The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1953-54

International Workshop on the Frontiers of Modern Plasma Physics

14 - 25 July 2008

Vortex formation in a plasma interacting with neutral flow.

M.I. Tanaka
Kyushu University, Fukuoka, Japan

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

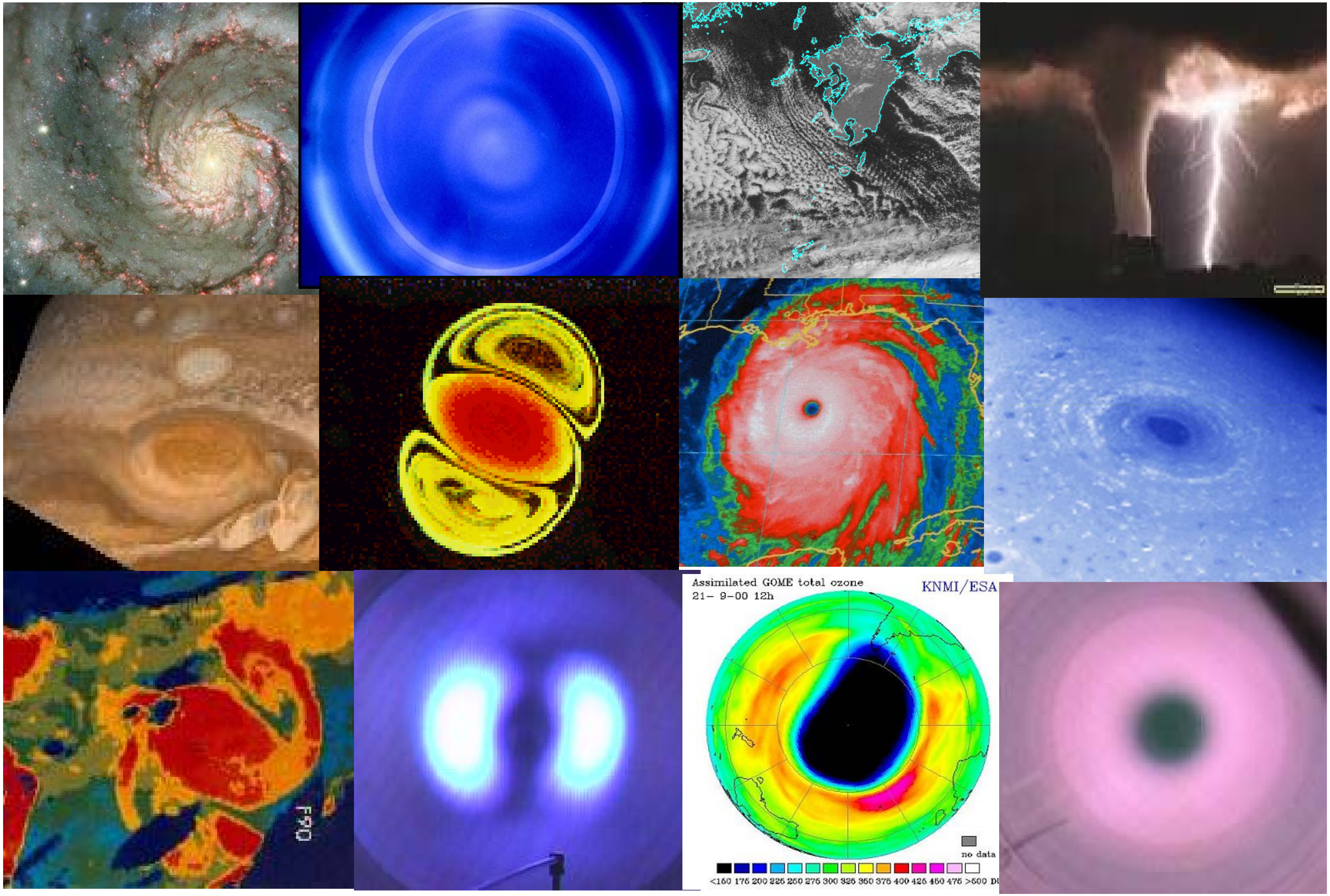
Vortex formation in a plasma interacting with neutral flow

International Workshop on the Frontiers of Modern Plasma Physics
ITCP Trieste July 24 2008

Masayoshi Y. Tanaka

Dept. High Energy Engineering Science
Kyushu University

Vortices in nature



vortex

Vortex has been fascinating scientists

common in nature

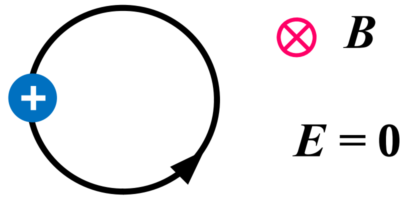
fundamental structure in nonlinear medium

In plasmas

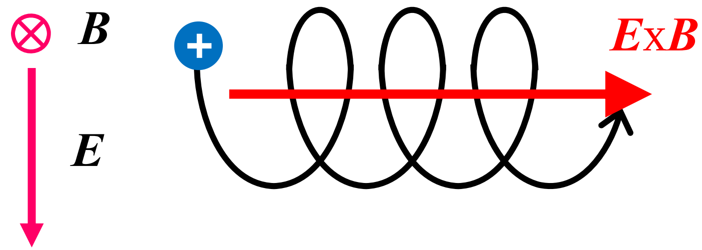
vortex is considered to play an important role on transport

understanding vortex is especially important

However it has not been fully understood



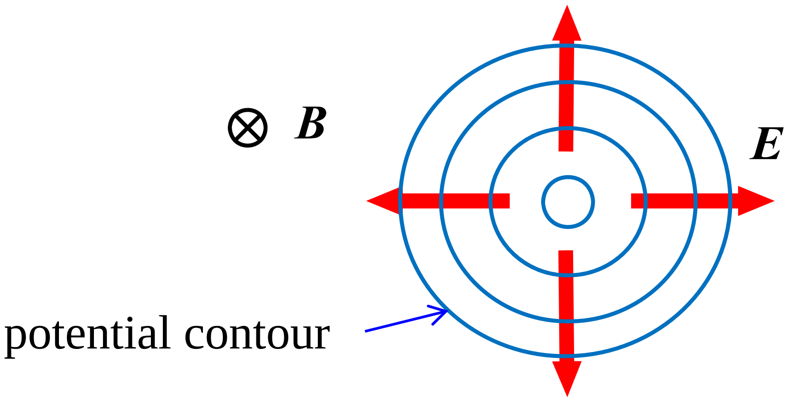
cyclotron motion



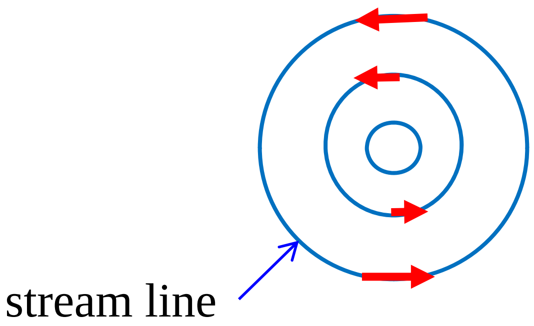
guiding center drift

When electric field and magnetic field are present, a charged particle moves toward ***E*x*B*** direction. (***E*x*B*** drift). Generally, when a force ***F*** is acting on a charged particle, the guiding center moves toward ***F*x*B*** direction

