MHD and Hybrid Simulation Study of FRC Plasmas

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Outline

1. Research Background
2. MHD simulation
   i. FRC translation and two FRC collision process
   ii. Comparison with ST merging
3. Hybrid simulation
   i. Feasibility of slow formation by plasma pressure supply
4. Summary

(my personal) Research Background

Plasma Ion Dynamics

1995-1998

Collisionless pitch-angle scattering at X-point

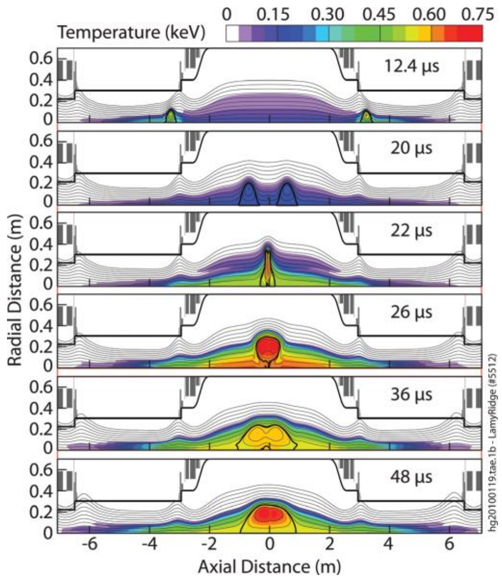
1998-2006

Adiabaticity breaking of plasma ions in core region

NB injected particle motion

2004-

Origin of spontaneous toroidal spin-up



C-2 experiment calculated by LamyRidge code

H. Y. Guo et al, Phys. Plasmas 18, 056110 (2011).

MHD

2004-2006

Fusion propulsion

2013-

Translation and two FRCs collision

Electron fluid equation + Ion particle model

⇩

Full-particle simulation

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Basic equations

Resistive Hall MHD equations

Eq. continuity

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{u})$$

Eq. Motion

$$\frac{\partial \mathbf{u}}{\partial t} = -(\mathbf{u} \cdot \nabla)\mathbf{u} + \frac{1}{\rho}\left[\frac{1}{\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p - \nabla \cdot \overleftrightarrow{\Pi}\right]$$

Energy Eq.

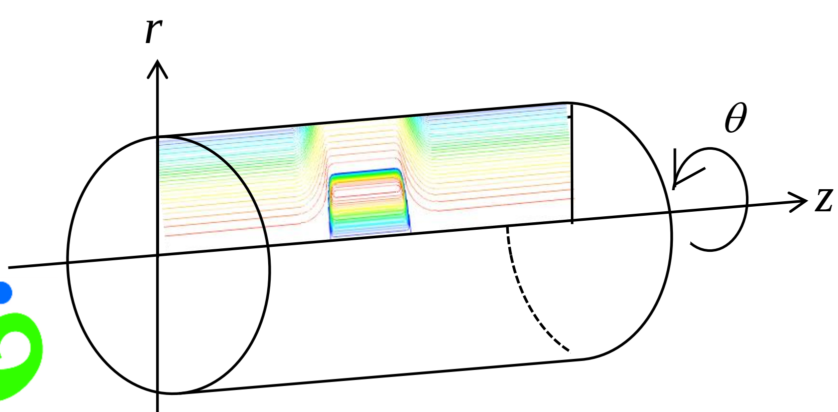
$$\frac{\partial p}{\partial t} = -(\mathbf{u} \cdot \nabla)p - \gamma\, p \nabla \cdot \mathbf{u} + (\gamma - 1)\left[\eta\, j^2 - \overleftrightarrow{\Pi} : \nabla \mathbf{u}\right]$$

Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left(\eta \mathbf{j} - (\mathbf{u} \times \mathbf{B}) + \frac{1}{e n_e}\left[(\mathbf{j} \times \mathbf{B}) - \nabla p_e\right]\right)$$

$$p_e = 0.5 p$$

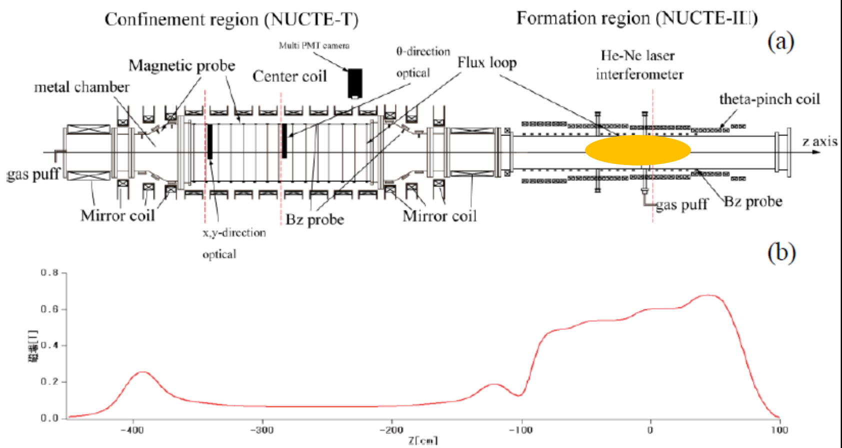
Hall term



- Cylindrical coordinate system
- G-S equilibrium as initial condition
- Axisymmetric system
- Resistivity dependent on the current density
- 4-th order Runge-Kutta method

