Computational study on neutral beam injection into a Field-Reversed Configuration

Toshiki Takahashi, Naotaka Iwasawa[1],
Yukio Yamada, Takayuki Kato, Daisuke Utsunomiya,
Haluo Sakata, and Yoshiomi Kondoh

Department of Electronic Engineering, Gunma University
[1]Satellite Venture Business Laboratory, Gunma University

Outline

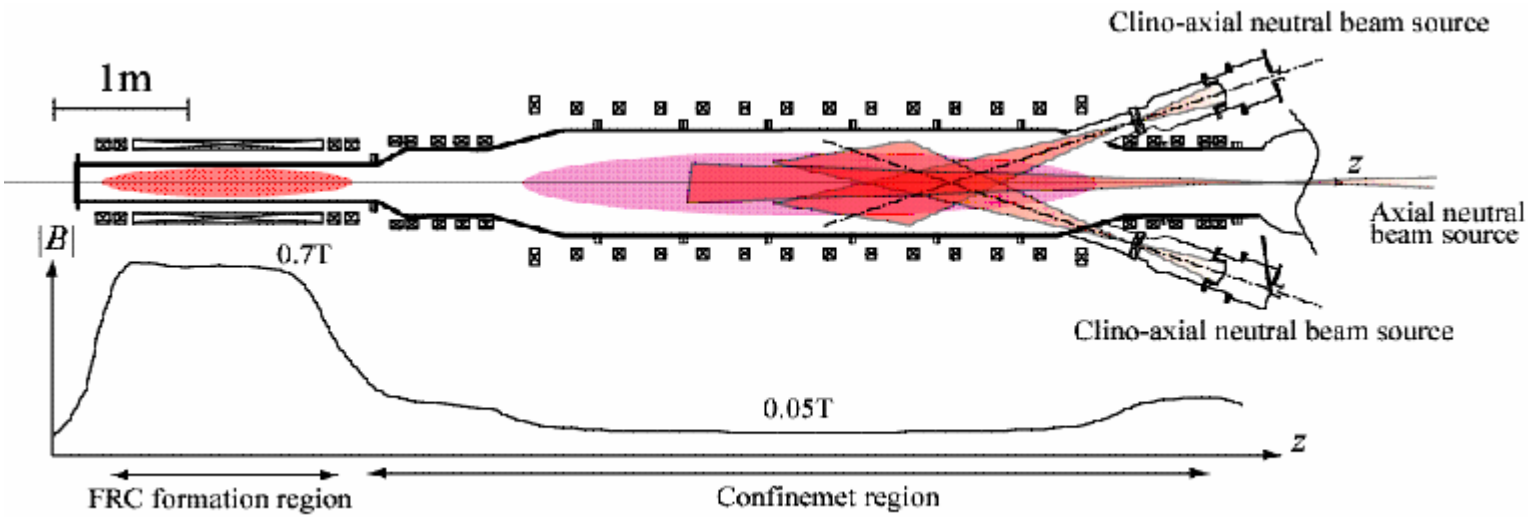
◆ Beam ion orbit calculation

- Loss mechanism of beam ions
- Power deposition profile
- Effect of neutral gas in edge region

◆ Hybrid simulation for beam injected FRC

- Model description
- Preliminary simulation result

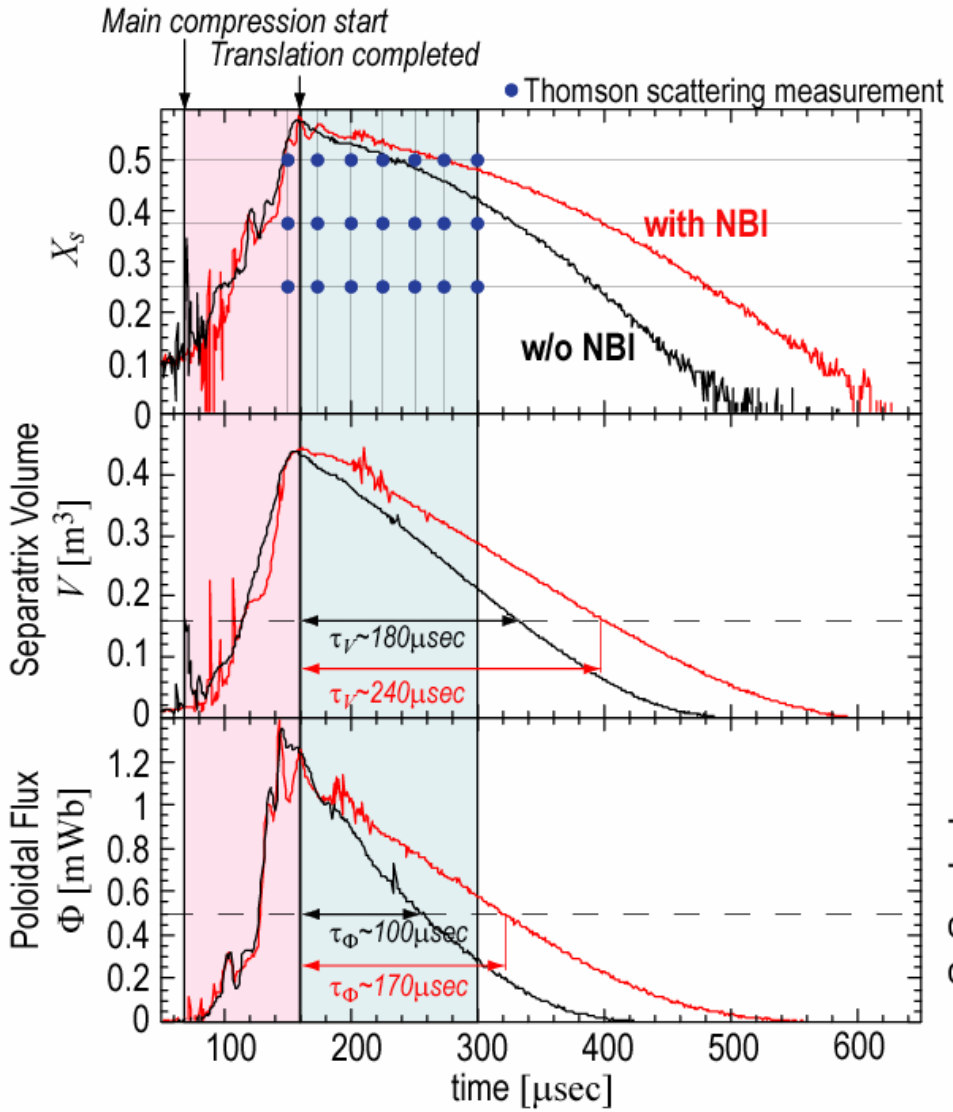
NBI experiment (FIX device)



By the experiment on the FIX, we have found

- Improvement of confinement
- Electron heating

T. Asai, Y. Suzuki, T. Yoneda, F. Kodera, M. Okubo, S. Okada, and S. Goto, Phys. Plasmas **7**, 2294 (2000).



Experimental conditions

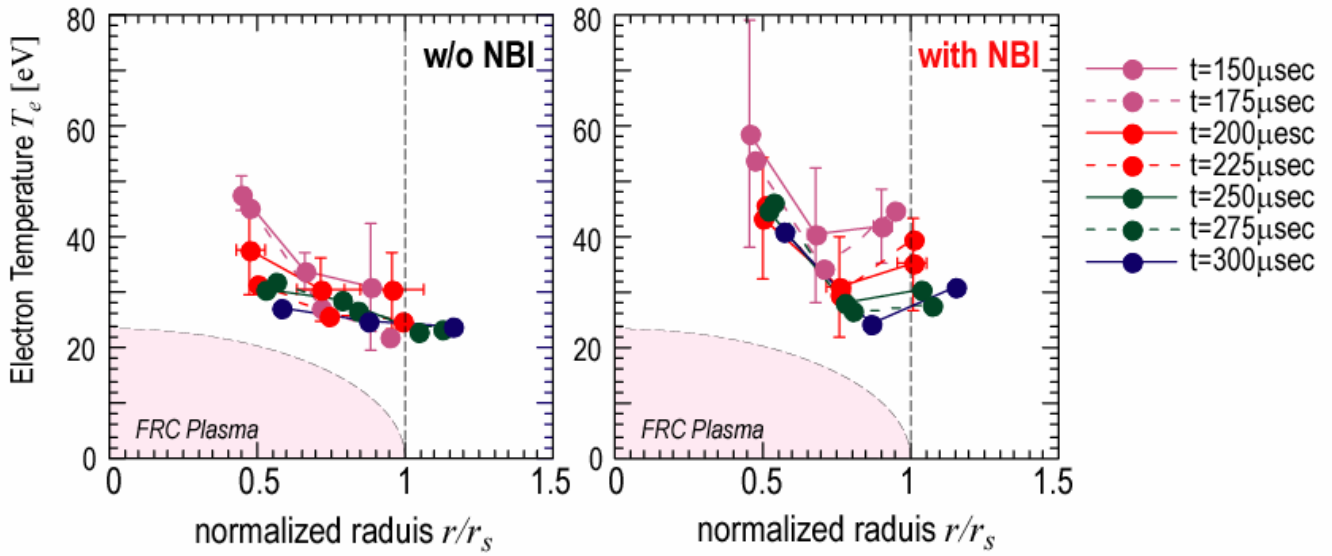
- Mirror ratio: 7~9
- NB energy: 13keV (H^0)
- NB current: 16~22A
- NB power: 200~250kW

Lifetime extension due to the NBI

- Plasma volume lifetime τ_V
  180μsec –> **240μsec**
- Flux lifetime τ_Φ
  100μsec –> **170μsec**

The NBI prolonged the plasma lifetime significantly. The NB effect was observed just after the translation completion, therefore the NB may cause some changes on the FRC plasma during the translation.

By courtesy of Dr. Inomoto



Radial profiles of electron temperature in FRCs with/without NBI

The NB-injected FRCs have T_e of about 10~20 eV higher than the standard FRCs.