cylindrical plasma

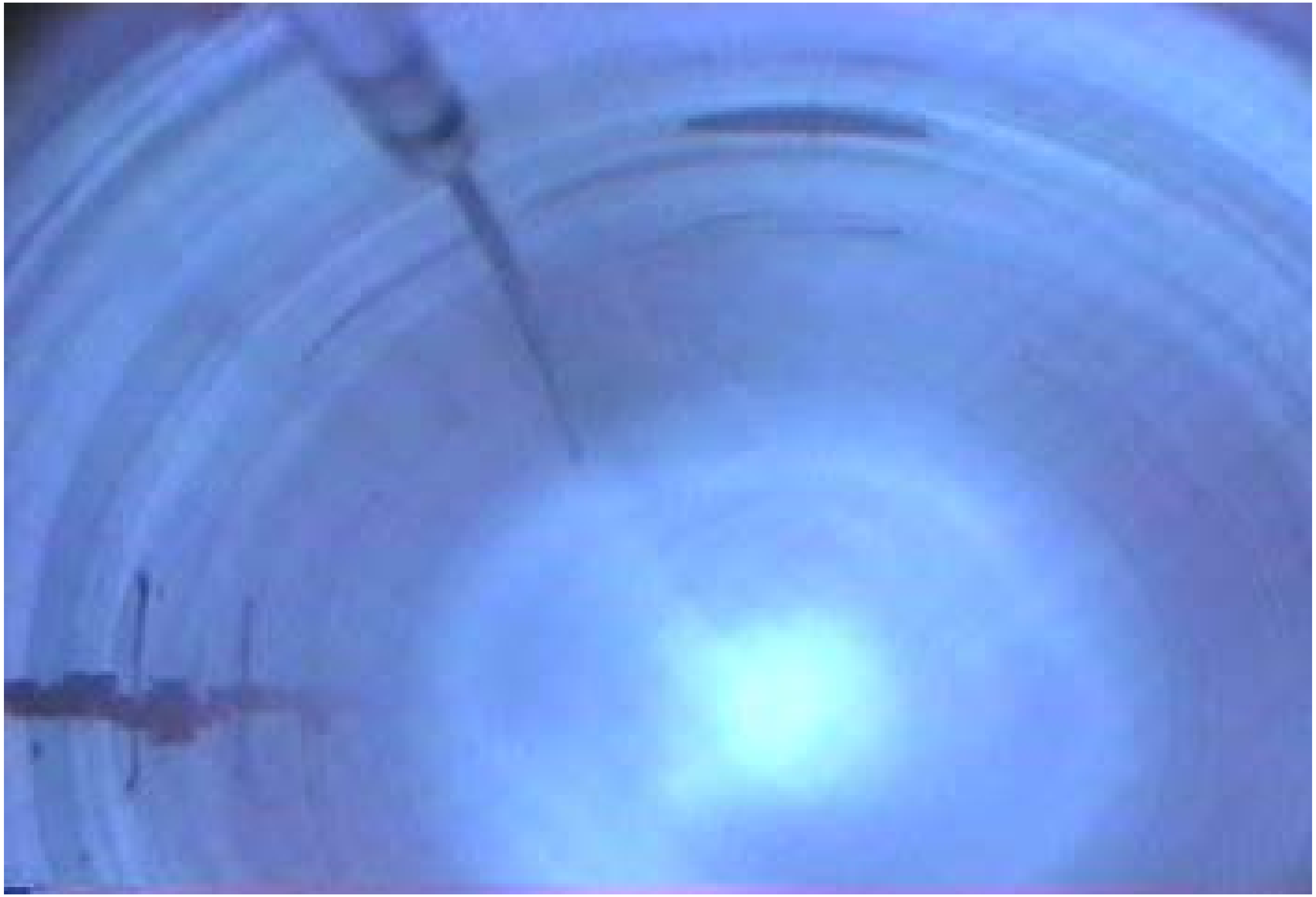


plasma motion



In ExB drift, potential contour is identical to the streamn line

Observation of plasma rotation

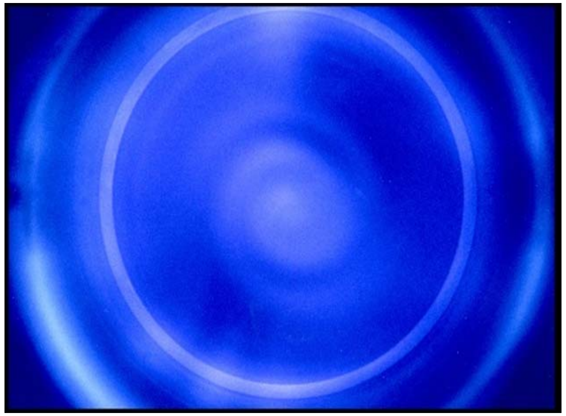


First direct observation of plasma rotation

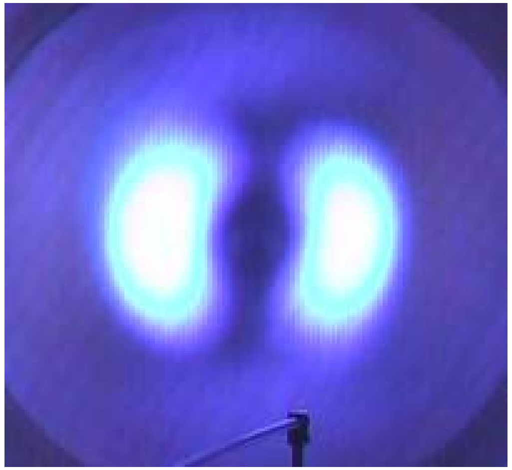
by the most primitive technique !

Observation of plasma rotation

Spiral Vortex



Tripolar Vortex



Plasma Hole

M. Kono and M.Y. Tanaka, Phys. Rev. Lett. 84, (2000) 4369

A. Okamoto et al., Phys. of Plasmas 10, (2003) 2211

J. Vranjes et. al. Phys. Rev. Lett. 89, (2002) 265002

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

Outline

anti-ExB vortex

– vortex formation in a plasma interacting with neutral flow--

Observation of anti-ExB vortex

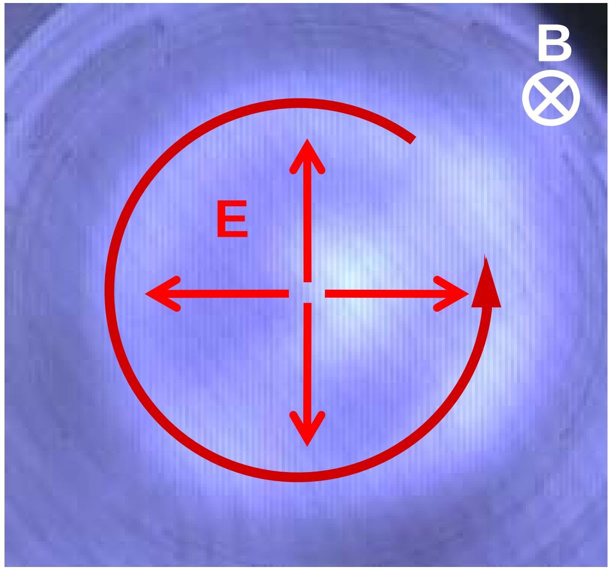
Measurment of neutral flow velocity

Flow velocity fields of ions and neutrals

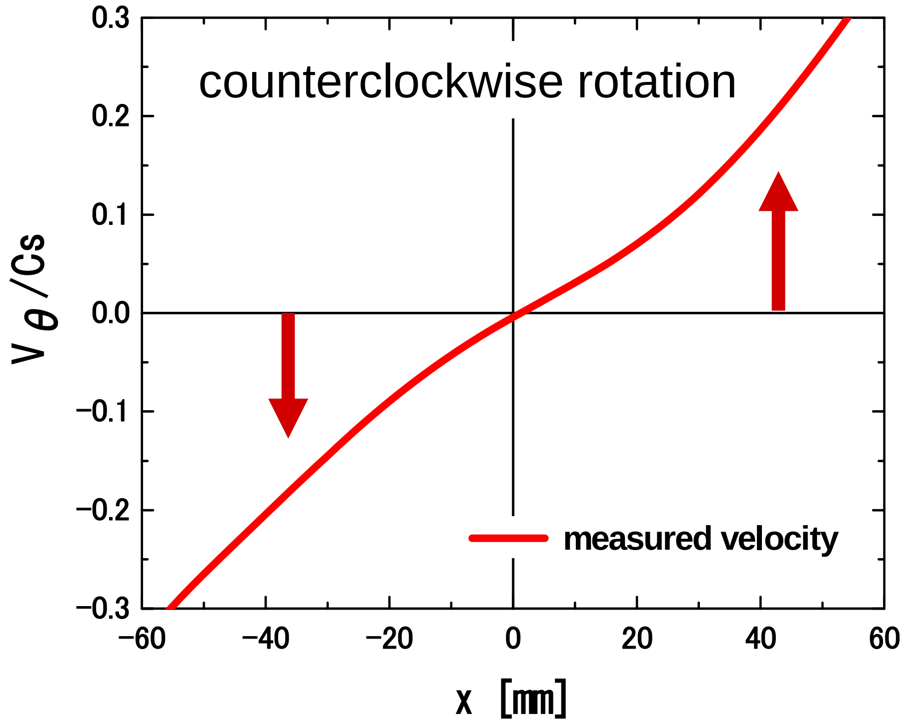
Summary

*E*x*B* drift if a plasma

End view image of a plasma



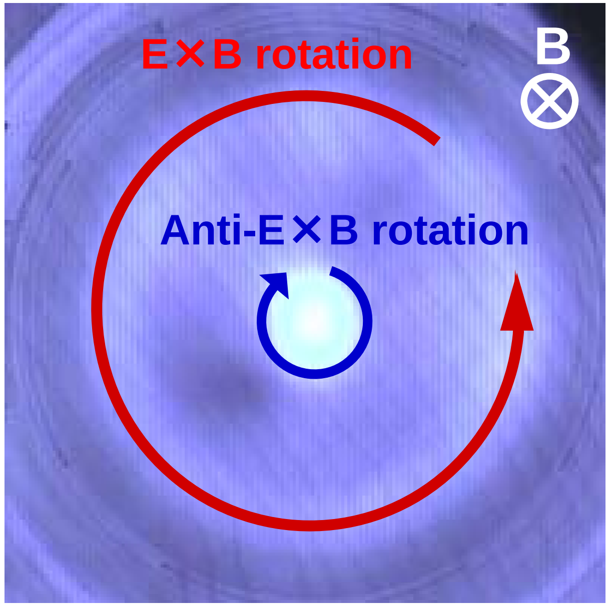
Radial profile of azimuthal flow velocity



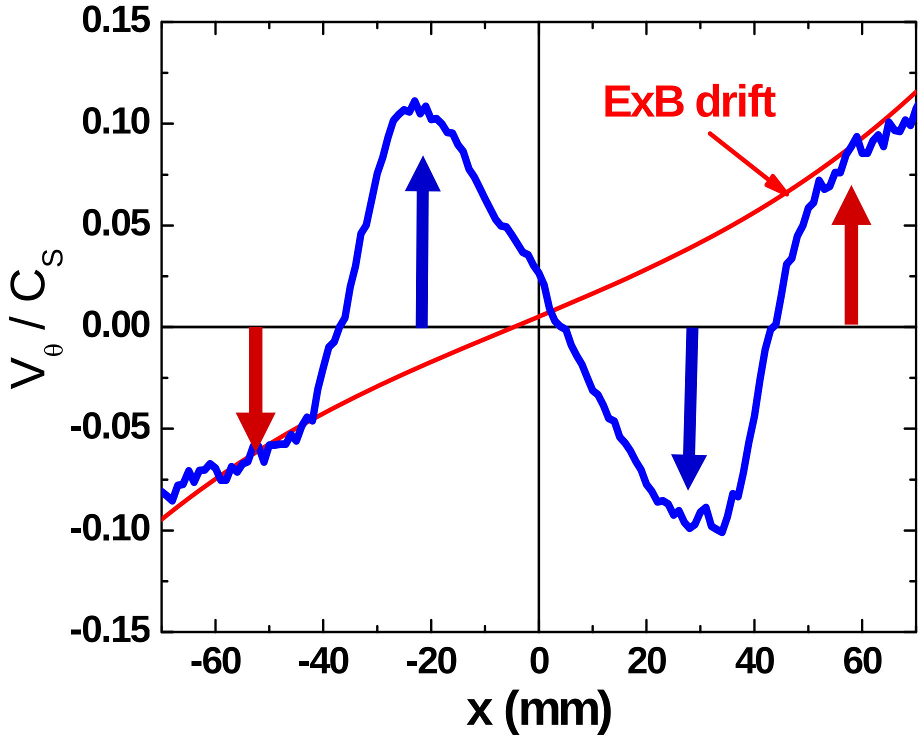
Usually, there exists an radial electric field in a plasma. Then the plasma is subjected to ExB motion, forming a vortical flow.