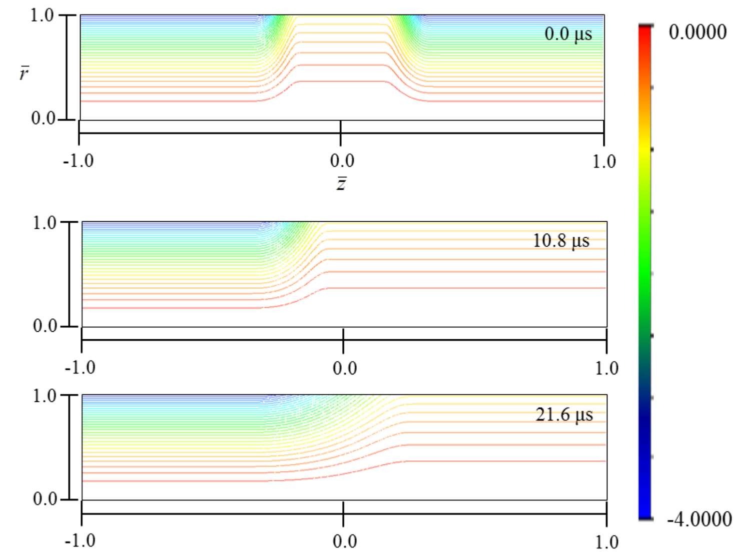
Translation by magnetic pressure gradient

Experiment



NUCTE-III/T and magnetic field profile

Present simulation



Time variation of external field structure

$$\mathbf{B}_{\text{total}} = \mathbf{B}_{\text{plasma}} + \mathbf{B}_{\text{external}}$$

MHD eq.
（e.g.） Faraday’s law

$$\frac{\partial \mathbf{B}_{\text{plasma}}}{\partial t} = \nabla \times \left(\mathbf{u} \times \mathbf{B}_{\text{total}} - \frac{\eta}{\mu_0} \nabla \times \mathbf{B}_{\text{total}} \right)$$

- Calculation of time evolution of field by plasma
- Inputting external field variation

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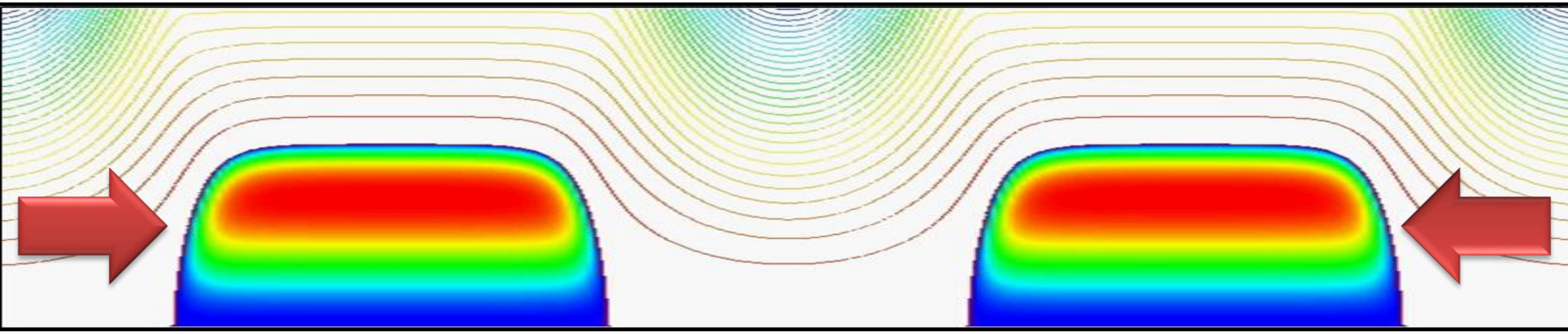
Collision simulation (1)

w/o magnetic assist: sequential external field control



Two FRCs collision, 0-72[μs].

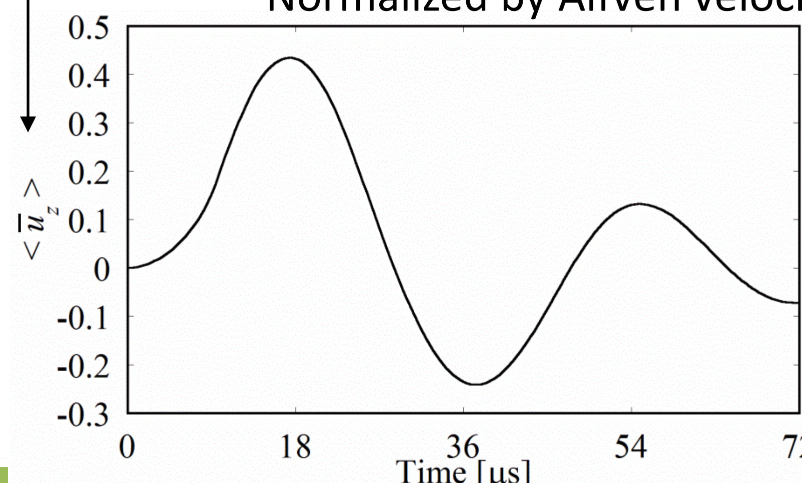
No magnetic reconnection event is observed.

Small translation velocity

- Max. 20km/s

External magnetic assist is needed

Normalized by Alfven velocity



Volume-averaged translation velocity

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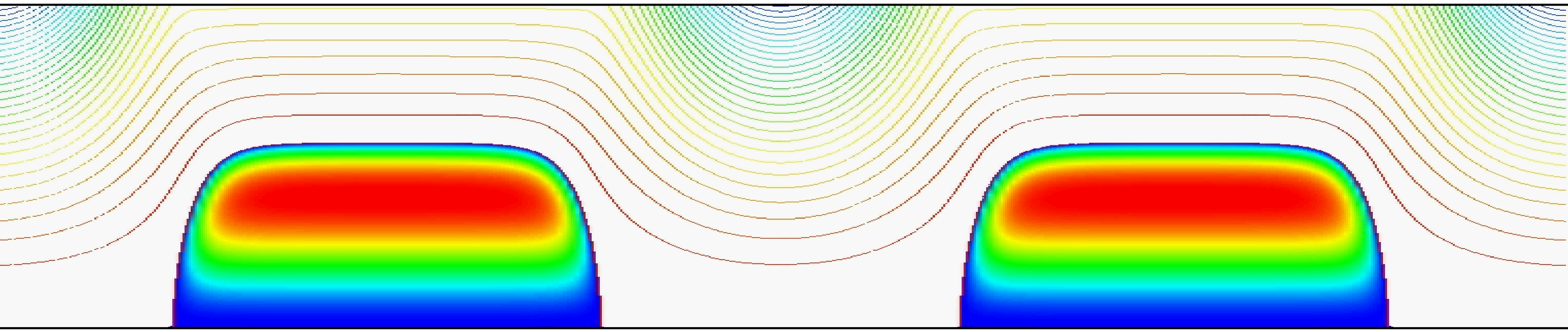
Collision simulation (2)