- This temperature inclement was observed just before the translation was completed (t=150μsec).
  <– The beam power may be absorbed more efficiently during the translaion phase.

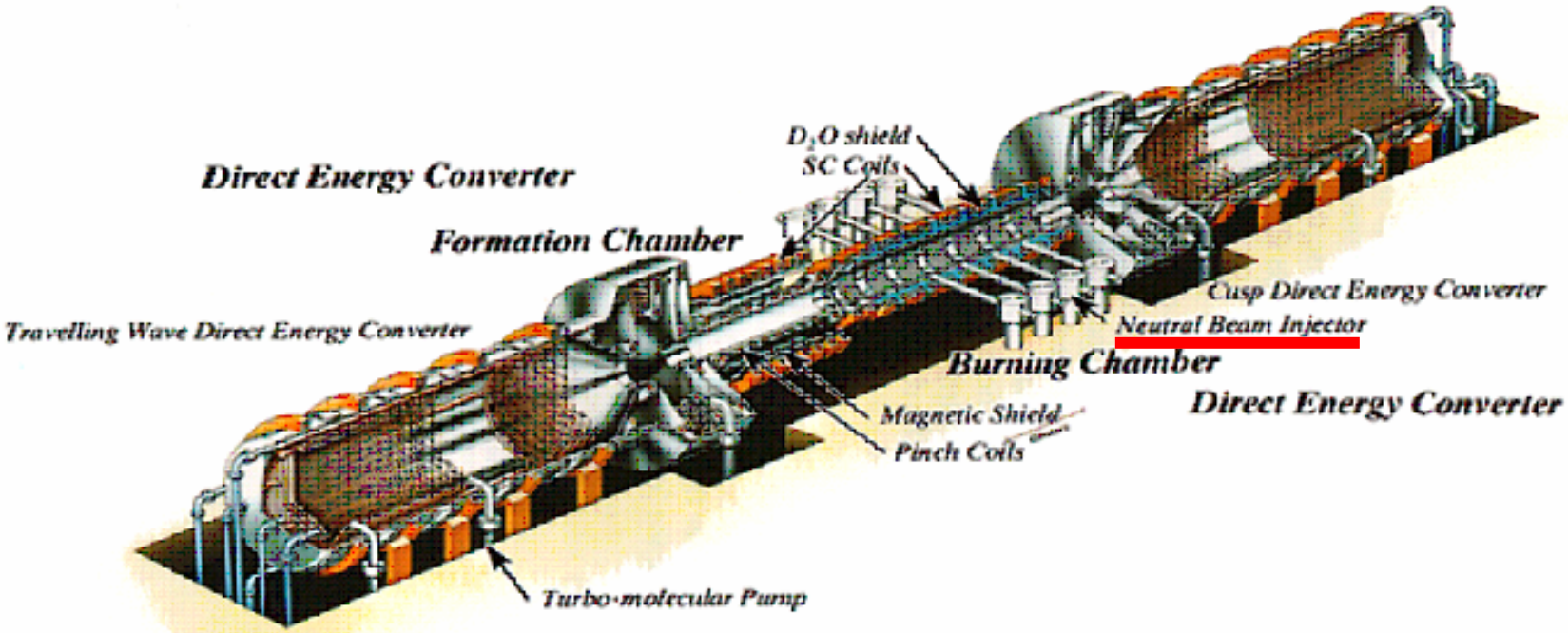
- The electrons are heated significantly at inner region (r/r_s=0.5) and around the separatrix.
  <– The beam power deposition may be localized according to the distribution function of the high energy beam ions.

  –> A calculation of particle trajectory and a direct measurement of high energy particles are required.

By courtesy of Dr. Inomoto

ARTEMIS

Conceptual D-^{3}He/FRC fusion reactor



An NB is injected tangentially .

Since the confinement region is designed to confine a fusion proton, a neutral beam injected fast ion is also trapped.

Computational study in Gunma University

Interests

- Beam ions are trapped long enough to heat the plasma?
- Is NBI effective to drive the plasma current?
- How is the global motion? How does it occur?

Neutral beam injection into FRCs

- Beam ion orbit calculation

  T. Takahashi *et al.*, Phys. Plasmas **11**, 3131 (2004).
  T. Takahashi *et al.*, Phys. Plasmas **11**, 3801 (2004).

- Global behavior of beam injected FRCs

  Ion particle + Electron fluid hybrid code

Analytical model

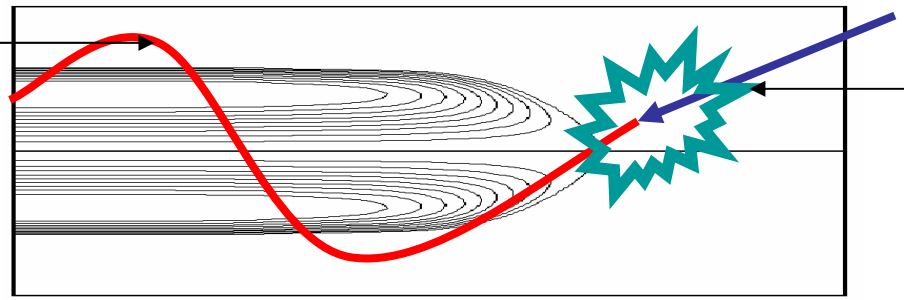
A neutral beam is ionized by

Charge exchange + direct ionization

Monte-Carlo method

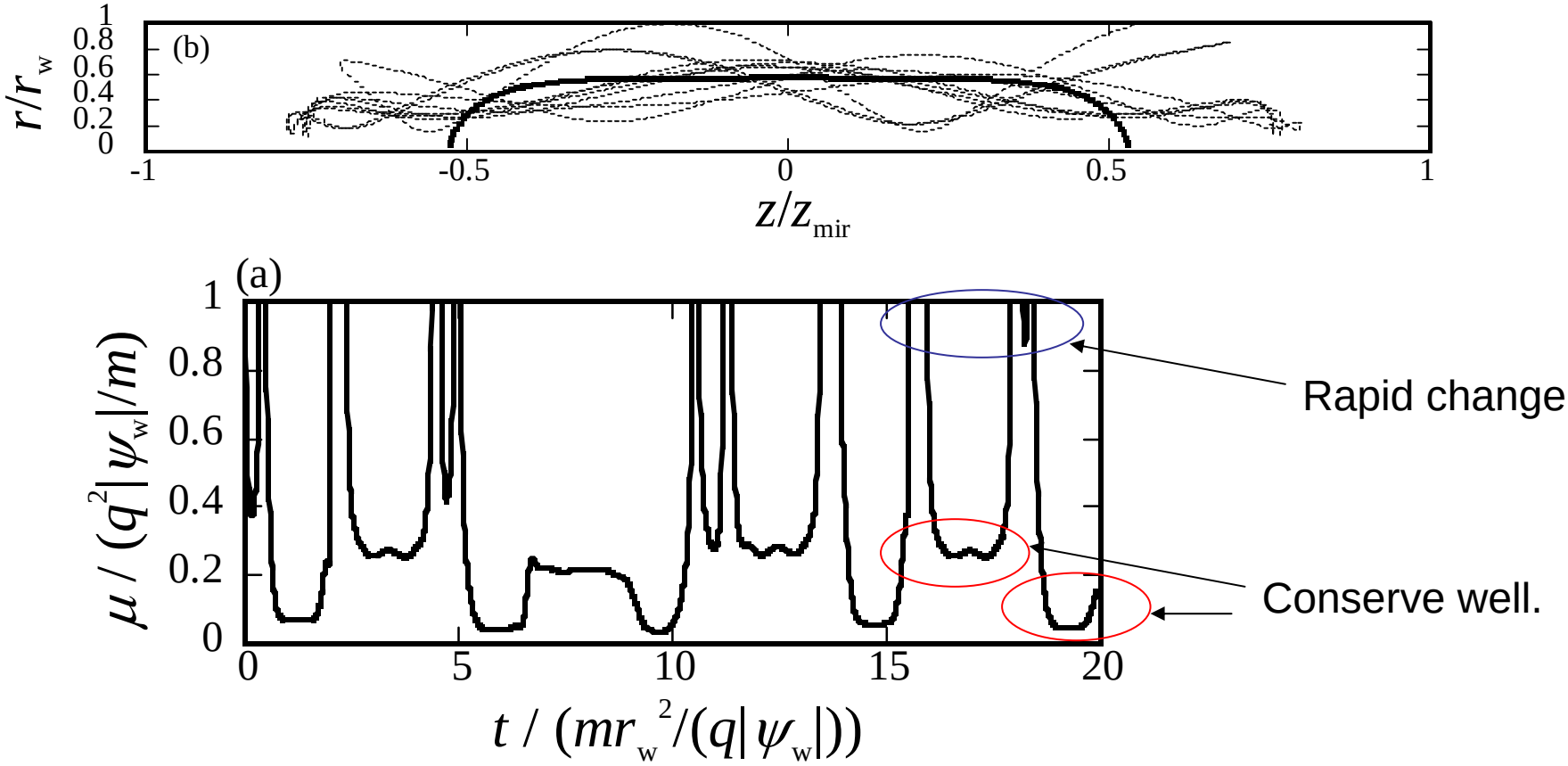
Numerical integration of equation of motion

$$m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = q\left(\mathbf{v}\times\mathbf{B}\right) - m\nu\,\mathbf{v}$$



Equilibrium state ← Grad-Shafranov eq.