Anti-ExB rotation of a plasma

End view image of a plasma



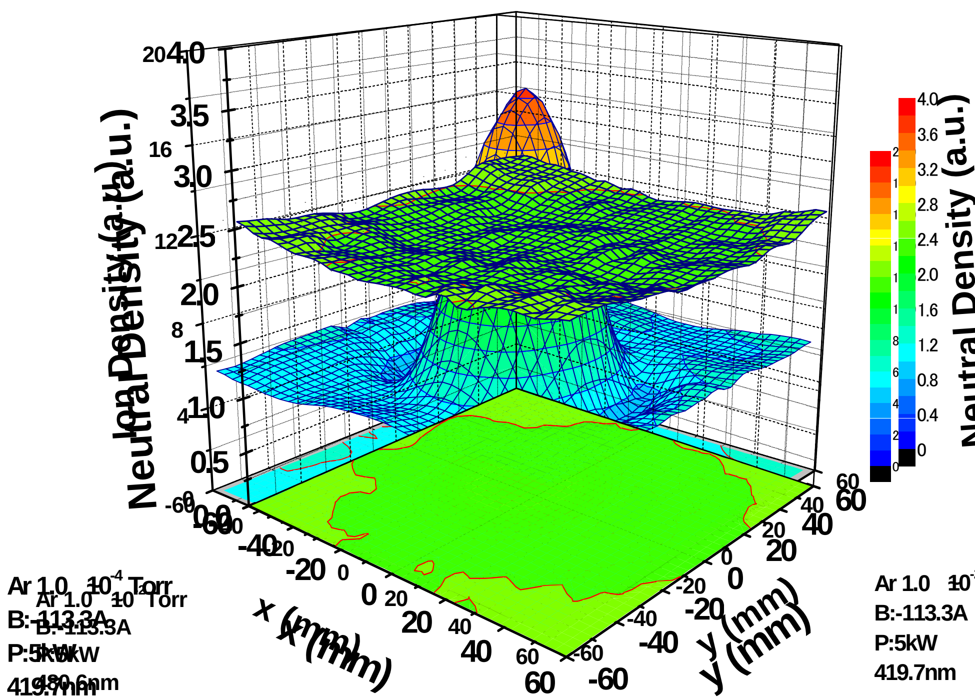
Radial profile of azimuthal velocity



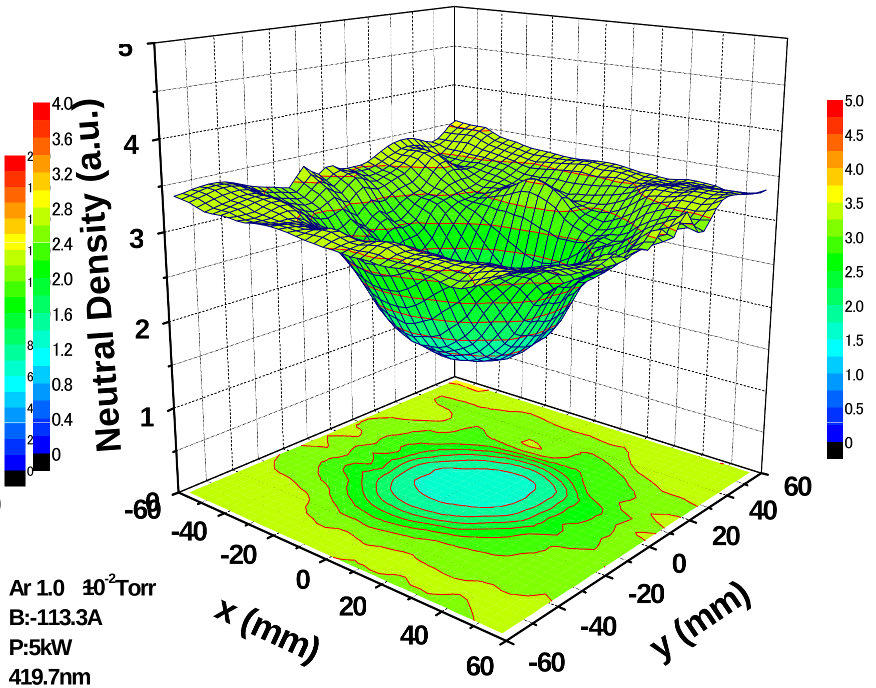
In the core region, the plasma rotates in the opposite direction to ExB drift! This vortex is referred to as anti-ExB vortex.

2D profile of plasma and neutral densities (anti-ExB vortex)

neutral density profile w/o anti-ExB vortex

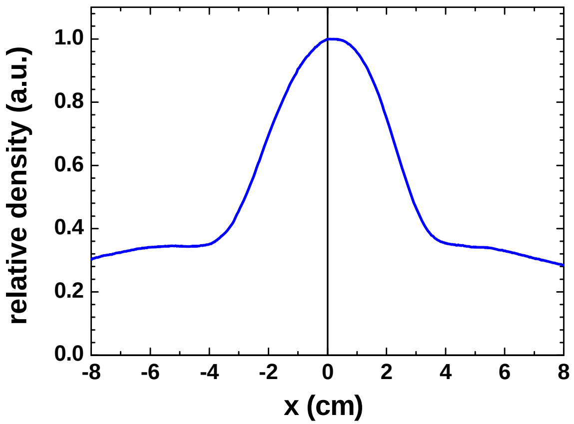


neutral density profile

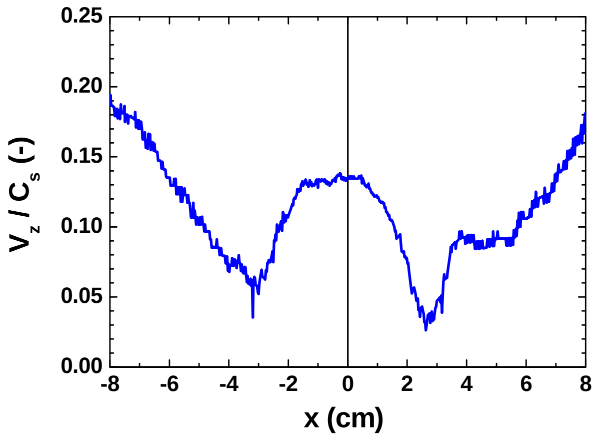


The plasma density in the core region is 2.5 time higher than the peripheral region, while the neutral density exhibits a deep depletion in the core, which suggests that interaction of plasma and neutral flow plays an important role on vortex formation.

Ion parallel flux

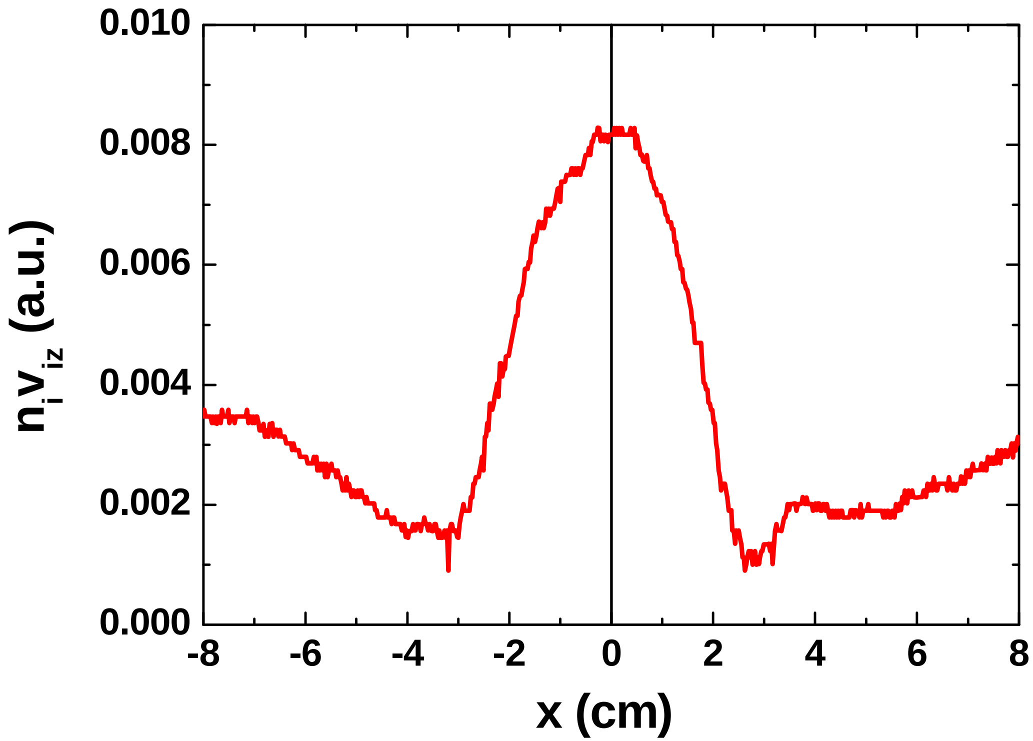


Density profile



Parallel flow velocity

Ion flux along the magnetic field



The ions are exhausted along the magnetic field

Indication of experimental observations

There exists an anti-ExB vortex.