w/ magnetic assist: sequential external field control



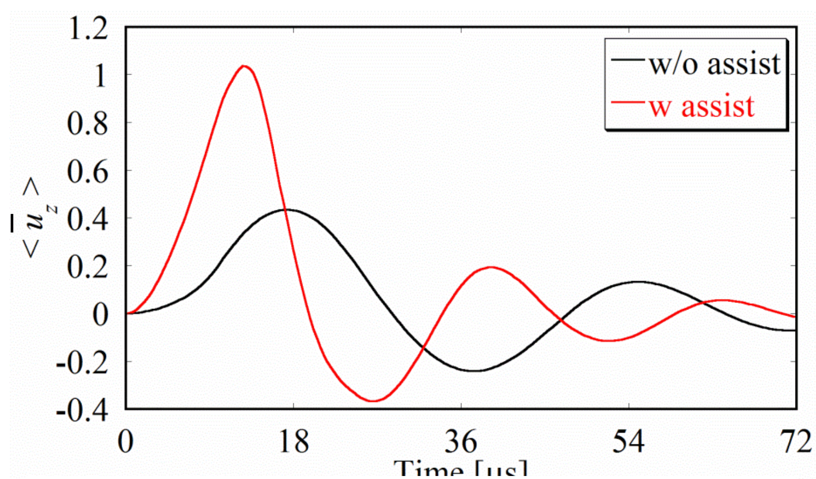
Collision simulation with magnetic assist，0-72[μs].

Magnetic reconnection occurs in the separatrix field line.

Larger translation velocity is observed

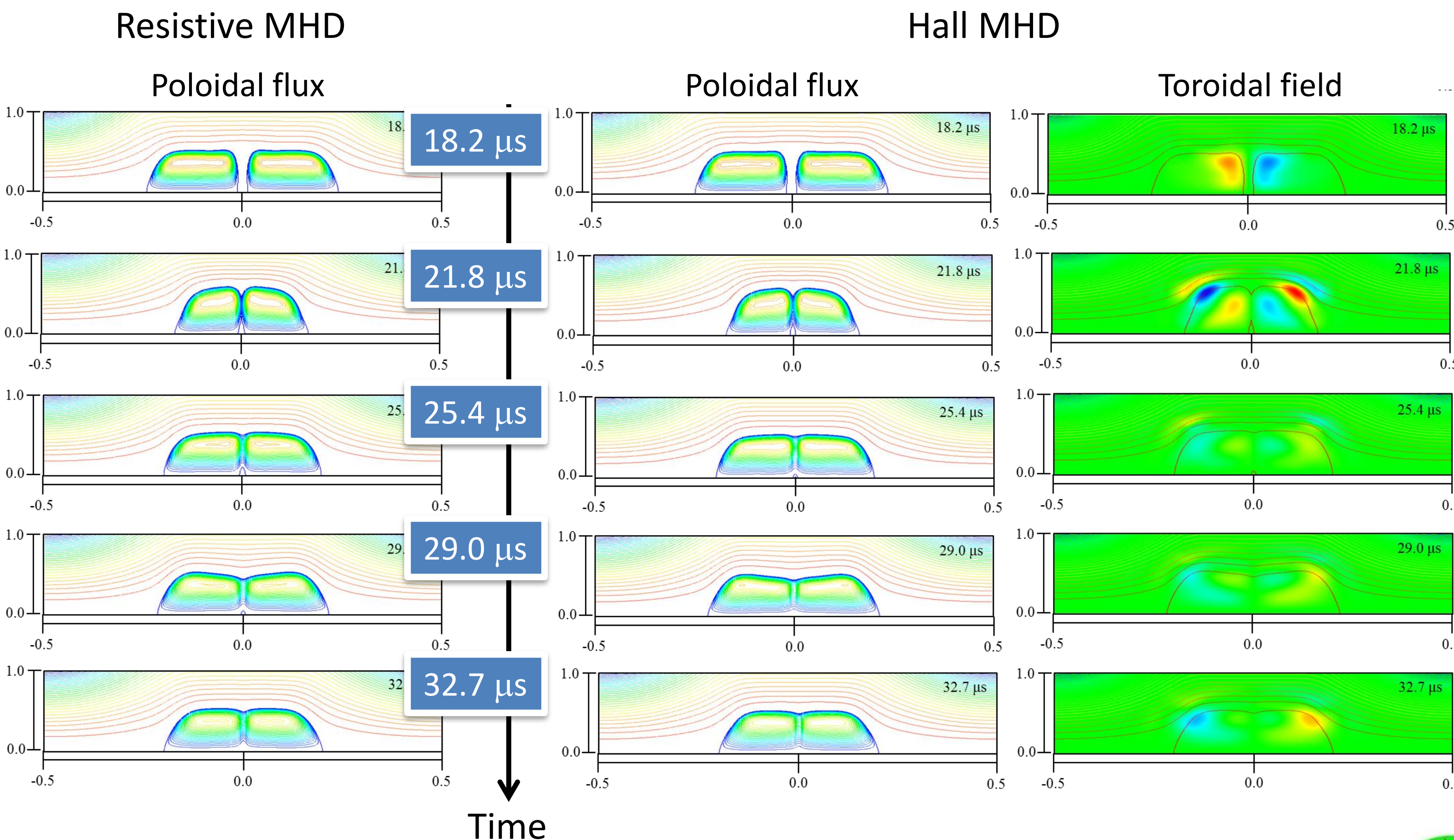
- About two times larger

Our result is different from the experiment



Volume-averaged translation velocity

Comparison of field structure



- Only slight difference between two models is observed
- No complete core merging can be reproduced