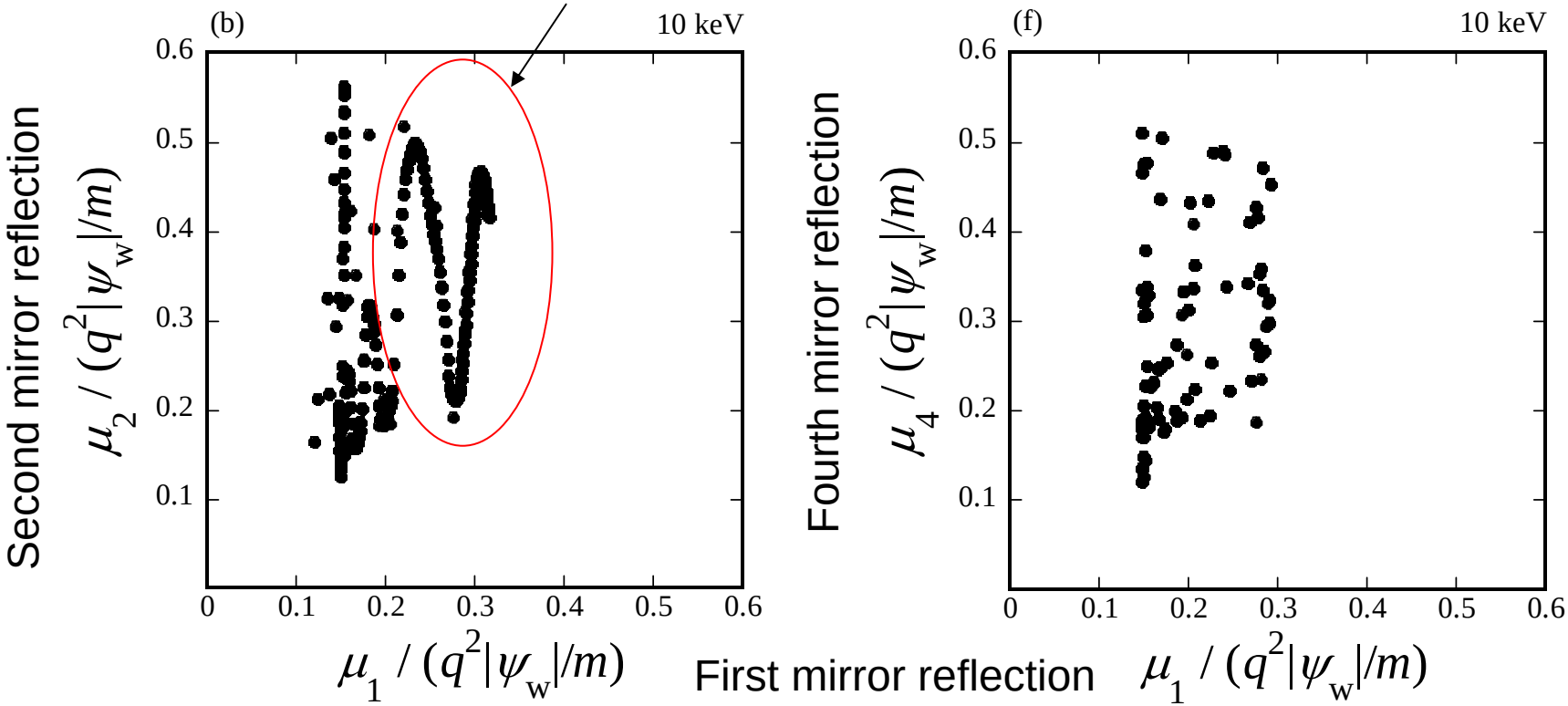
Beam ion orbit



Time evolution of the magnetic moment

Correlation of magnetic moment

Points draw a waving curve



Correlation is still remained

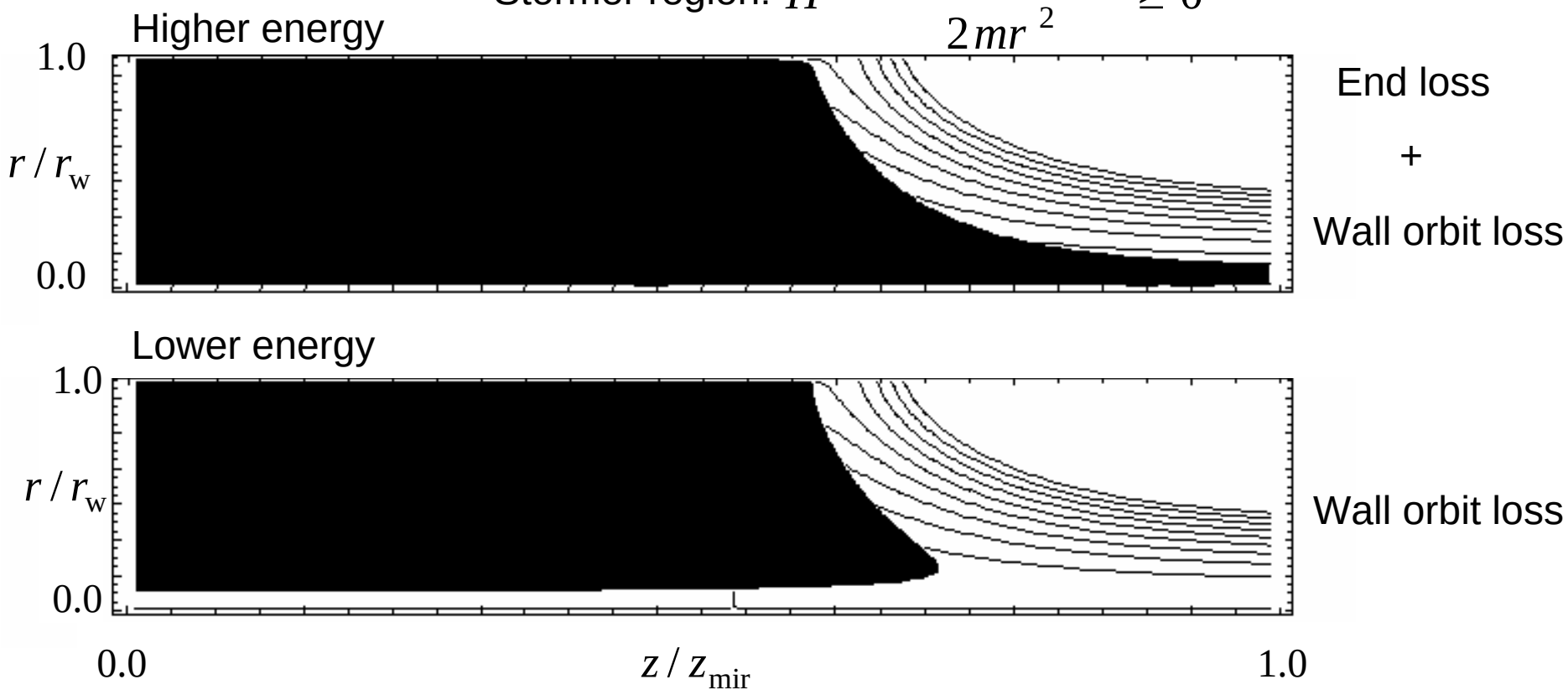
Correlation is disappeared

Fast ions are accessible ergodically in the region which is specified by those energy and effective potential

Accessible Region

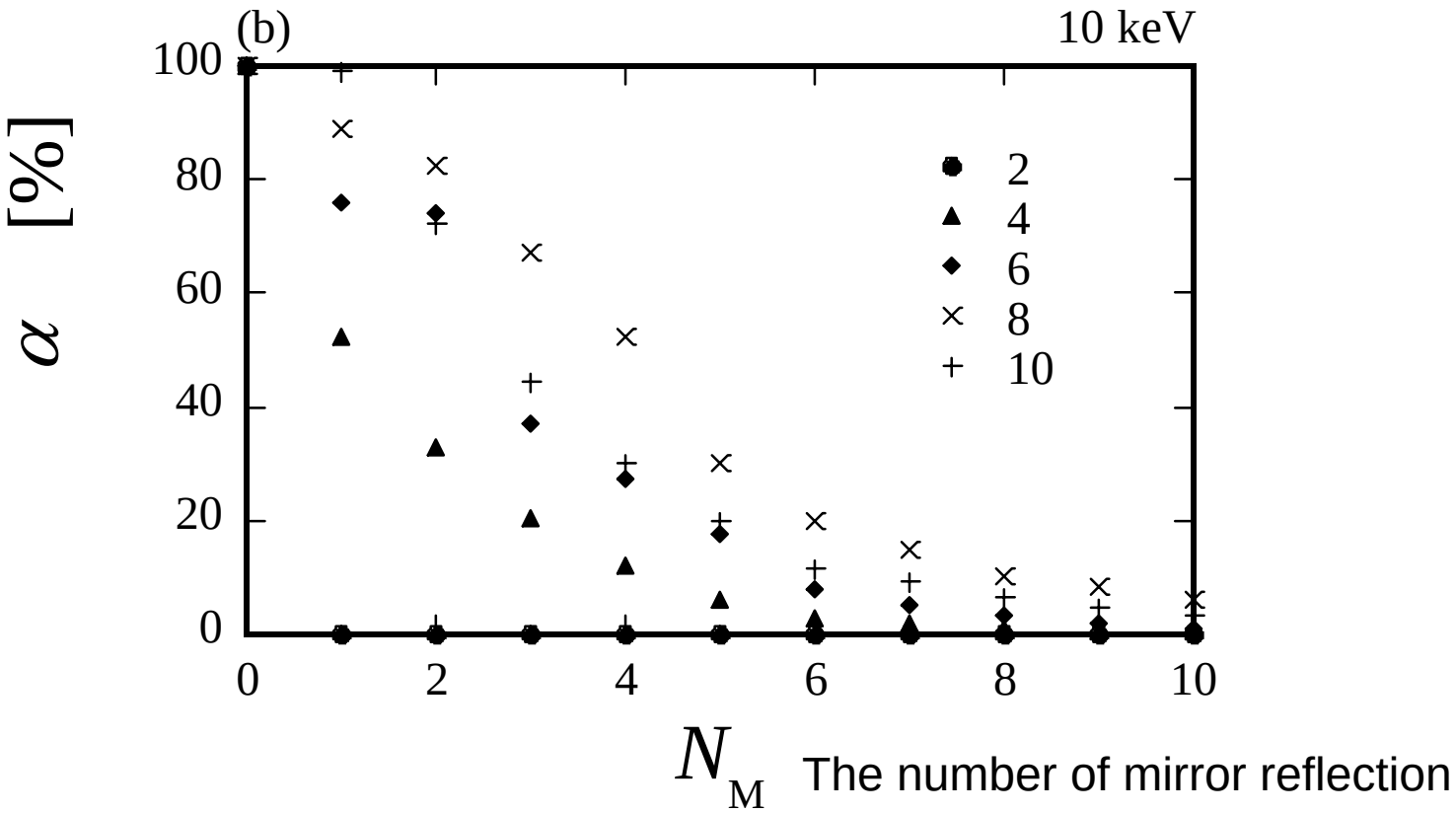
Moving in accessible region ergodically, a fast ion suffers…