↓

This means that there is an another force acting on ions, which dominates the electric force.

There is a deep depletion in neutral density.

↓

Interaction between plasma and neutral flow may play an important role on generation of the vortex.

Momentum change in charge exchange process

Sena effect

MOBILITY OF IONS IN THE PARENT GAS 167

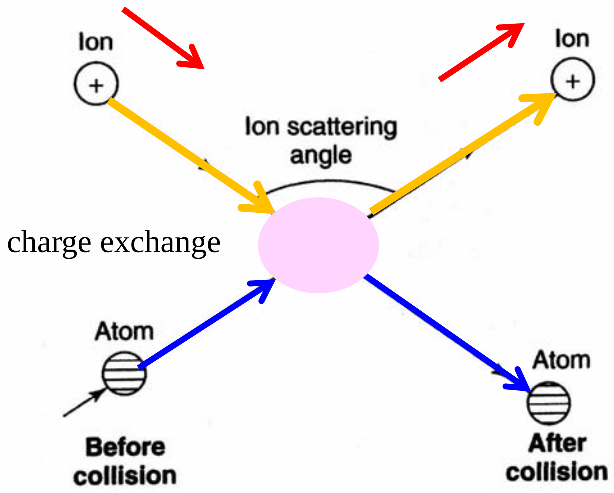
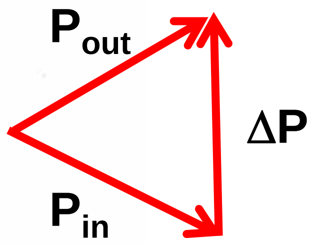


Figure 11.1 Illustration of the resonant charge exchange of an ion and atom without elastic scattering (Sena effect).

Physics of Ionized Gases by B.M. Smirnov Chap.11



Momentum change in charge exchange process is very large.

Charge exchange collision is dominant in low temperature plasmas.

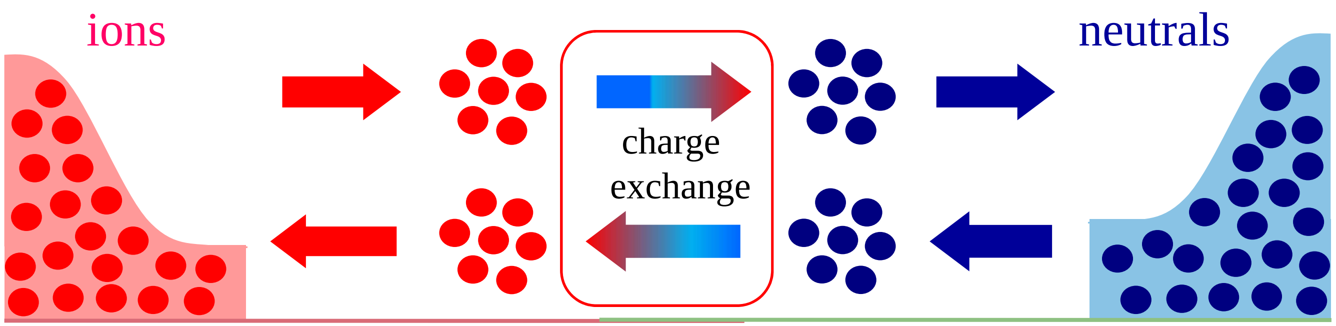
Effective momentum transfer may take place through charge exchange collision.

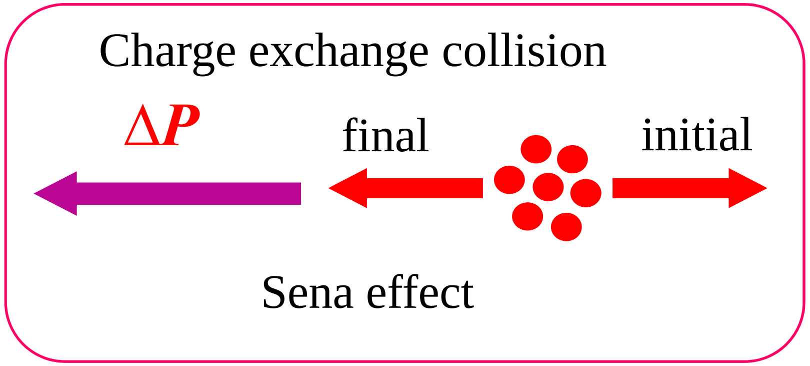
Generation of force by Sena effect

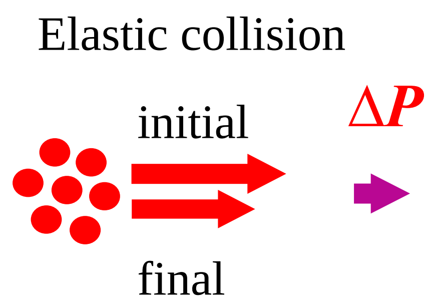
force acting on ion fluid = net momentum transport per unit time

$$F = \Delta P / \Delta t$$

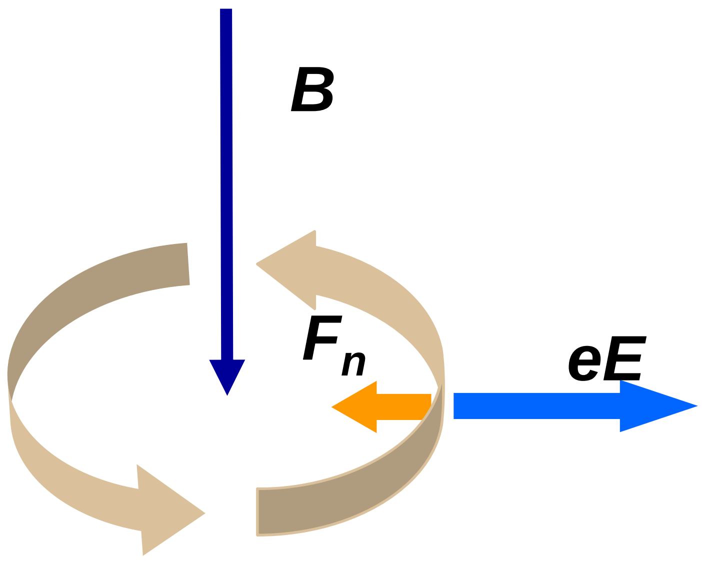
ion flow	momentum exchange	neutral flow



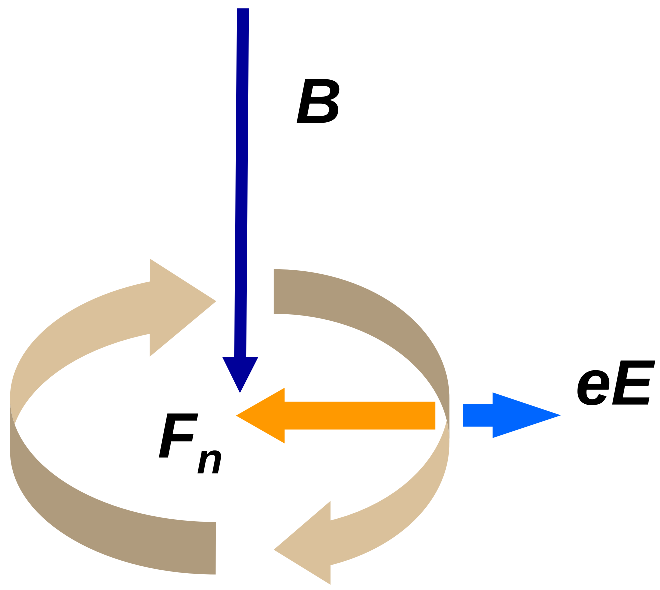




Generation of anti-ExB rotation



***E*x*B* rotation**



Anti-*E*x*B* rotation

When the electric force dominates the force due to ion-neutral interaction (Fn), the total force is directed outward and the resultant drift motion is conterclockwise. When Fn dominates the electric force, the total force is directed inward, and the resultant rotation is clockwise.

Measurement of neutral velocity field

To confirm above-mentioned mechanism, visualization of neutral velocity field is needed

Neutral flow velocity should be measured by an optical method.
Laser-Induced Fluorescence(LIF) method is the most powerful technique.

However, the flow velocity of neutrals is supposed to be very slow and the corresponding Doppler shift is 10^7Hz (laser frequency is 10^{14} Hz).

Therefore, the frequency resolution should be extremely high (10^{-7}).
We have to develop a very high resolution LIF system .