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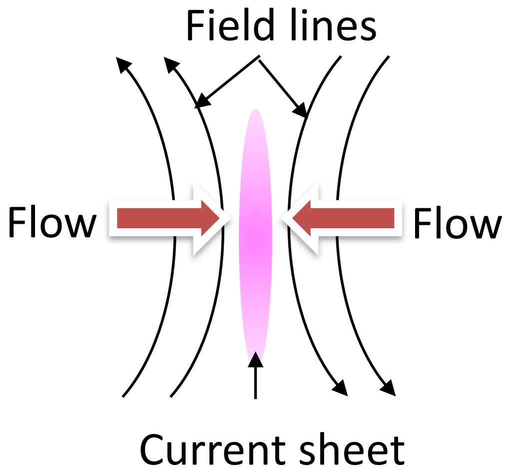
High resolution resistive MHD simulation

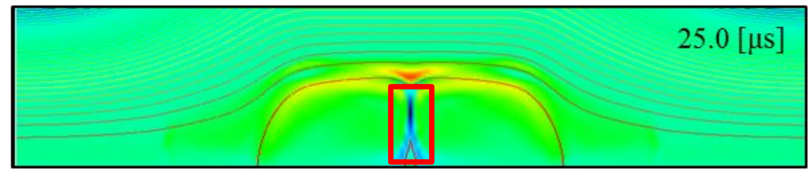


Reconnection region

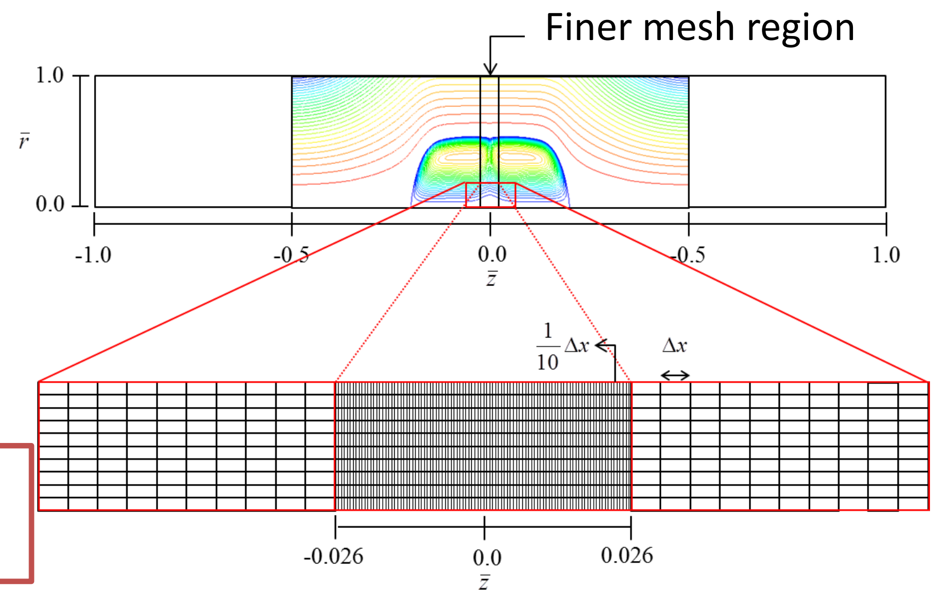
Current sheet width
~ 4-5 axial meshes Δz

Fine magnetic structure in the reconnection region can not be calculated by MHD model.

1/10 mesh size region is prepared in high-resolution MHD model.



2D profile of the current density



Calculation mesh structure

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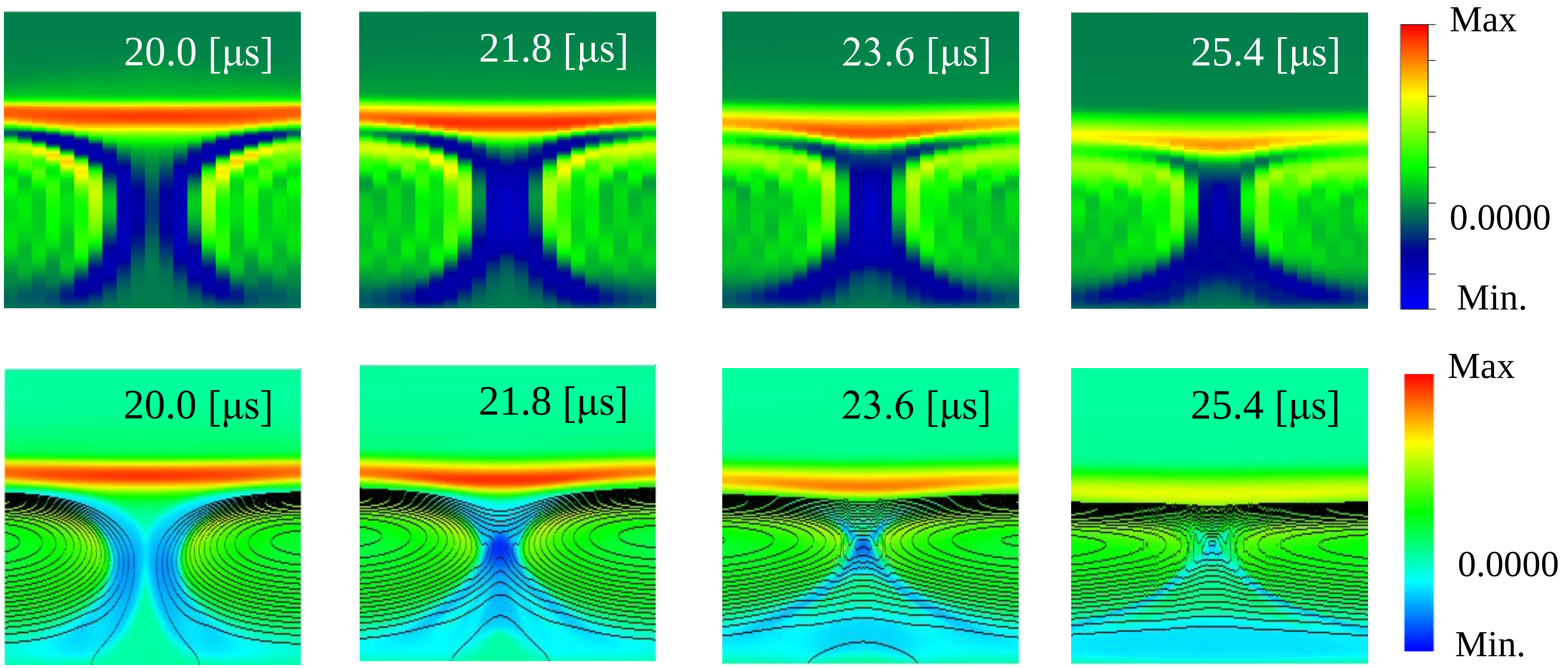
High resolution simulation results