Störmer region: $H - \frac{(P_\theta - q\psi)^2}{2mr^2} \geq 0$



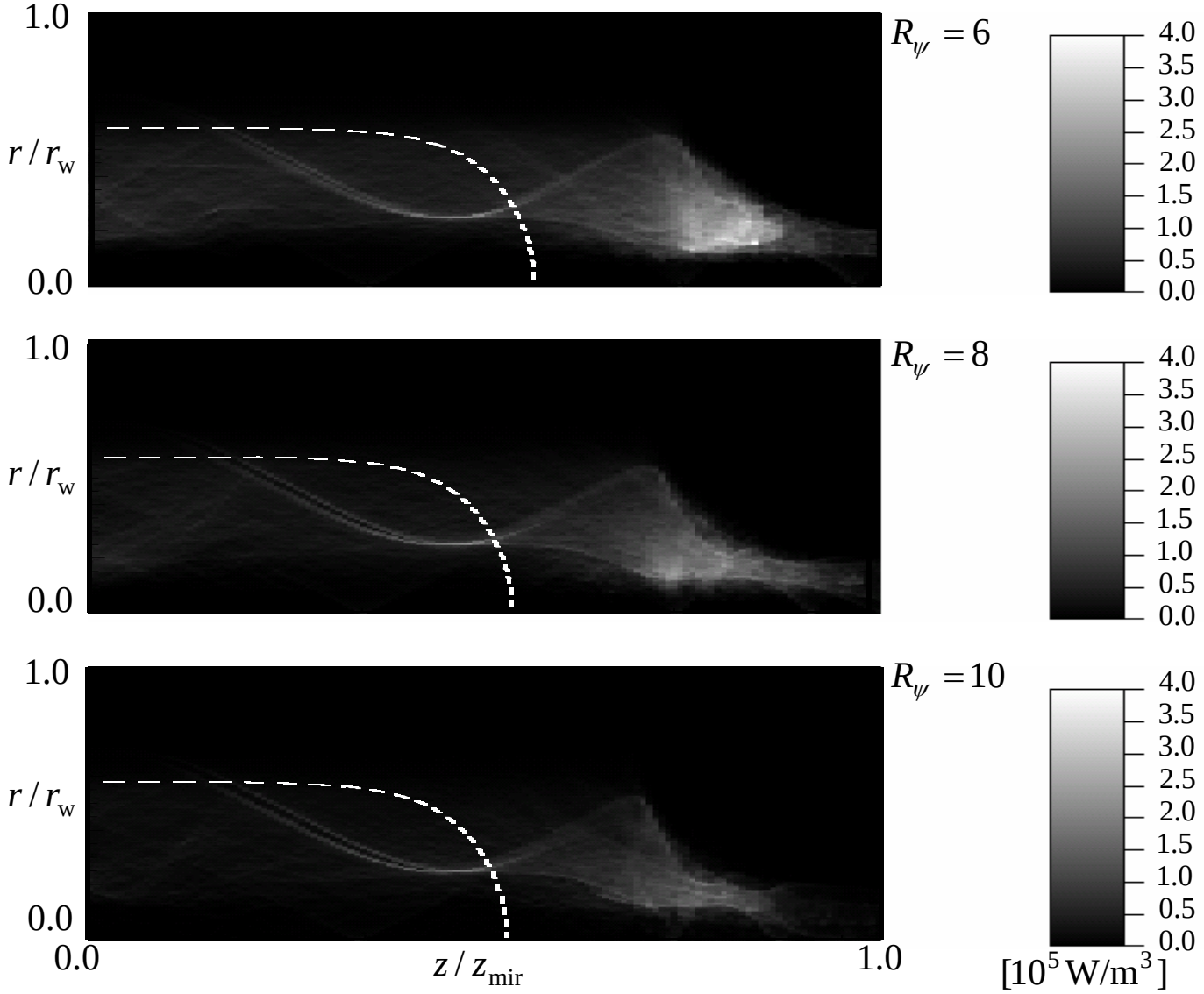
Wall orbit loss can not be suppressed by only the strong mirror field.
necessary to control the beam energy. (It is difficult experimentally…)

Beam ion confinement



- Beam ions are lost gradually.
- The mirror ratio of 8 is the best.

Local power deposition profile



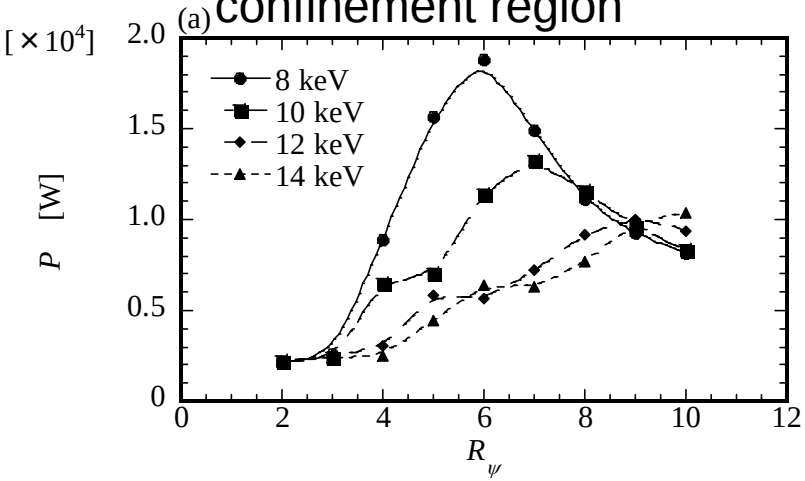
The beam energy = 8 keV

$$R_\psi \equiv \left| \frac{\psi(r = r_w, z = z_{mir})}{\psi(r = r_w, z = 0)} \right|$$

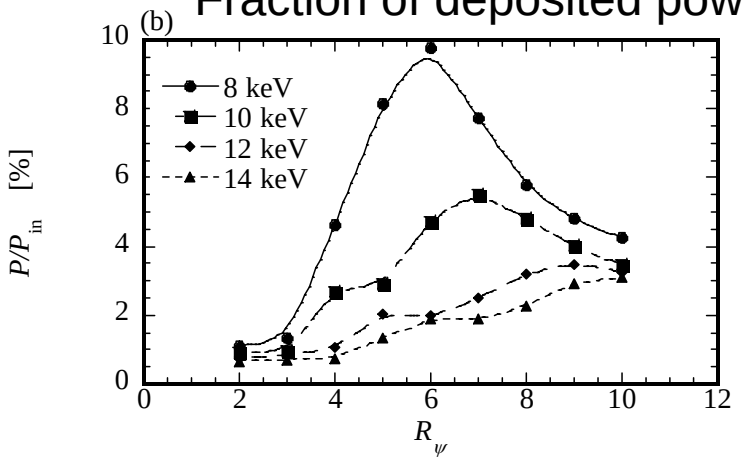
- Deposition in the edge is significant
  - ✓ Long duration
  - ✓ Beam ion focusing
  - ✓ Not-low density in edge
- The best deposition $R_\psi = 6$

Power deposition

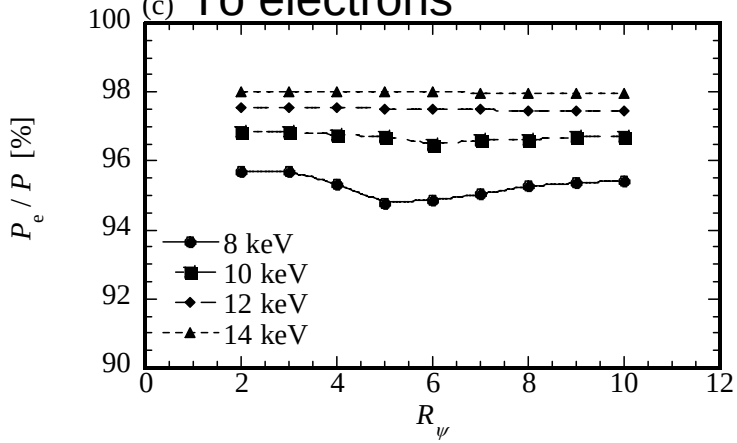
Total deposition in the confinement region