Outline

anti-ExB vortex

– vortex formation in a plasma interacting with neutral flow--

Observation of anti-ExB vortex

Measurment of neutral flow velocity

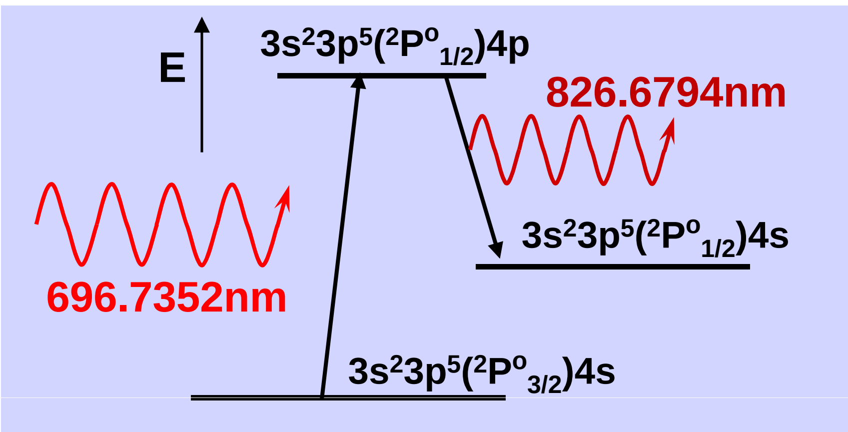
Flow velocity fields of ions and neutrals

Summary

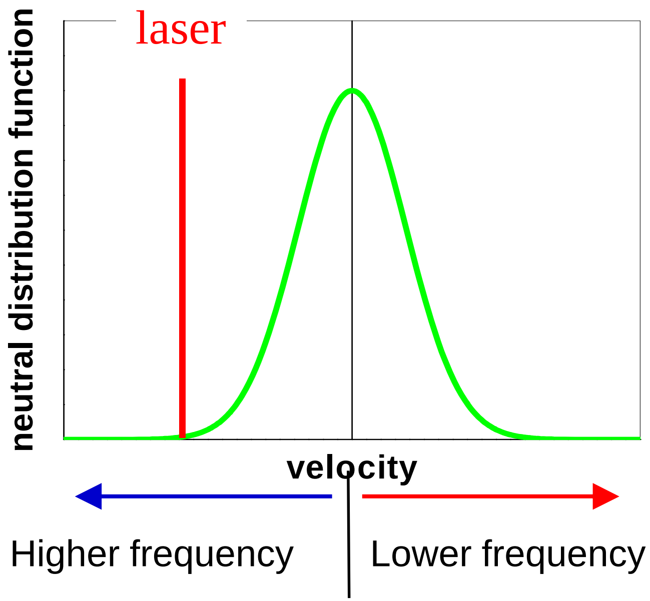
Laser Induced Fluorescence

A laser excites meta-stable atoms to an upper level . The excited atoms emit photons in deexcitation process (laser induced fluorescence).

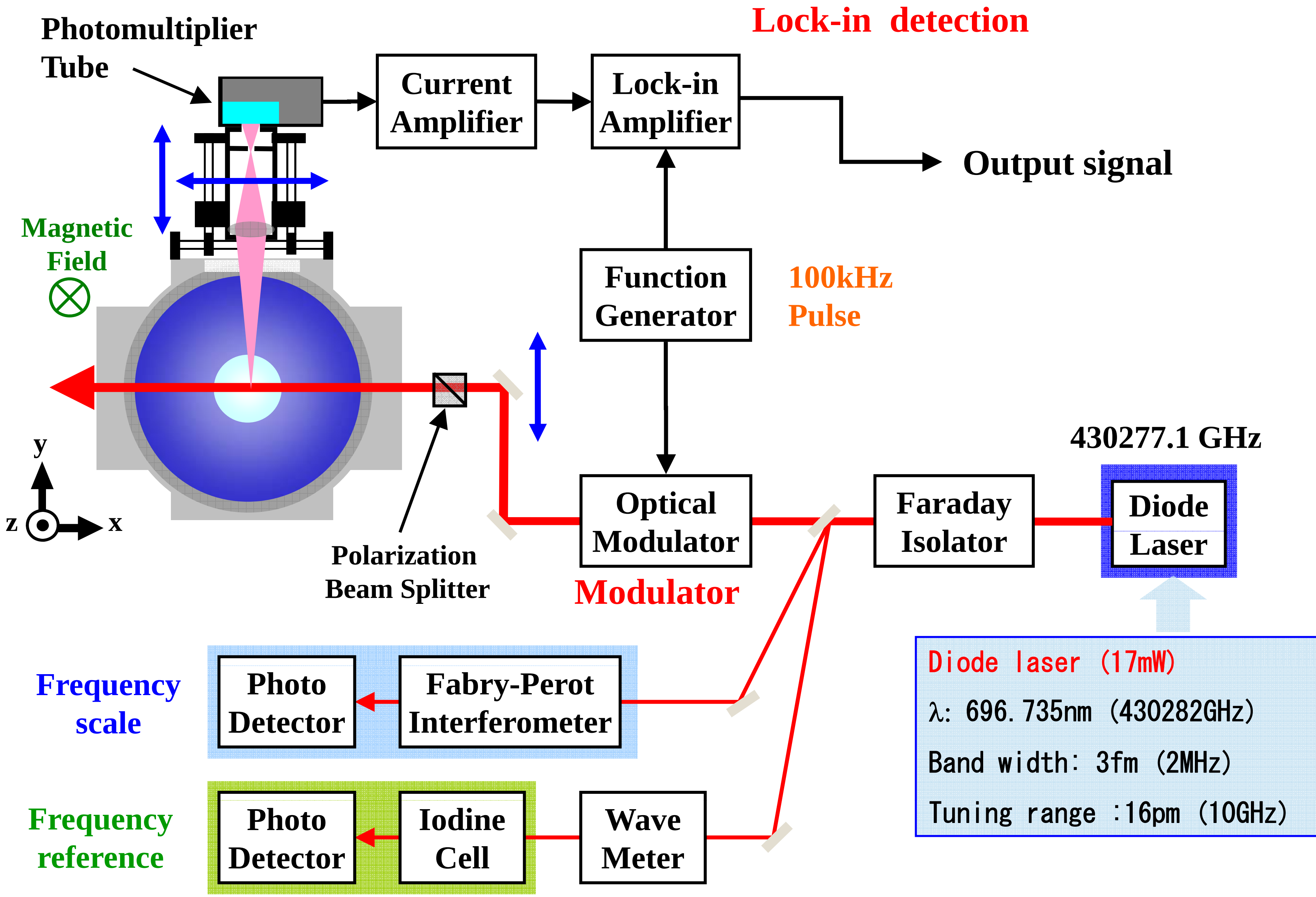
By tuning laser frequency, we can obtain the LIF spectrum, which is proportional to the distribution function.



LIF Scheme



LIF Doppler spectroscopy system



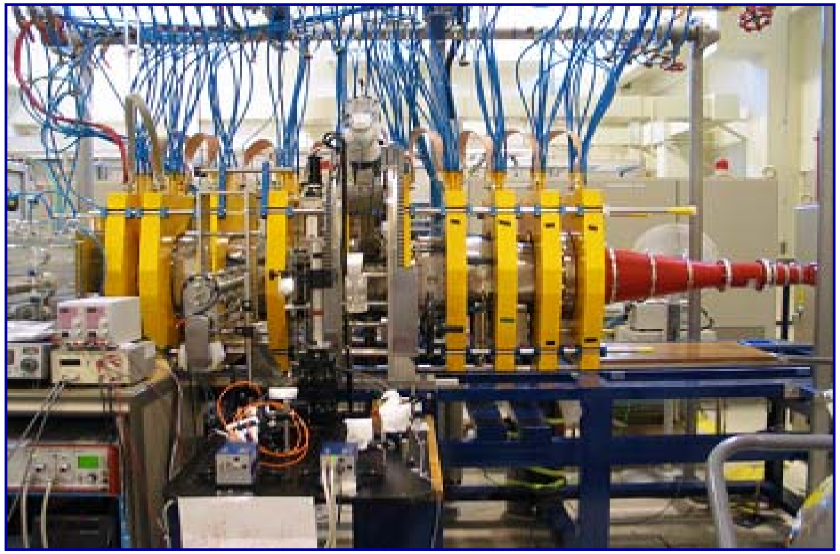
Diode laser (17mW)

λ: 696.735nm (430282GHz)

Band width: 3fm (2MHz)

Tuning range :16pm (10GHz)

HYPER-I device



Plasma production:

Electron cyclotron resonance

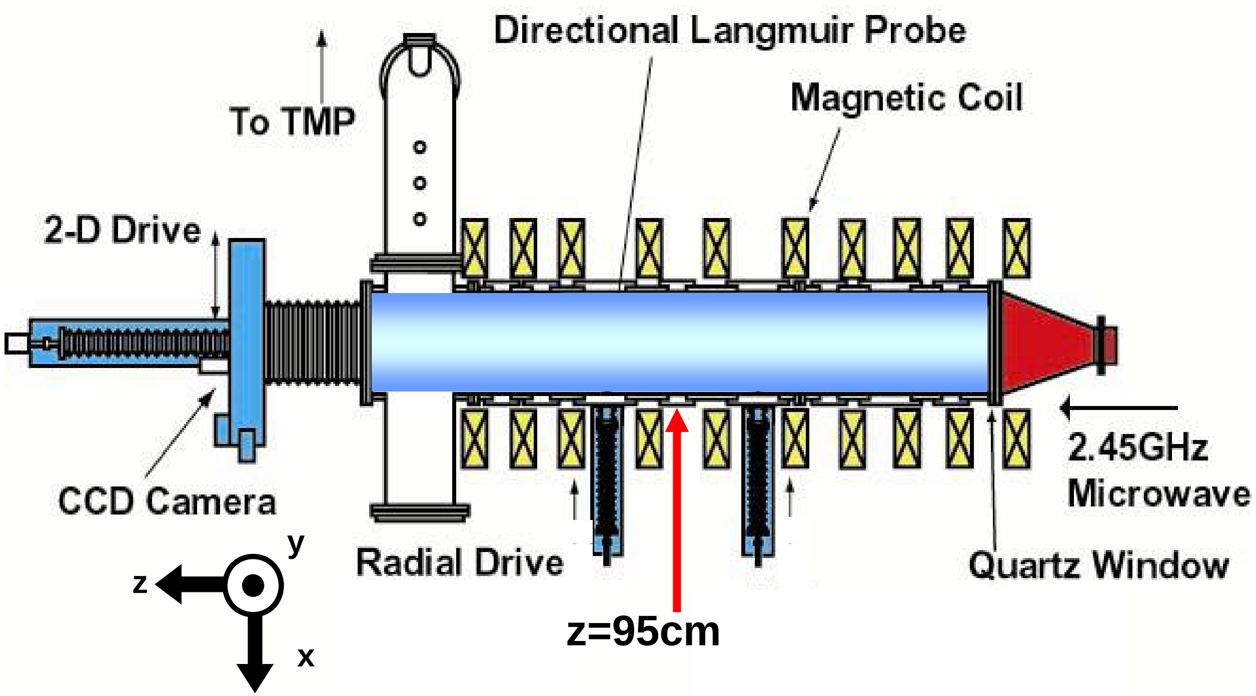
Size: ϕ30cm×200cm

Microwave : 2.45GHz

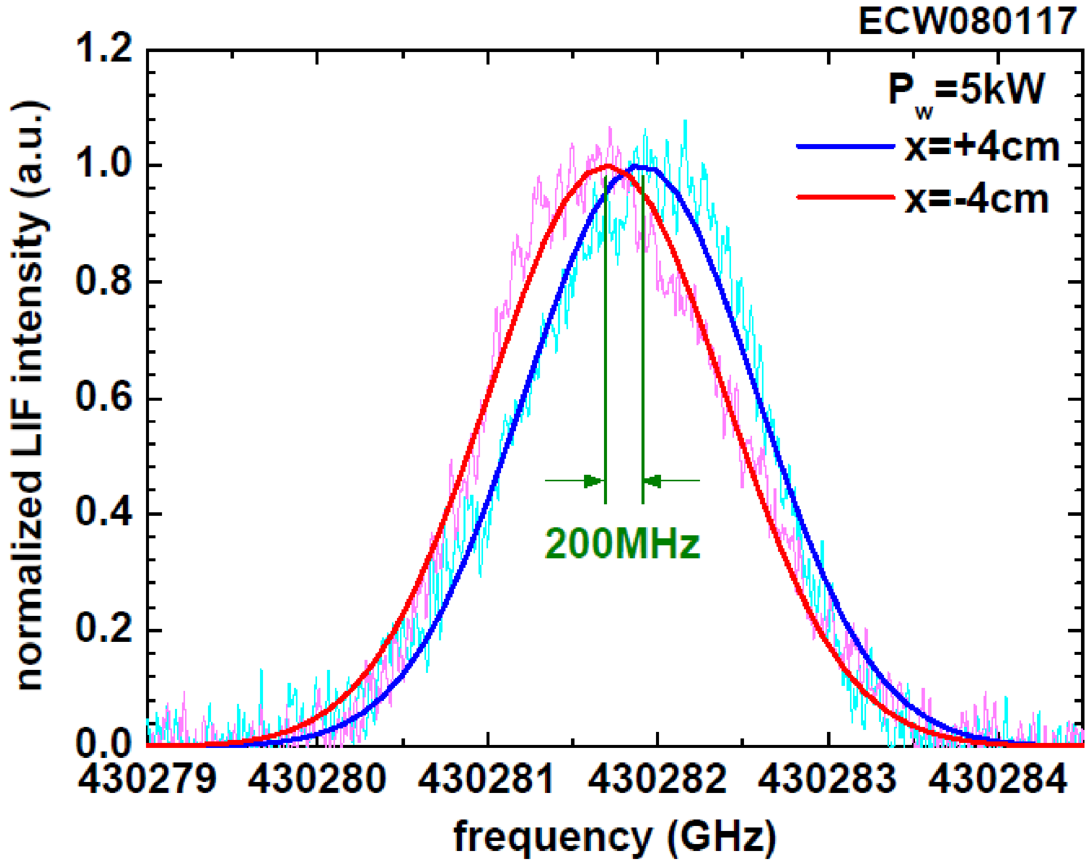
Input power: 250W ～5kW

Magnetic field: ～ 0.11T

Gas presssure: 1×10^{-2} Torr (Ar)



Doppler shift (high power case)



The LIF spectrum at different positions show a clear difference. Doppler shift of 200MHz corresponds to 130m/sec.

Outline

anti-ExB vortex

– vortex formation in a plasma interacting with neutral flow--

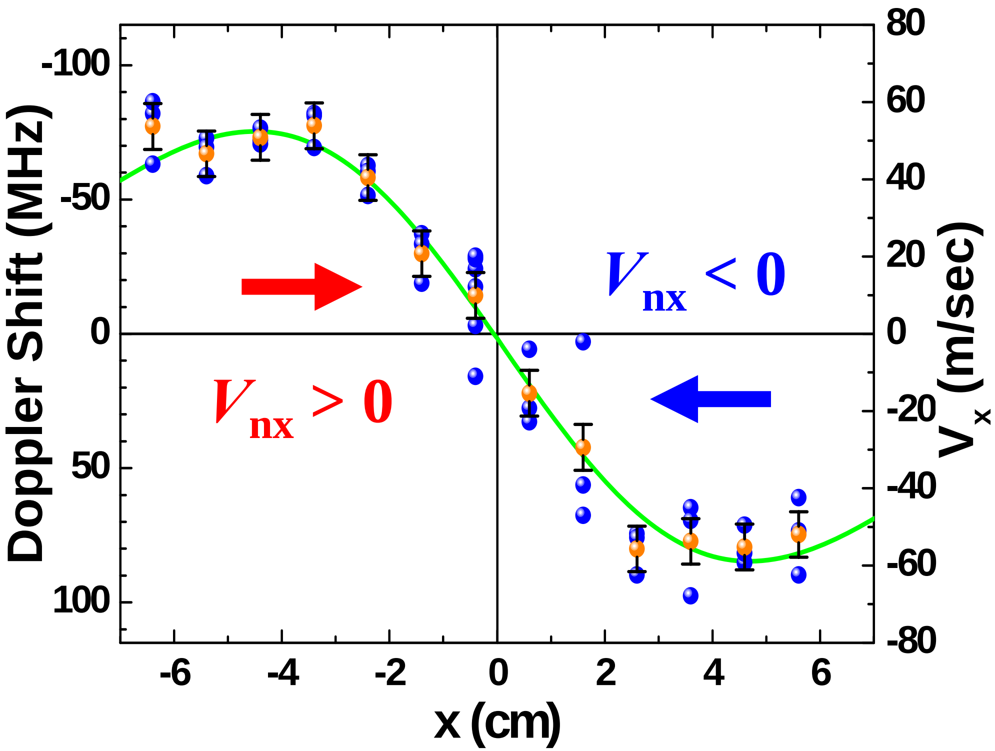
Observation of anti-ExB vortex

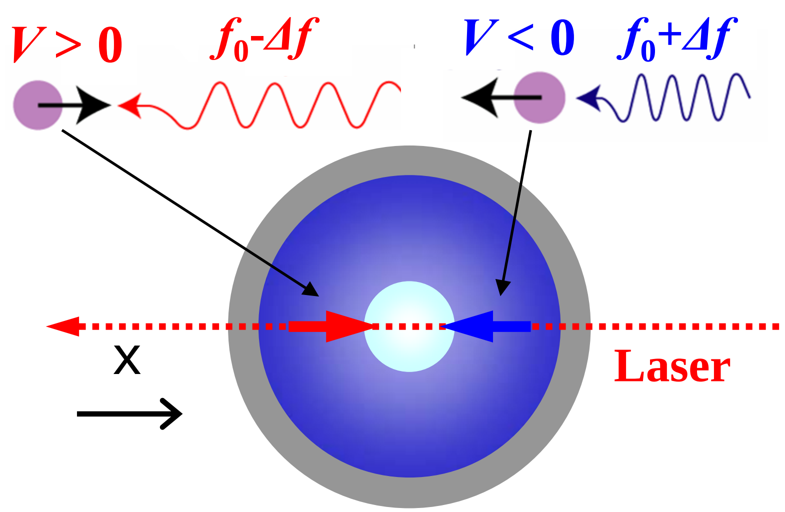
Measurment of neutral flow velocity

Flow velocity fields of ions and neutrals

Summary

Doppler shift profile of LIF spectrum (radial velocity)