Current density profile in the reconnection region



2D current density profile. （Top） Conventional model （bottom） high-resolution model

Width of the current sheet
- Up to 5 meshes in conventional model
- Up to 12 meshes in high-resolution model

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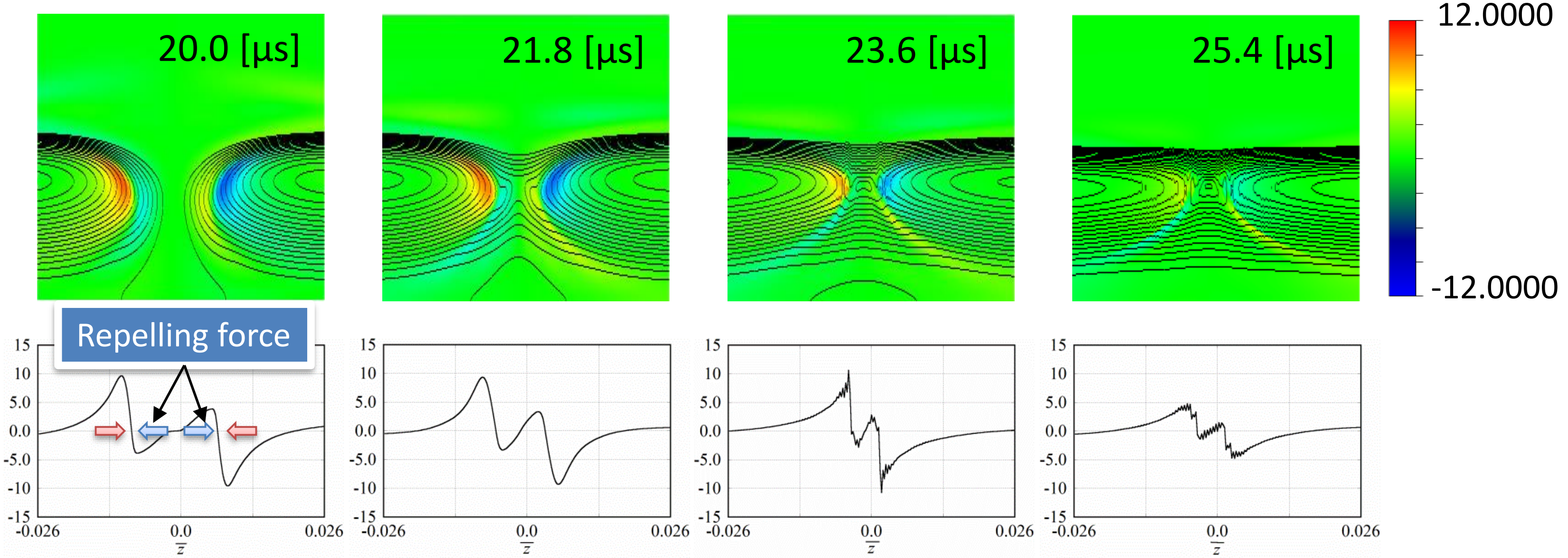
Force in reconnection region

$\mathbf{j}\times\mathbf{B}-\nabla p$: Dominant force components in our MHD model



(Top) 2D Force profile, (Bottom) Axial force profile ($r = R$) R: major radius

- Attracting force acts on two FRC plasmas
- Repelling force, however, is found near the separatrix surface