Fraction of deposited power

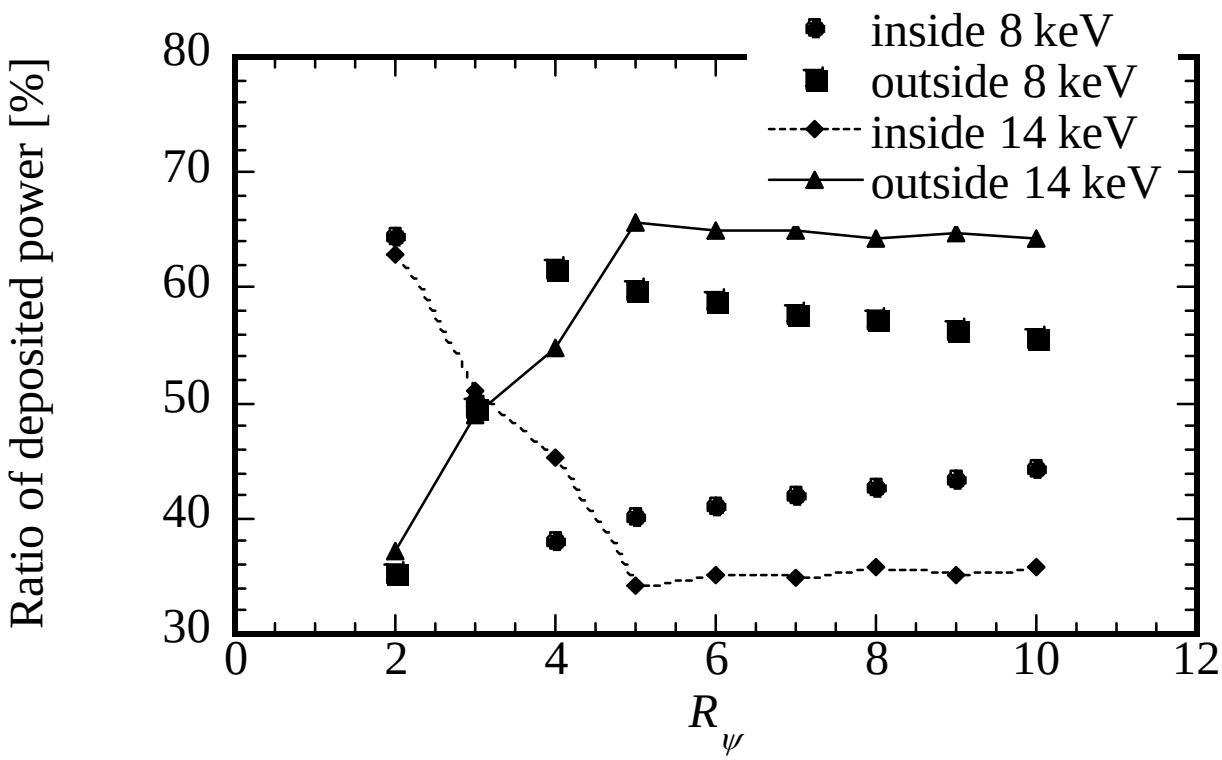


To electrons



- Up to 95 % deposition power goes to electrons
- Confinement of beam ions is not always improved by stronger mirror field.

Power deposition inside the separatrix



FIX plasma parameters

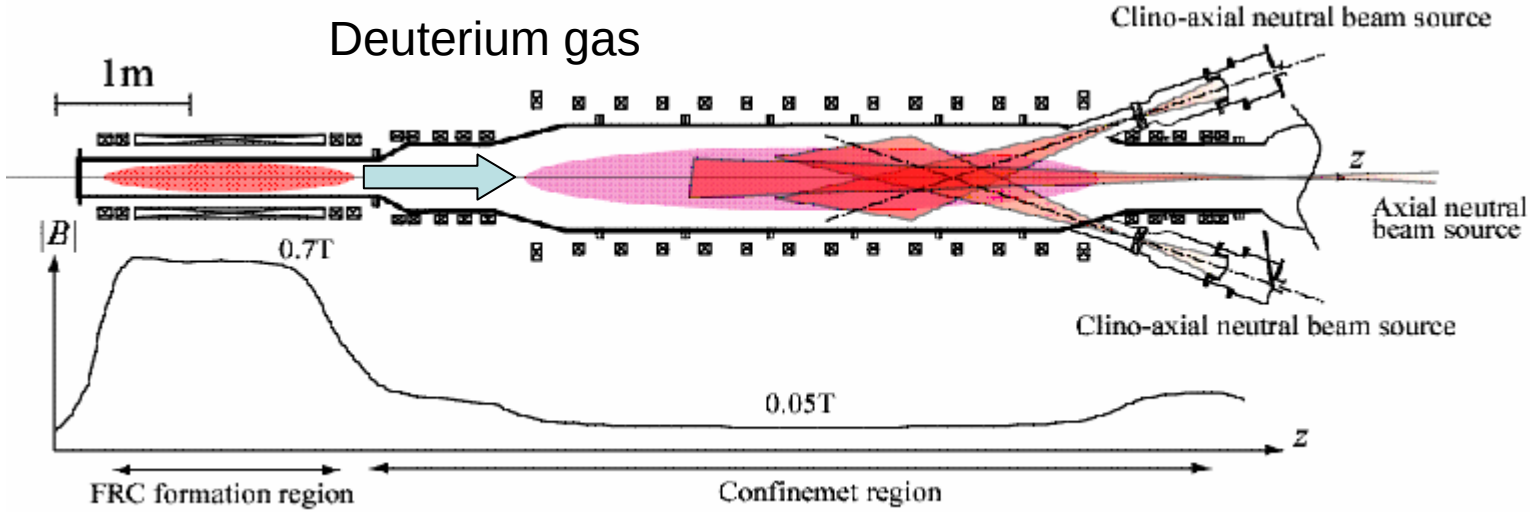
$$B_{\mathrm{ext}} \approx 0.05\ \mathrm{T}$$

$$T_{\mathrm{i}} \approx 100\ \mathrm{eV}$$

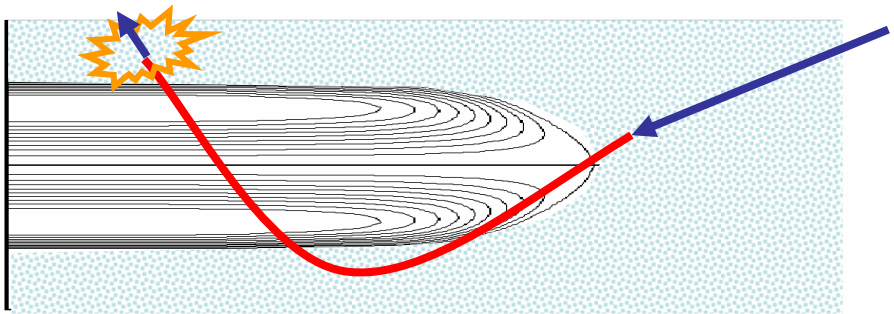
$$T_{\mathrm{e}} \approx 50\ \mathrm{eV}$$

Power deposition inside the separatrix --- 35~45%
Low energy beam is necessary to heat the core of FIX plasma

Effect of neutral gas in the edge



Charge exchange $H^+ + D_2 \rightarrow H + D_2^+$



: Deuterium gas

Assumption

Uniform neutral gas pressure outside the separatrix

No neutral gas inside the separatrix.

Charge exchange cross-section

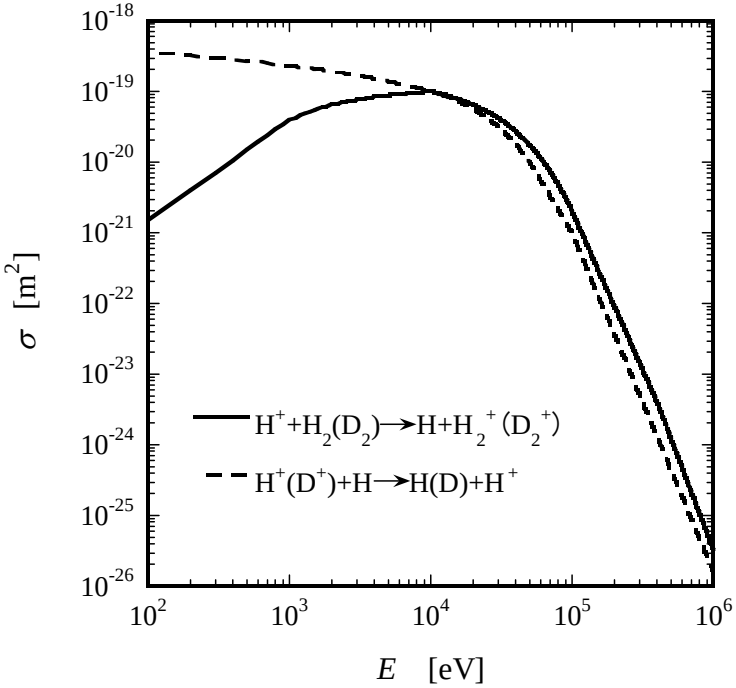
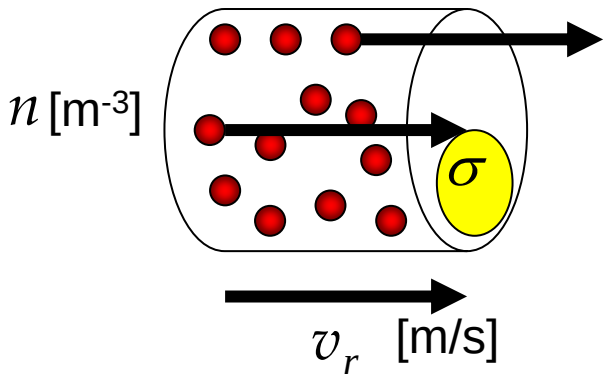