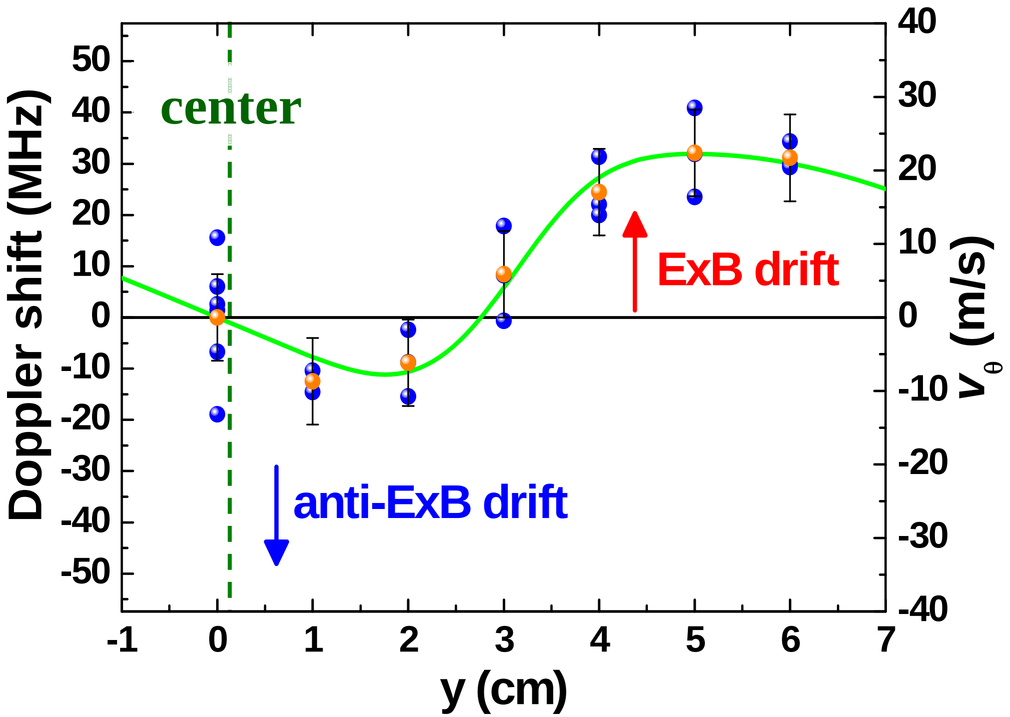


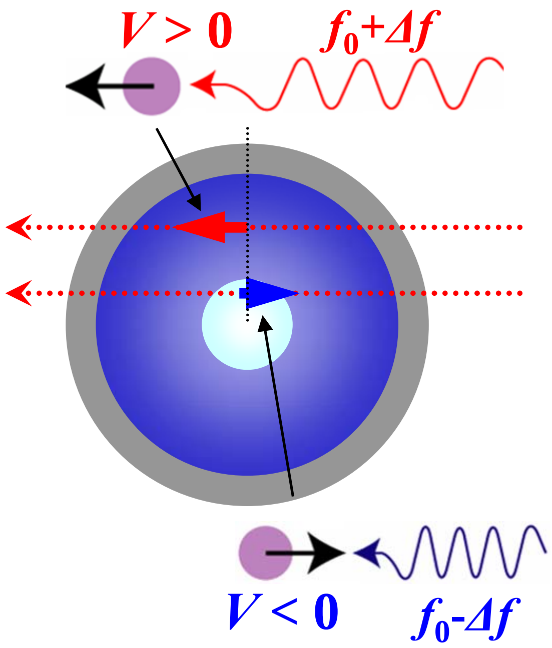
Inward flow of neutrals

The Doppler shift in x > 0 region is positive, which means that the neutral flow in this region is leftward. The flow in the x < 0 region is rightward. There exists inward flow in the plasma.

Profile of azimuthal flow

Doppler shift profile of LIF spectrum (azimuthal velocity)



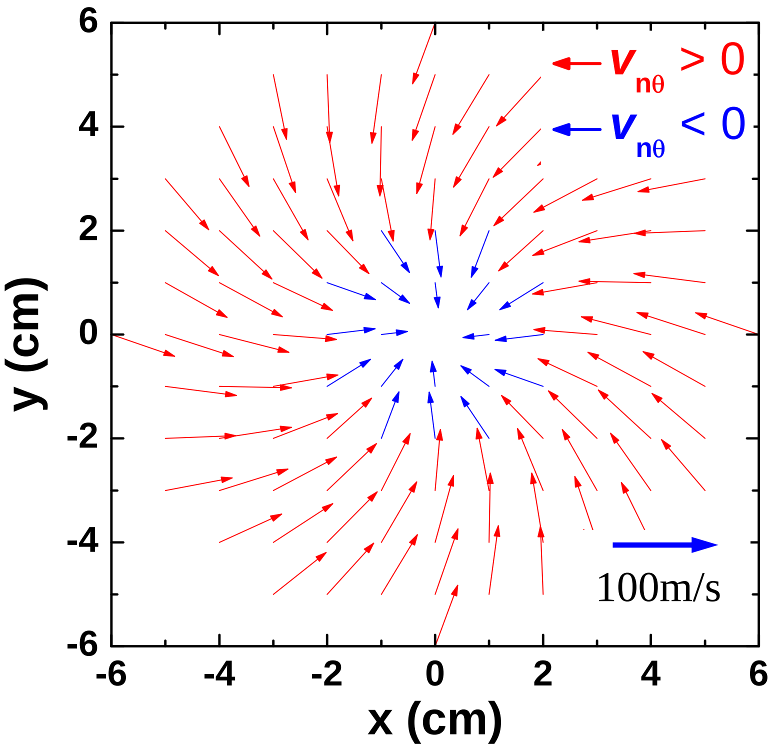


Azimuthal flow of neutrals

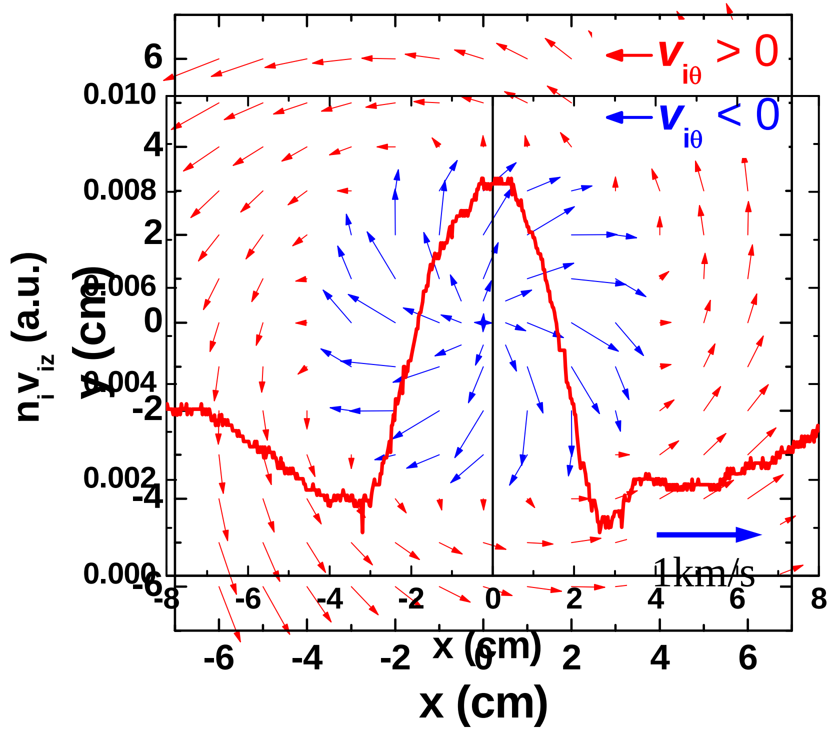
The Doppler shift in core region y < 3cm is negative, which means that the neutral flow in this region is clockwise. The flow in the outer region is counterclockwise.

Velocity Field

Neutral flow velocity field



Ion flow velocity field



Assuming axial symmetry, we construct the vector field plot of neutral flow (left). The ion flow field measured with a probe is shown in the right. Red arrows indicate counterclockwise rotation, blue arrow clockwise rotation. Radially converging neutrals, which change into ions through charge exchange collision, are exhausted along the magnetic field.

Model equation of plasma interacting with neutral flow

Momentum change

momentum input from neutrals

$$\Delta \boldsymbol{P} / \Delta t = (-\boldsymbol{P}_{\mathrm{out}} + \boldsymbol{P}_{\mathrm{in}}) / \Delta t = -\nu_{in} M_{\mathrm{i}} n_{\mathrm{i}} \boldsymbol{u}_i - \nu_{ni} M_{\mathrm{n}} n_{\mathrm{n}} \alpha \,\mathrm{grad} n_{\mathrm{n}}$$

momentum loss of ions

Equation of motion for ions

$$M n_{\mathrm{i}} \left[\frac{\partial \mathbf{u}_{\mathrm{i}}}{\partial t} + (\mathbf{u}_{\mathrm{i}} \cdot \nabla) \mathbf{u}_{\mathrm{i}} \right] = e n_{\mathrm{i}} (-\nabla \phi + \mathbf{u}_{\mathrm{i}} \times \mathbf{B}) - \nu_{\mathrm{in}} M n_{\mathrm{i}} \mathbf{u}_{\mathrm{i}} - \nu_{\mathrm{in}} M n_{\mathrm{i}} \alpha \nabla \log n_{\mathrm{n}}$$

