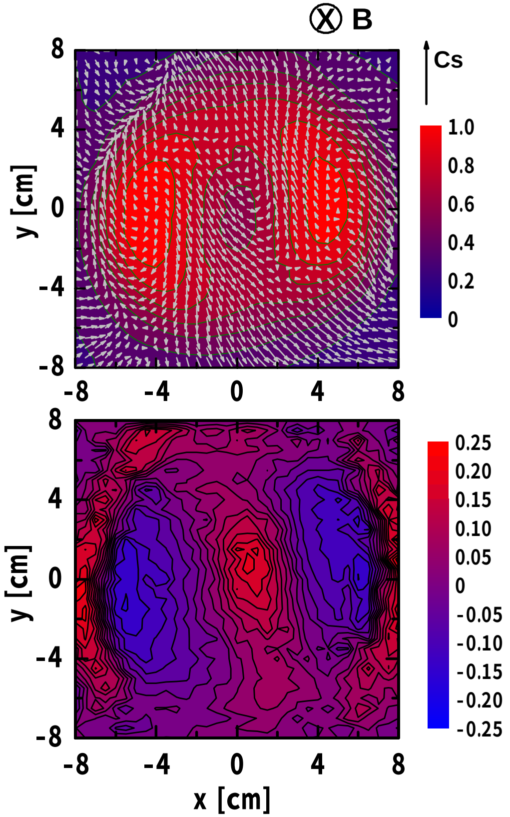
2) The rotation direction of each vortex is opposite to that of *E* x *B* rotation.

3) Net momentum transfer occurs through the charge-exchange interaction and produces an effective force.

4) This effective force due to neutral density gradients may dominate the electric force and drives ions into anti-*E*x*B* rotation.

5) The neutral density can be considered as the stream function of the ion flow field.

6) The present result will be important in considering flow structure in partially ionized plasmas or surface plasmas.



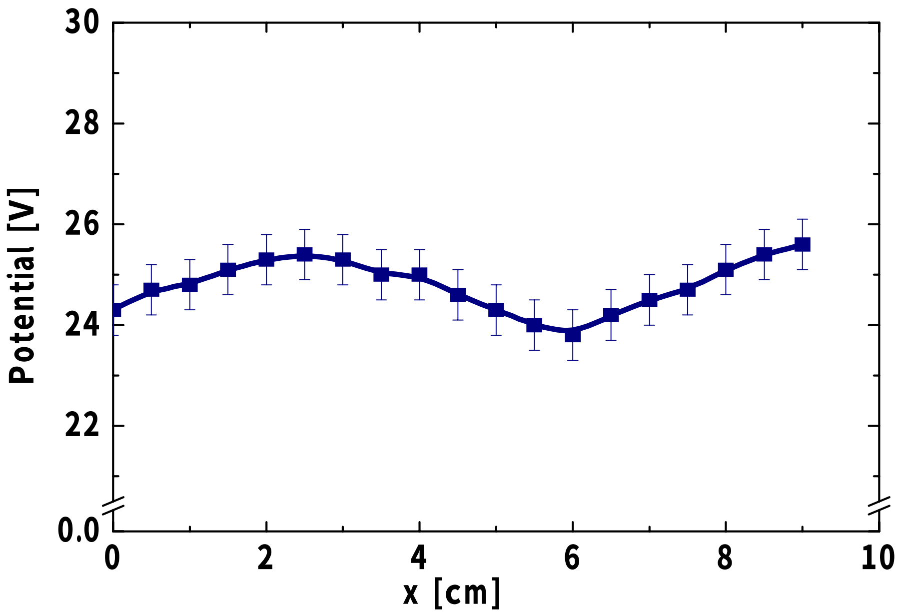
ECW

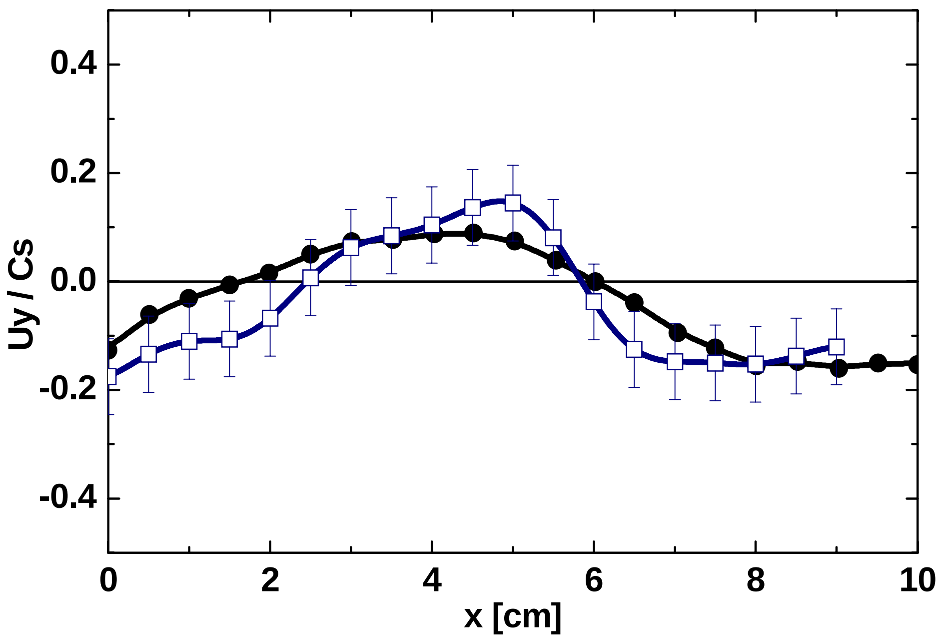
Plasma is rich in vortex physics

Plasma is rich in vortex physics

Nov. 19, 2002

E×Bドリフトによるプラズマの回転典型的な例





- **動作圧力** 8.3×10^{-4} Torr
- **プラズマの回転は**E×B**ドリフトによる**