Fig. Analytical curve used in our simulation

Reaction rate



Particle flux = nv_r

Rate of reaction = $nv_r\sigma$

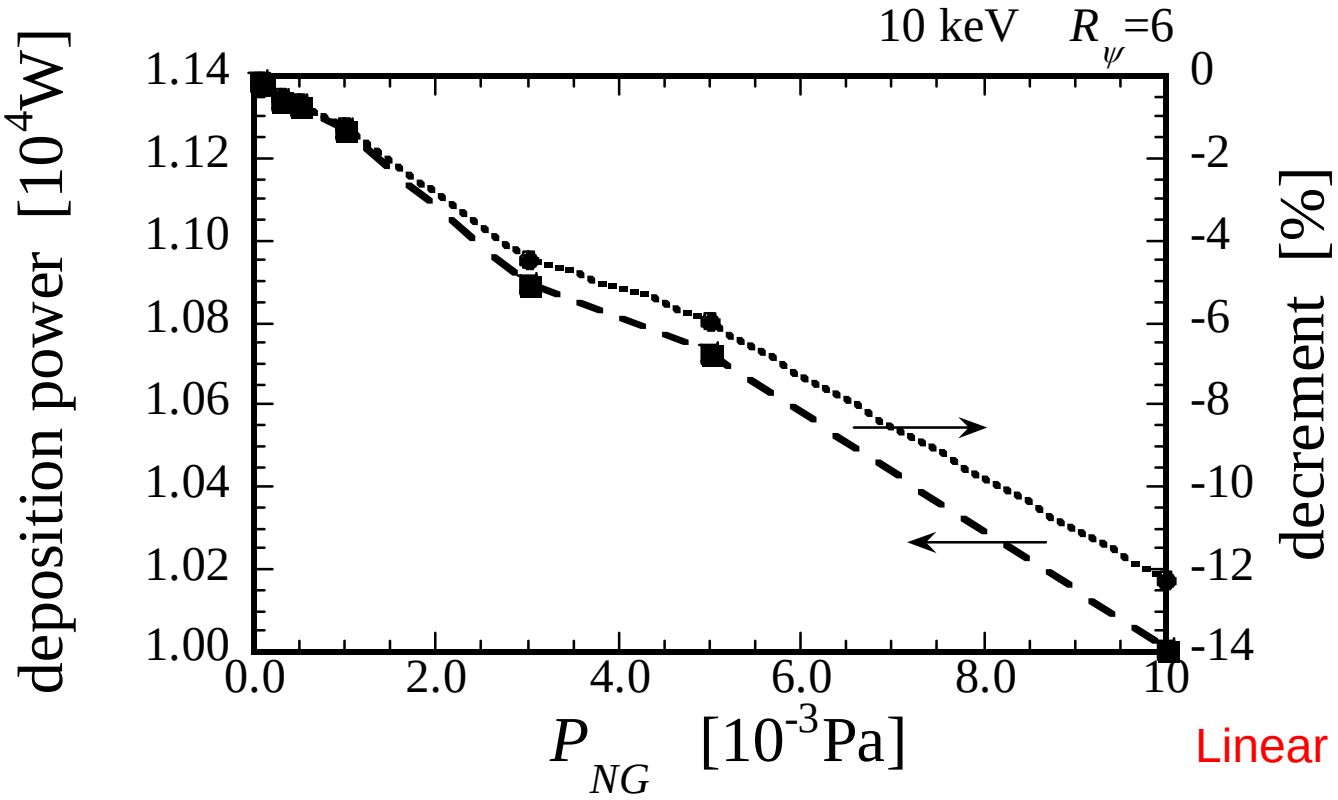
The reaction in Δt is $nv_r\sigma\,\Delta t$

$nv_r\sigma\,\Delta t \geq \xi$ Charge is exchanged

Database

http://dbshino.nifs.ac.jp

Effect on the deposition power



Linear decrease

About 0.01 Pa ⟶ decrement is 10 %

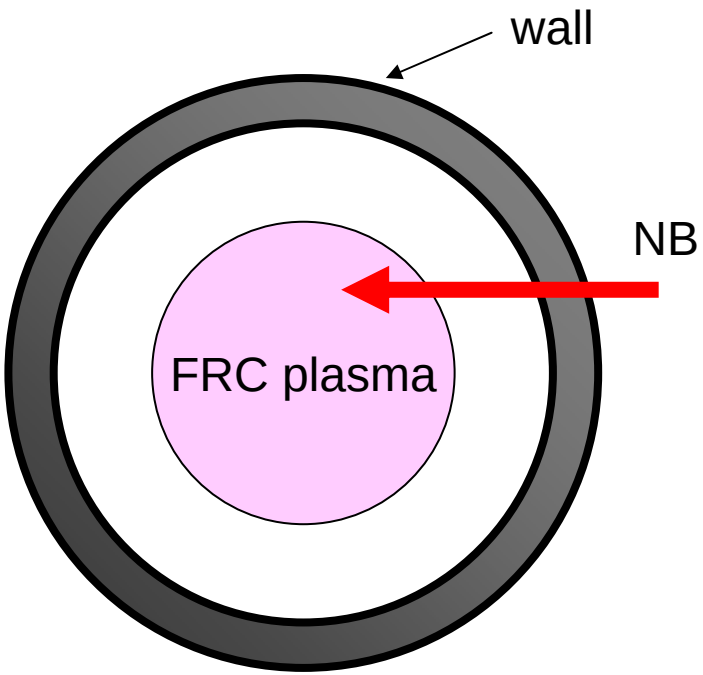
$$n_{NG} = \frac{p}{kT} \approx \frac{1\times10^{-2}}{1\times10^{-23}\times300} \approx 0.3\times10^{19} \qquad \frac{n_{NG}}{n} \approx \frac{0.3\times10^{19}}{5.0\times10^{19}} \approx 0.06$$

Low gas pressure

Evolution of beam injected plasma

Target and calculation principle

- Evolution of 2-dimensional beam injected FRC-like plasma
- Ion particle and electron fluid hybrid code
- Tangential injection on the midplane
- Slowing down collision (b-e, e-i)
- Heat generation for electrons



Midplane: $z = 0$

Hybrid model

Equation of motion for ions and beam ions (particle)

$$m_\alpha \frac{\mathrm{d}\mathbf{v}_\alpha}{\mathrm{d}t} = q_\alpha \left(\mathbf{E} + \mathbf{v}_\alpha \times \mathbf{B}\right) - m_\alpha \nu_{\alpha \mathrm{e}} \left(\mathbf{v}_\alpha - \mathbf{u}_\mathrm{e}\right) \qquad \alpha = \mathrm{i}, \mathrm{b}$$

Fluid equation of motion for Massless electron

$$-en_\mathrm{e}\left(\mathbf{E} + \mathbf{u}_\mathrm{e} \times \mathbf{B}\right) - \boxed{\nabla p_\mathrm{e}} + \mathbf{R}_\mathrm{eb} + \mathbf{R}_\mathrm{ei} = \mathbf{0}$$

$$\mathbf{R}_{ab} \equiv \iiint m_a \mathbf{v}\, C_{ab}\, \mathrm{d}\mathbf{v}$$

Momentum conservation $\mathbf{R}_{ab} + \mathbf{R}_{ba} = \mathbf{0}$ $\qquad \mathbf{R}_\mathrm{eb} = -\mathbf{R}_\mathrm{be} = m_\mathrm{b} n_\mathrm{b} \nu_\mathrm{be} \left(\mathbf{u}_\mathrm{b} - \mathbf{u}_\mathrm{e}\right)$

→ Heat balance equation for electrons

$$\frac{3}{2} n_\mathrm{e} \left[\frac{\partial T_\mathrm{e}}{\partial t} + \left(\mathbf{u}_\mathrm{e} \bullet \nabla\right) T_\mathrm{e} \right] + n_\mathrm{e} T_\mathrm{e} \left(\nabla \bullet \mathbf{u}_\mathrm{e}\right) = \boxed{Q_\mathrm{eb} + Q_\mathrm{ei}}$$

??

Calculation of heat generation for ion

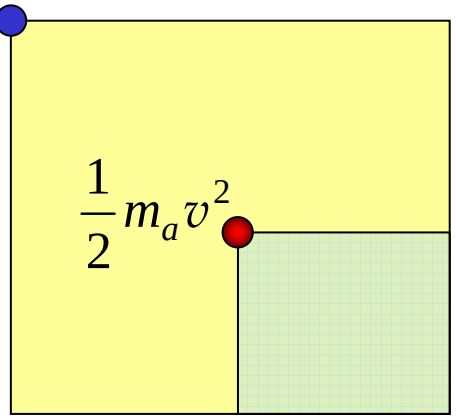
Change of thermal energy density per unit time due to *collision*

$$Q_{ab} \equiv \iiint \frac{1}{2} m_a v_{\mathrm{r}}^2 \, C_{ab} \, \mathrm{d}\mathbf{v}$$

To calculate the rate of change of ion pressure

$n_a, \mathbf{u}_a$

obtained



$$\left\langle \frac{1}{2} m_a v^2 \right\rangle = \frac{1}{2} m_a u_a^2 + \left\langle m_a \mathbf{u}_a \bullet \mathbf{v}_{\mathrm{r}} \right\rangle + \left\langle \frac{1}{2} m_a v_r^2 \right\rangle$$

$$= \frac{1}{2} m_a u_a^2 + kT_a \qquad \text{(2-D case)}$$

Thermal energy =Ensemble kinetic energy - flow energy

Ion heat generation (2-D case)

$$Q_{\alpha \mathrm{e}} = \frac{n_\alpha kT_\alpha \left(x_i, y_j, t + \Delta t\right) - n_\alpha kT_\alpha \left(x_i, y_j, t\right)}{\Delta t} \qquad \alpha = \mathrm{i}, \mathrm{b}$$

Heat generation Q (fluid)