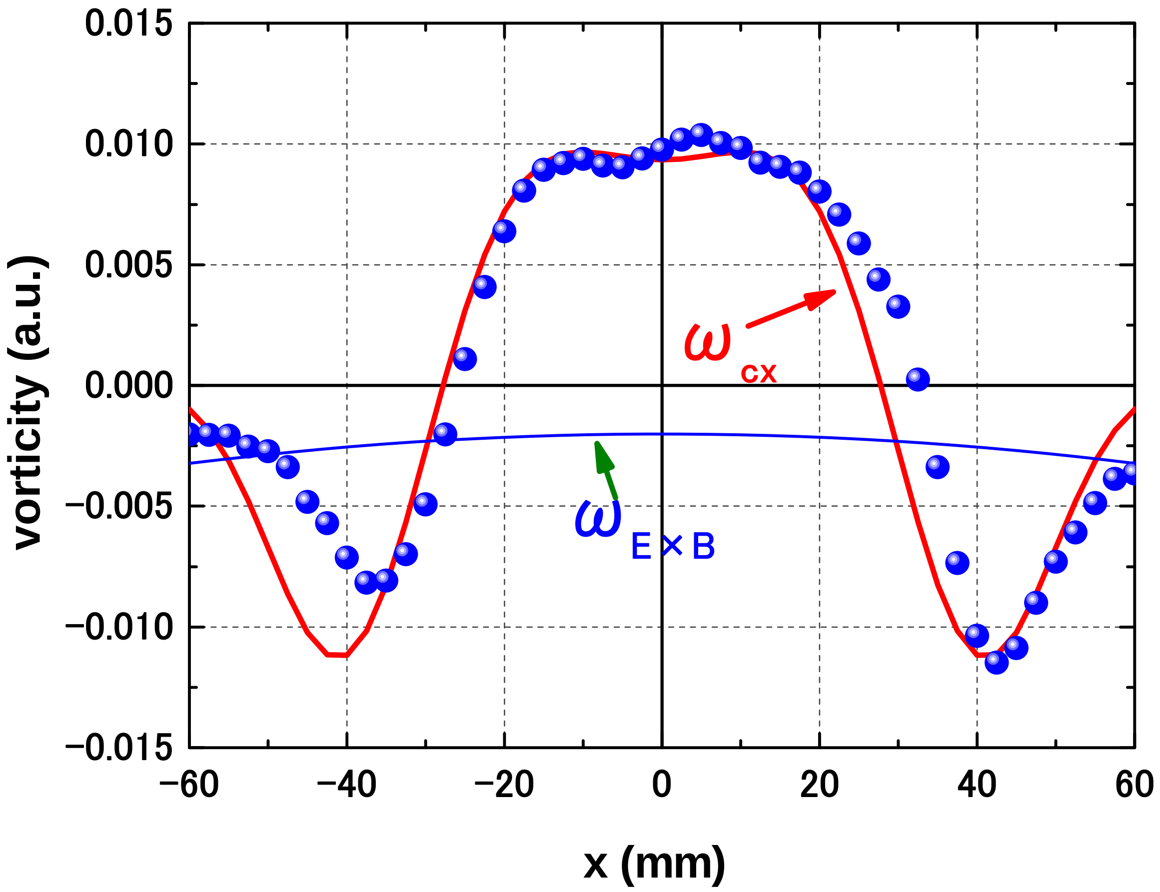
Assuming steady tste and neglecting the nonlinear terem, we have

$$\mathbf{u}_{\mathrm{i}\perp} = \frac{1}{\omega_{\mathrm{ci}}{}^2 + \nu_{\mathrm{in}}{}^2} \left[\begin{array}{l} \dfrac{e}{M} \left(\omega_{\mathrm{ci}} \mathbf{e}_z \times \nabla_\perp \phi - \nu_{\mathrm{in}} \nabla_\perp \phi \right) \\ \qquad + \left(\omega_{\mathrm{ci}} \nu_{\mathrm{in}} \alpha \mathbf{e}_z \times \nabla_\perp \log n_{\mathrm{n}} - \nu_{\mathrm{in}}{}^2 \alpha \nabla_\perp \log n_{\mathrm{n}} \right) \end{array} \right]$$

Vorticity

$$\omega_z = (\mathrm{rot}\, \mathbf{u}_\perp)_z = \frac{\omega_{\mathrm{ci}}}{\omega_{\mathrm{ci}}^2 + \nu_{\mathrm{in}}^2} \left[\nabla_\perp^2 \left(\frac{e}{M} \phi + \nu_{\mathrm{in}} \alpha \log n_{\mathrm{n}} \right) \right]$$

Vorticity Profile



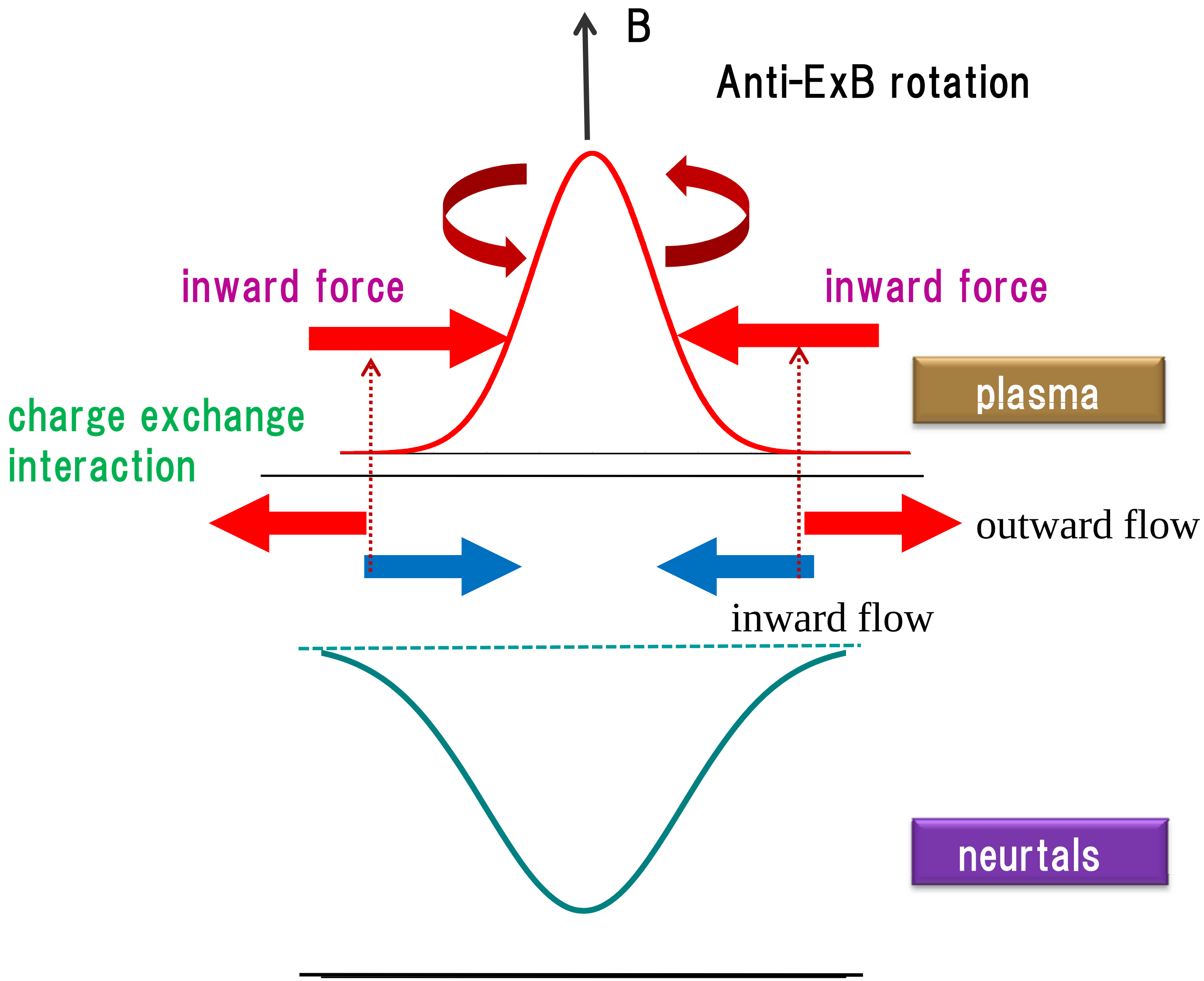
Vorticity

$$\omega_z \propto \nabla^2 \ln n_n$$

(ion-neutral interaction is dominant)

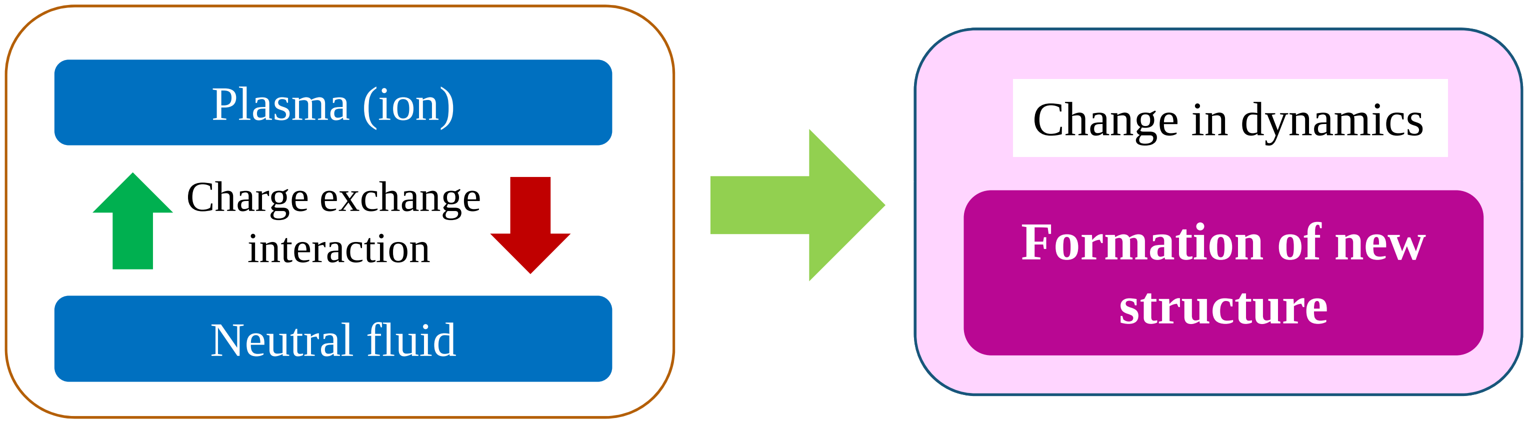
The observed vorticity profile well agrees with that expected from the ion-neutral interaction.

Formation of anti-ExB vortex



Summary

The interaction between ion and neutral flows essentially changes ion dynamics. Sena effect is important in momentum transport, and the resultant force due to this effect provides a new route to vortex formation in plasmas



Colleagues

Experiment

M. Aramaki (Nagoya Univ.)

S. Yoshimura (NIFS)

K. Ogiwara (Kyushu Univ.)

S. Etoh (Kyushu Univ.)

K. Terasaka (Kyushu Univ.)

Theory

M. Kono (Chuo Univ.)

J. Vranjes (Leuven Univ.)

Thank you for your attention.