Difficulty in FRC merging by resistive MHD model

ST plasma merging

Required subject of fusion research = Core Fueling

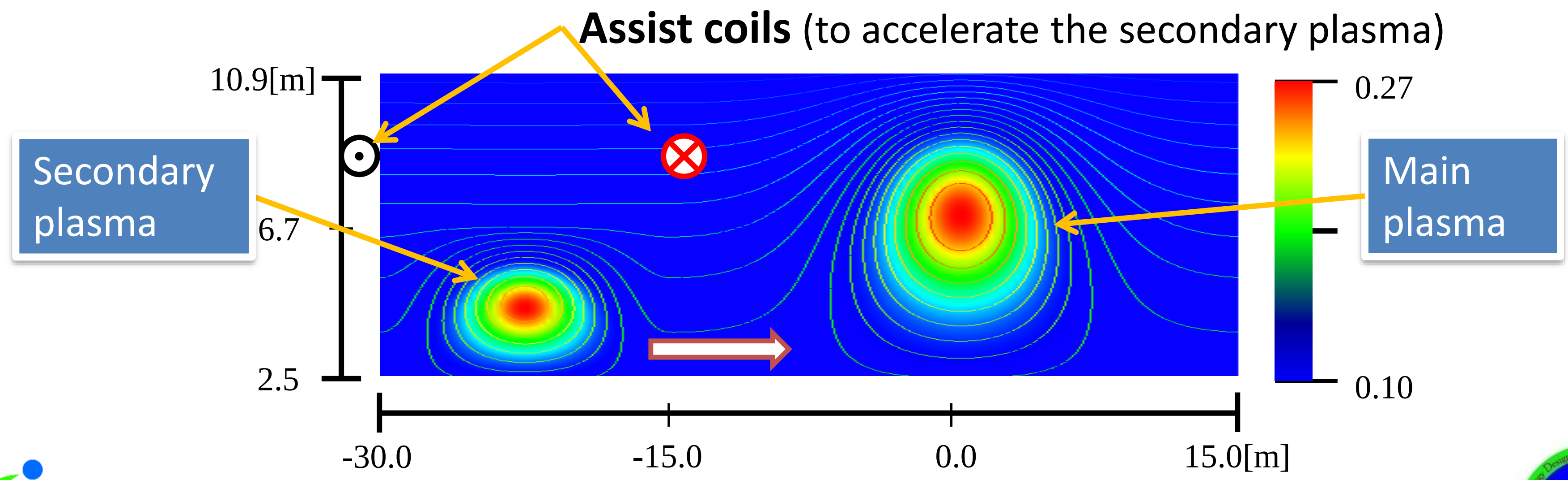
→ Merging fueling method[1]

[1] O. Mitarai *et al*., Fusion Eng. Des. **109-111** Part B, 1365 (2016).

Feasibility study

3D MHD simulation code -MIPS[2]-

[2] Y. Todo *et al*., PFR **5**, S2062 (2010).



Initial poloidal flux and pressure profiles of ST plasmas

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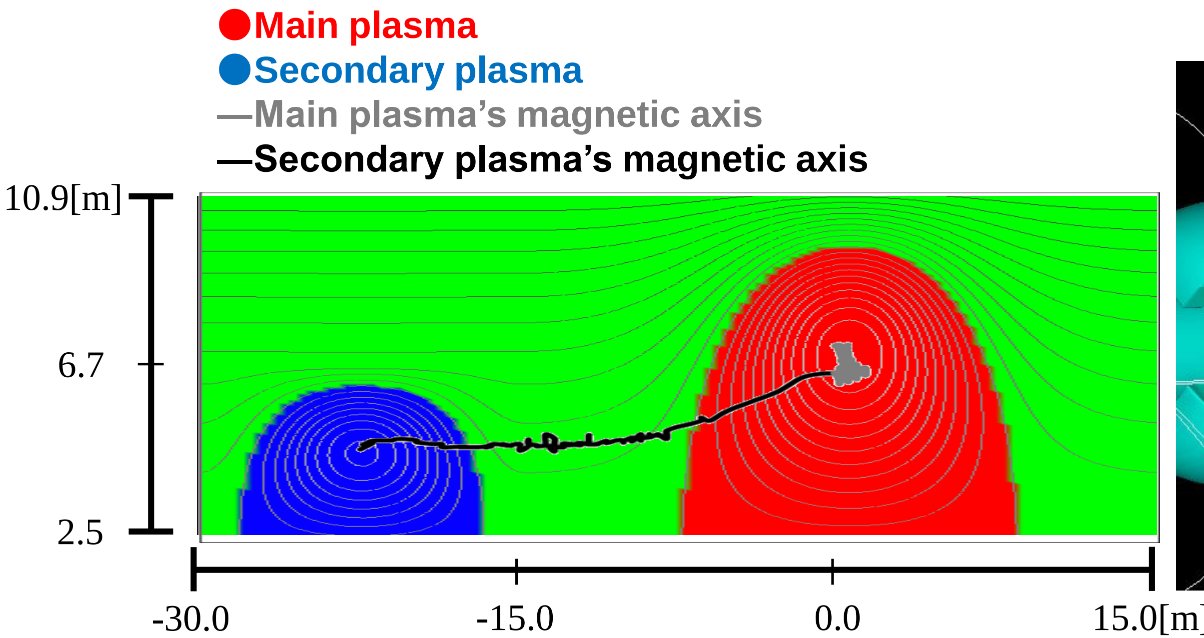
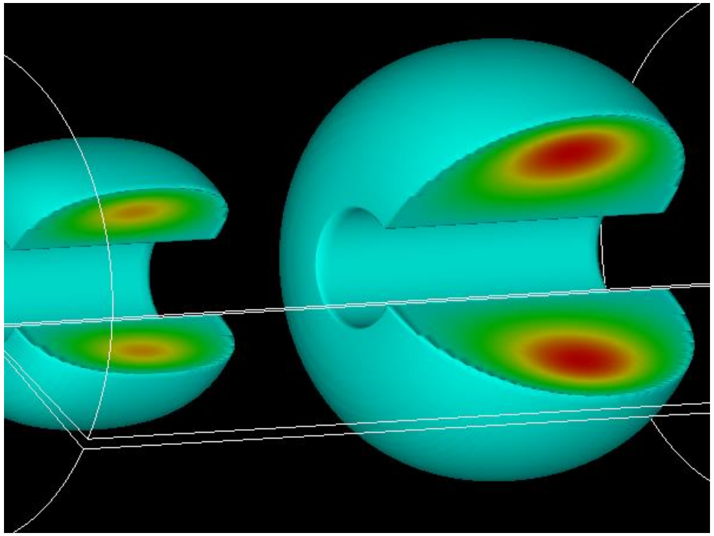
Translation and merging process



Trace of two ST plasmas



3D poloidal flux structure

1. Collision occurs at 260 t_A, and then the reconnection process starts.
2. During 600-630 t_A the magnetic axes of two plasmas approach rapidly, and the secondary plasma is absorbed into the main plasma.