Energy conservation

$$\boxed{\iiint \frac{1}{2} m_a v^2 \, C_{ab} \, \mathrm{d}\mathbf{v} + \iiint \frac{1}{2} m_b v^2 \, C_{ba} \, \mathrm{d}\mathbf{v} = 0}$$

$$\mathbf{v} = \mathbf{u}_a + \mathbf{v}_\mathrm{r}$$

$\mathbf{v}_\mathrm{r}$: random velocity

$\mathbf{u}_a$: flow velocity

$$\underbrace{\iiint \frac{1}{2} m_a u_a^2 \, C_{ab} \, \mathrm{d}\mathbf{v}}_{=0} + \iiint m_a \mathbf{u}_a \bullet \mathbf{v}_\mathrm{r} \, C_{ab} \, \mathrm{d}\mathbf{v} + \iiint \frac{1}{2} m_a v_\mathrm{r}^2 \, C_{ab} \, \mathrm{d}\mathbf{v}$$

$$+ \underbrace{\iiint \frac{1}{2} m_b u_b^2 \, C_{ba} \, \mathrm{d}\mathbf{v}}_{=0} + \iiint m_b \mathbf{u}_b \bullet \mathbf{v}_\mathrm{r} \, C_{ba} \, \mathrm{d}\mathbf{v} + \iiint \frac{1}{2} m_b v_\mathrm{r}^2 \, C_{ba} \, \mathrm{d}\mathbf{v} = 0$$

$$Q_{ab} + Q_{ba} + \mathbf{u}_a \bullet \mathbf{R}_{ab} + \mathbf{u}_b \bullet \mathbf{R}_{ba} = 0$$

$$\boxed{\begin{aligned} Q_{ab} &\equiv \iiint \frac{1}{2} m_a v_\mathrm{r}^2 \, C_{ab} \, \mathrm{d}\mathbf{v} \\ \mathbf{R}_{ab} &\equiv \iiint m_a \mathbf{v} \, C_{ab} \, \mathrm{d}\mathbf{v} \end{aligned}}$$

definition

From the momentum conservation

$$Q_{ab} + Q_{ba} + (\mathbf{u}_a - \mathbf{u}_b) \bullet \mathbf{R}_{ab} = 0$$

fluid particle

→Heat generation term for electron

Hybrid Model

Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

Ampere's law

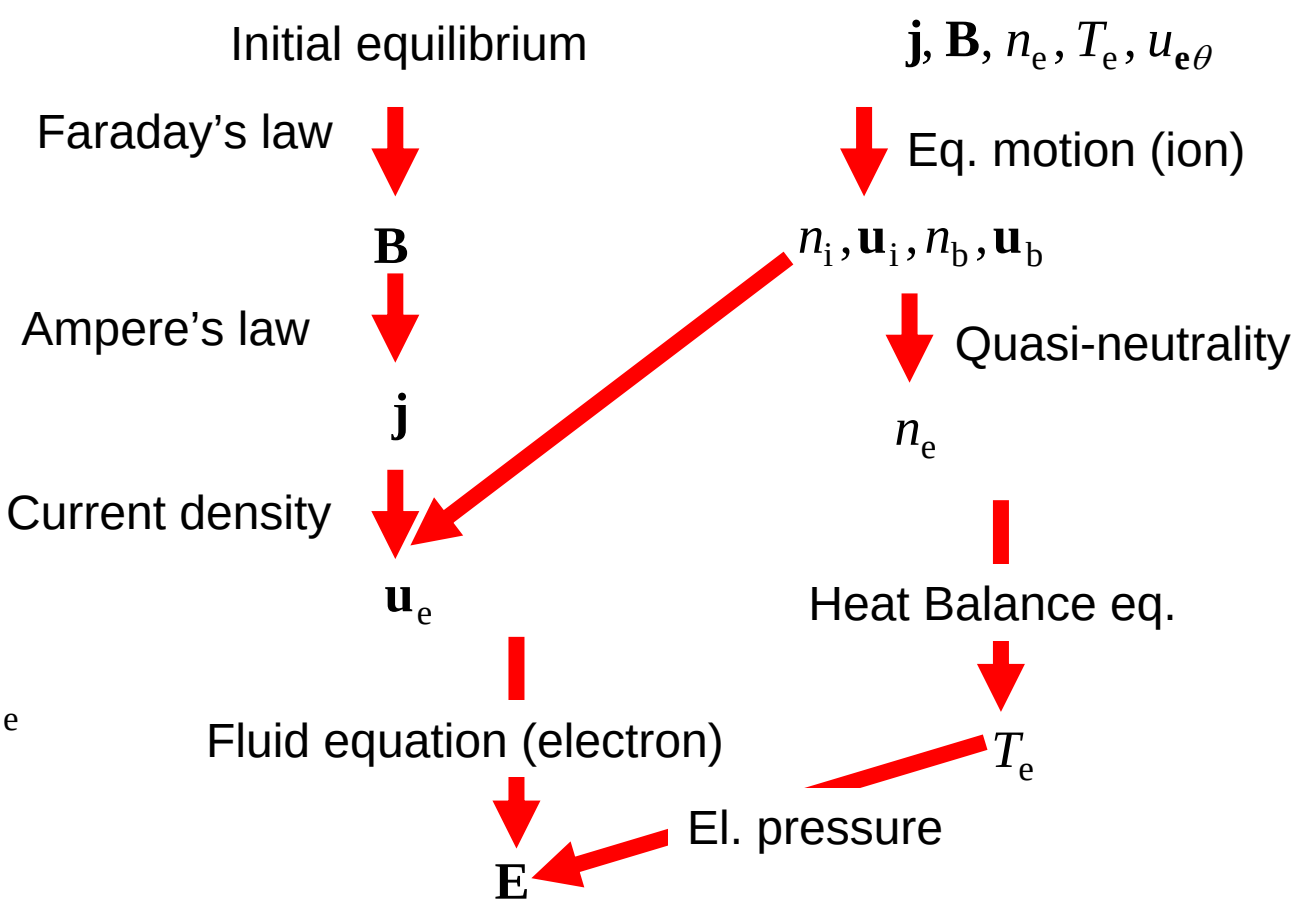
$$\mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$$

Quasi-neutrality

$$n_\mathrm{e} = Z_\mathrm{i} n_\mathrm{i} + n_\mathrm{b}$$

Current density

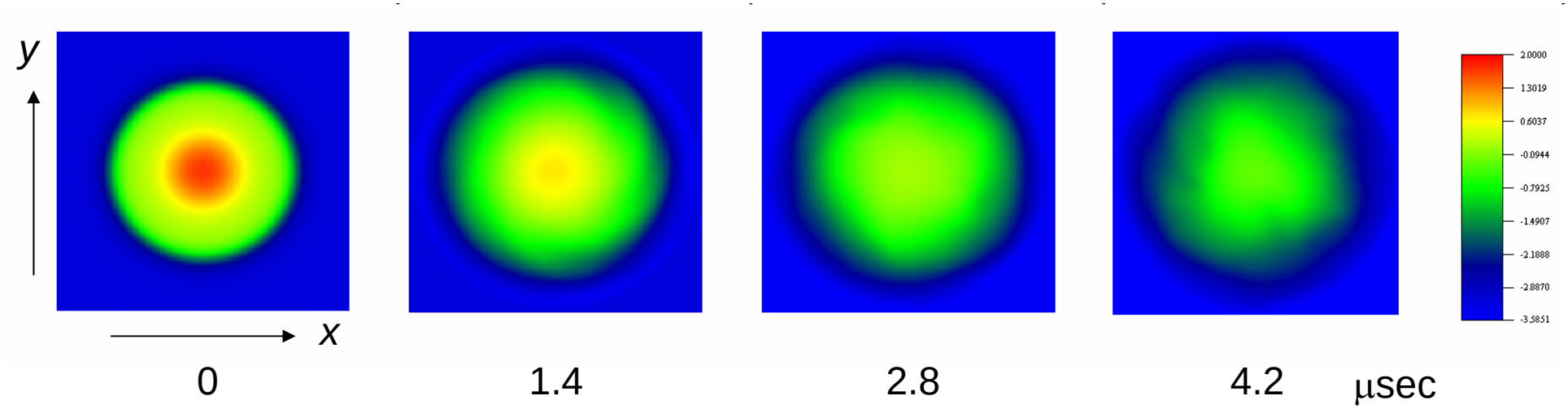
$$\mathbf{j} = Z_\mathrm{i} e n_\mathrm{i} \mathbf{u}_\mathrm{i} + e n_\mathrm{b} \mathbf{u}_\mathrm{b} - e n_\mathrm{e} \mathbf{u}_\mathrm{e}$$

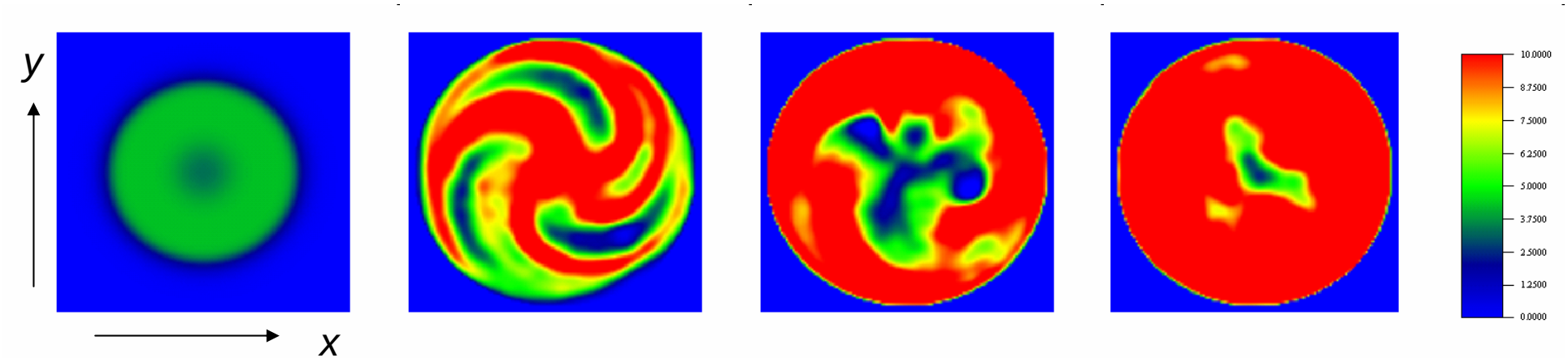


All physical quantities at the next time step are determined.

Magnetic field & electron pressure

Magnetic field

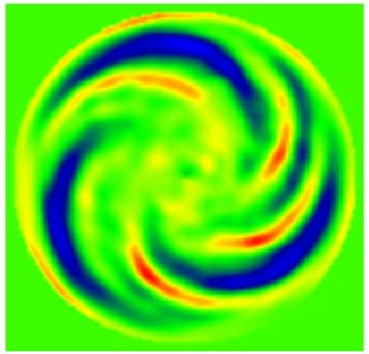




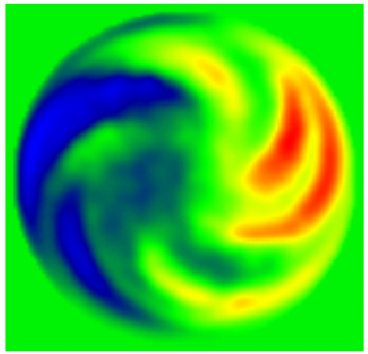
Electron pressure

Flow, Electric field

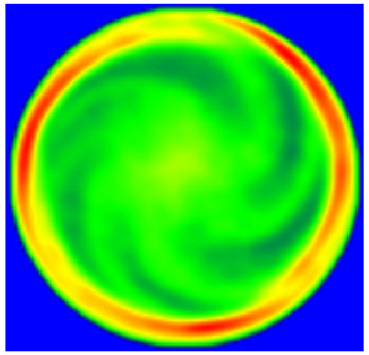
1.4 μsec



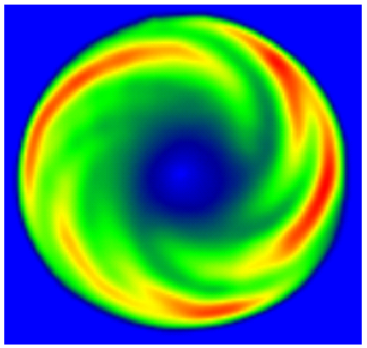
E_r



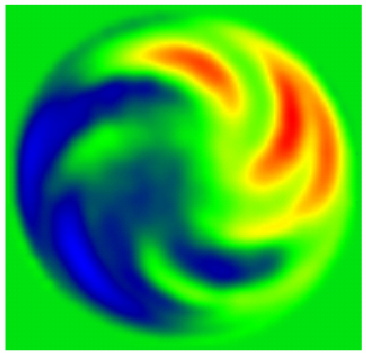
U_{ix}



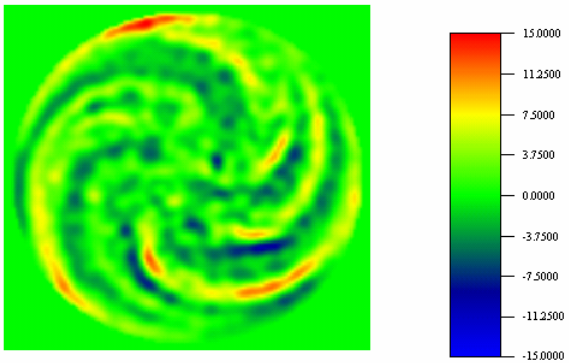
n_i



j_θ

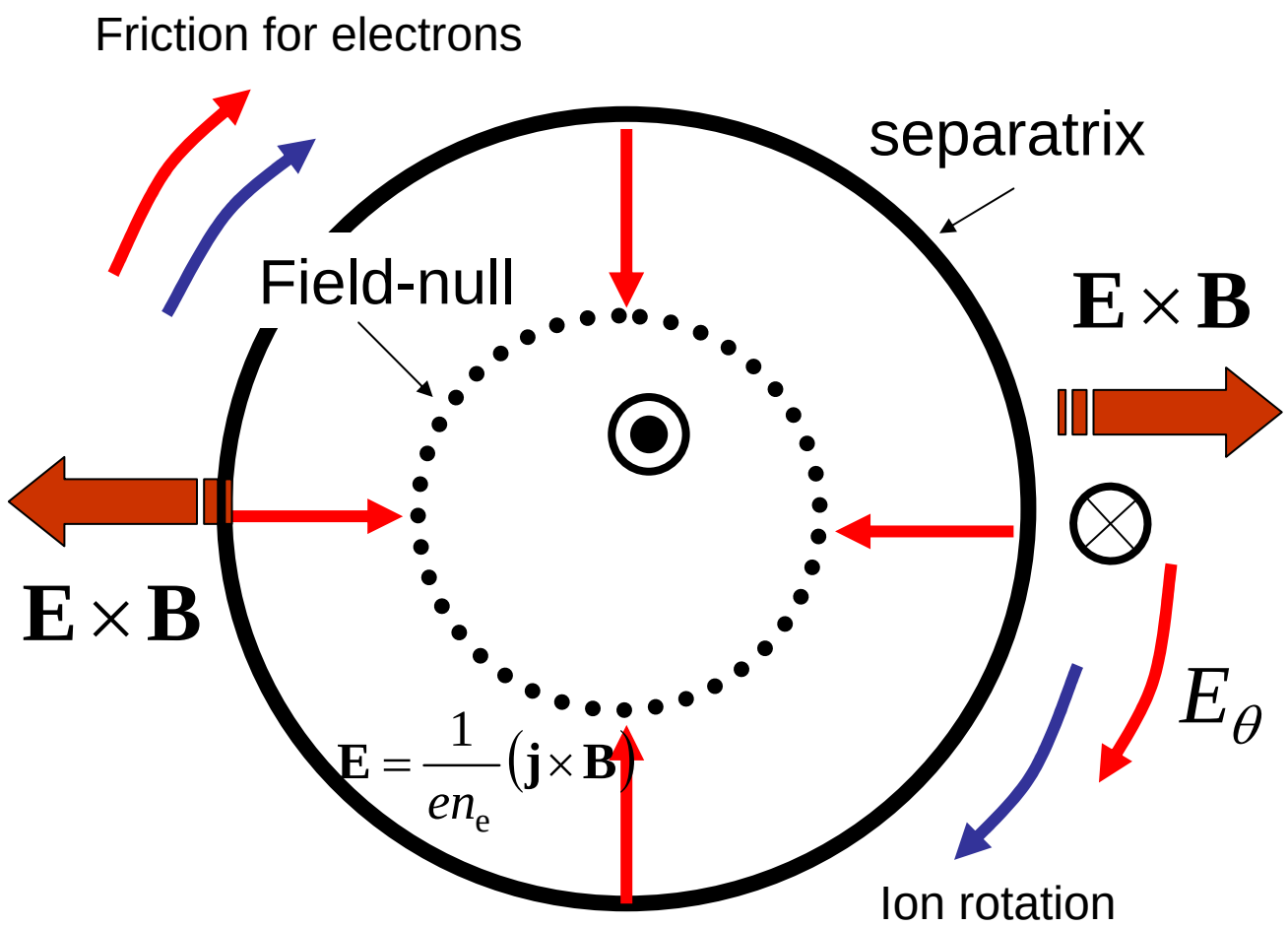


U_{er}



Q_{ei}

Discussion



Electric field
(Hall term)

↓

Ion rotates

↓

Electron is dragged

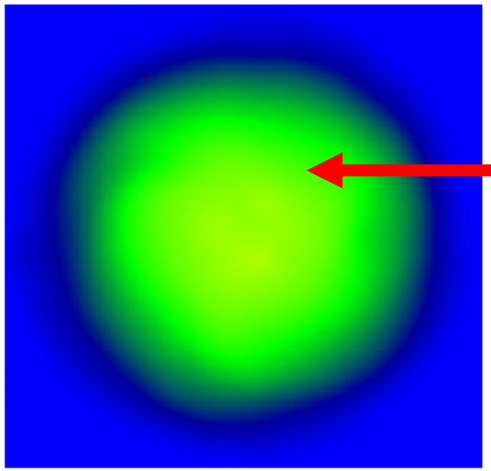
↓

Electric field

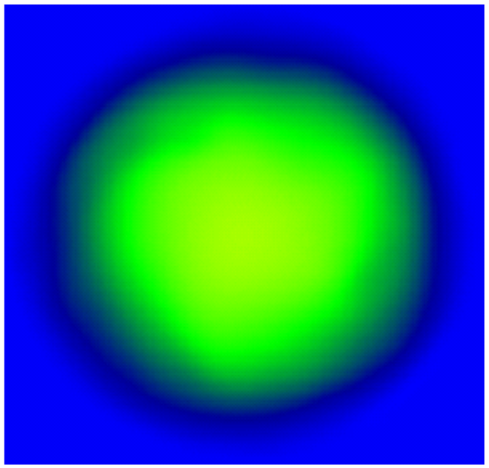
↓

$\mathbf{E}\times\mathbf{B}$ drift

NB is injected, though…



Magnetic field profile 1.4 μsec after the injection

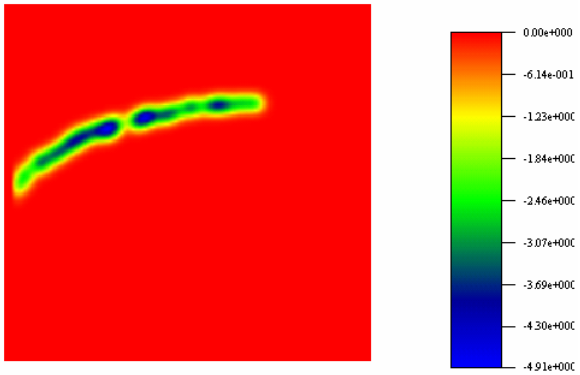


With NB

No difference can be found

Without NB

Beam current = 20 A
Beam speed = 10 thermal speed



Beam ion impacts wall directly

Beam energy should be decreased

Summary

- Calculation of beam ion orbit
  - NB-injected fast ions exhibit the non-adiabatic motion. Due to this, the beam ion suffers from a wall orbit loss. Target plasma parameter efficient for NBI heating should be investigated.
  - The neutral gas in the edge region is not needed to worry.

Summary

- Hybrid calculation
  - Considering the electron pressure and friction force due to collision, we made the hybrid code to calculate the global motion of NB-injected 2-D FRC.
  - 2-D FRC decays too rapidly. Further investigation is necessary.
  - 3-D FRC will be simulated in a near future.