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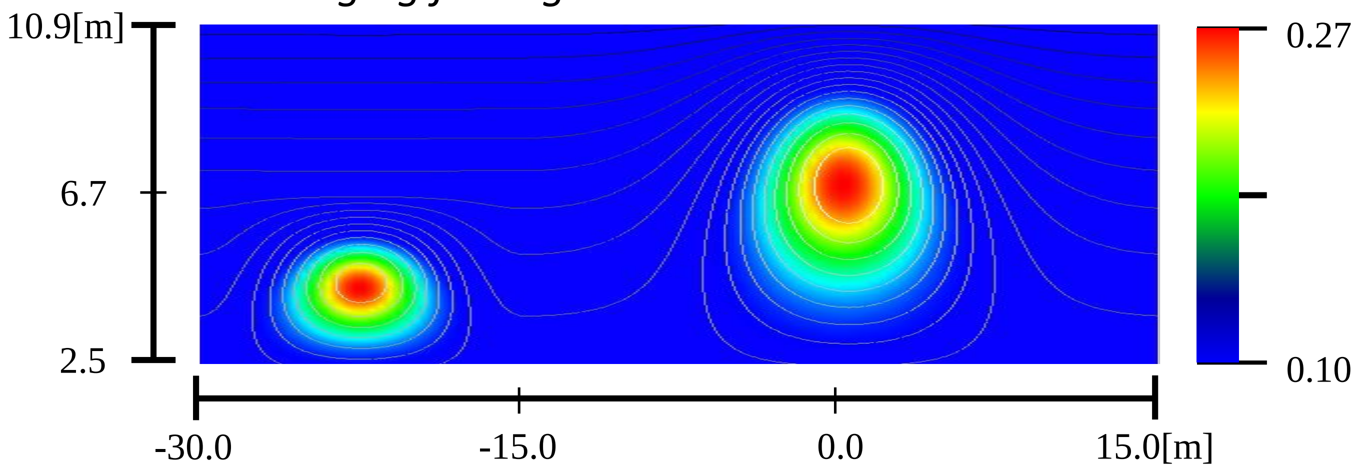
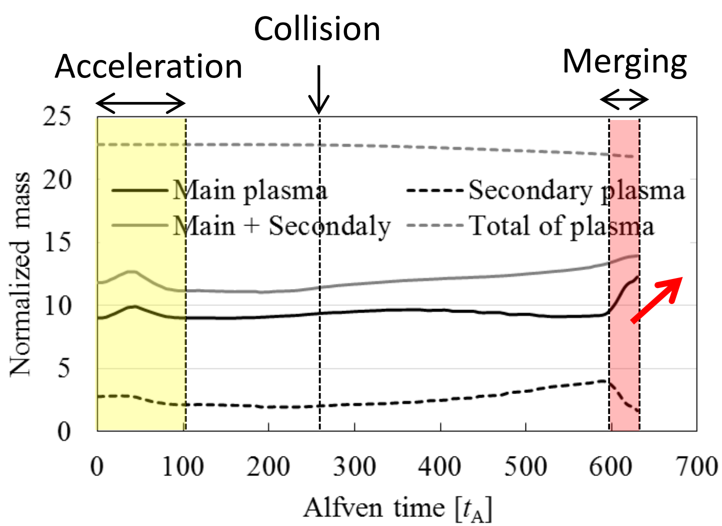
Core fueling and current drive

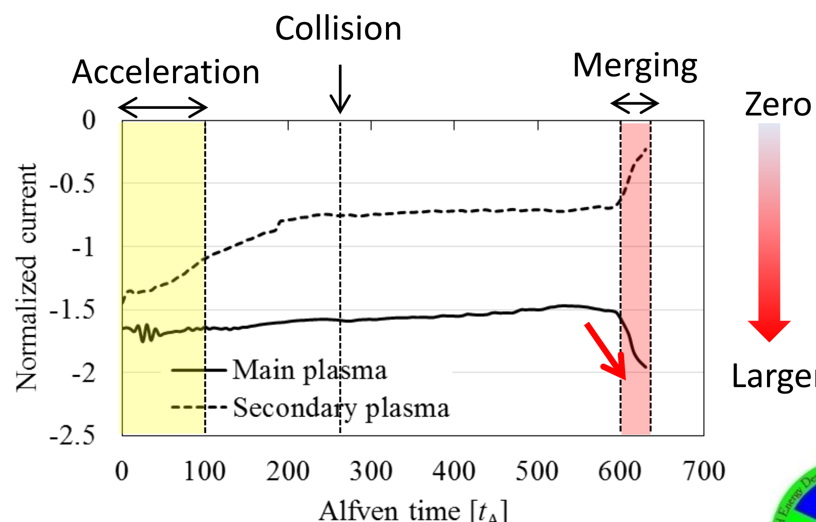
-Merging fueling and current drive will work-



2D plot of the plasma pressure on a poloidal cross-section



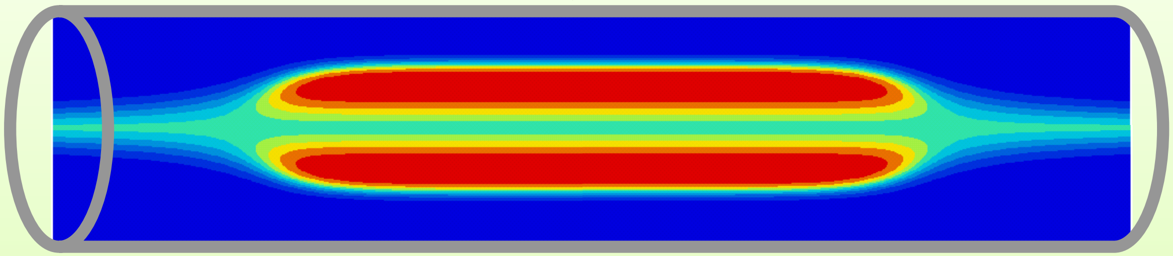
Particle



Current

Can we produce FRC by giving the pressure gradient?

Formation of FRC: Field Reversed Theta Pinch (FRTP) method



$$\vec{j} \times \vec{B} = \nabla p$$

Diamagnetic current — Pressure gradient

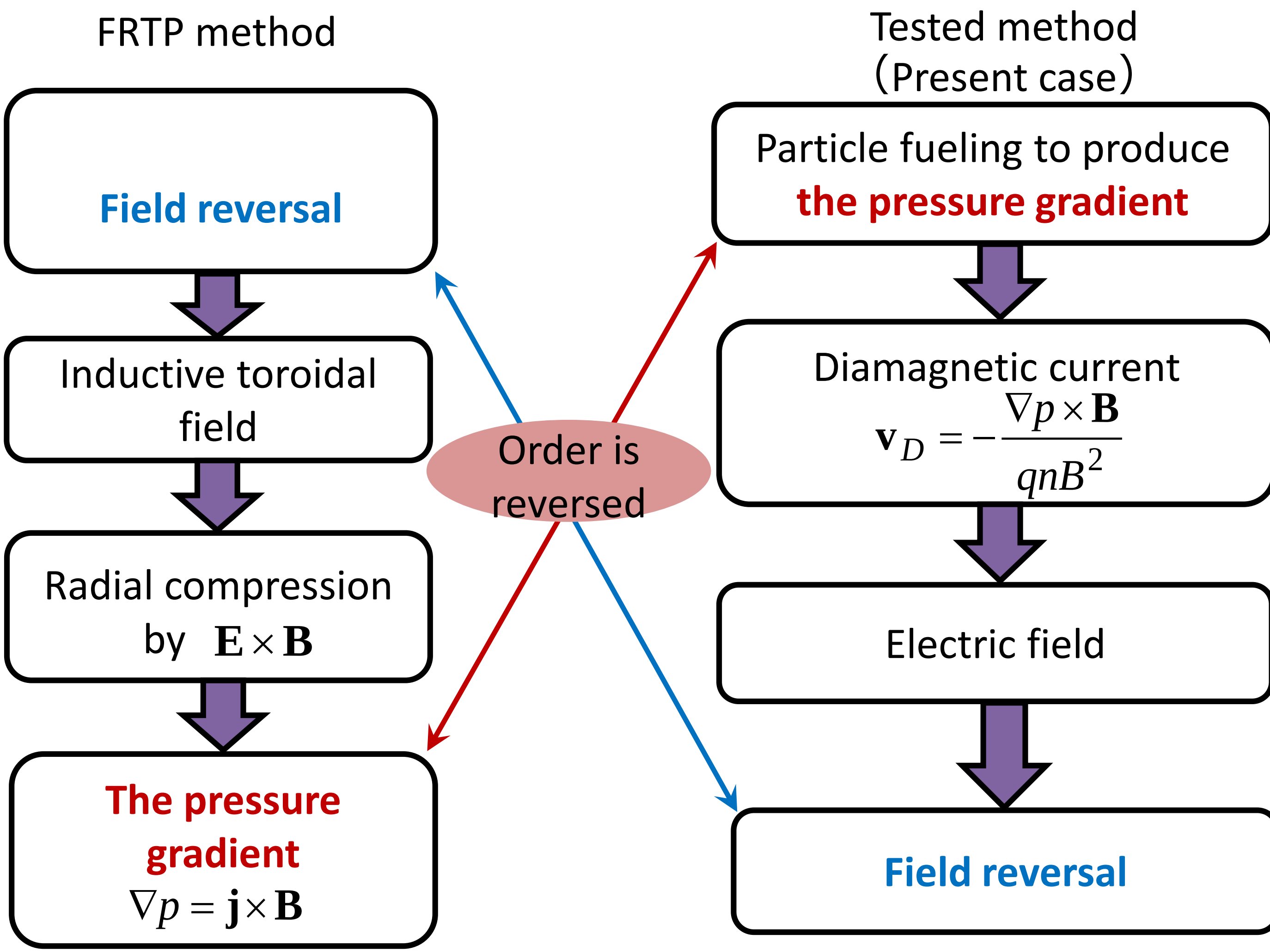
Is it possible to generate an FRC by the following scenario?

The pressure gradient
→ the diamagnetic current
→ a field-reversed configuration

3D hybrid simulation

Goal We clarify the possibility to occur field reversal without field-reversed the pinch method by using 3D hybrid simulation

Difference of sequence



Hybrid simulation model

Equation of motion for α species

$$m_\alpha \frac{\mathrm{d}\mathbf{v}_\alpha}{\mathrm{d}t} = q_\alpha(\mathbf{E} + \mathbf{v}_\alpha \times \mathbf{B}) - \sum_\beta m_\alpha \nu_{\alpha\beta}(\mathbf{v}_\alpha)(\mathbf{v}_\alpha - \mathbf{u}_\beta)$$

Collisional pitch angle scattering can be also considered by the Monte-Carlo method

Equation of motion for massless electron fluid

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

$$\mathbf{R}_\mathrm{ei} = -\mathbf{R}_\mathrm{ie} = \int m_\mathrm{i}\nu_\mathrm{ie}(\mathbf{v}_\mathrm{i} - \mathbf{u}_\mathrm{e}) f_i(\mathbf{v}_\mathrm{i})\mathrm{d}\mathbf{v}_\mathrm{i}$$

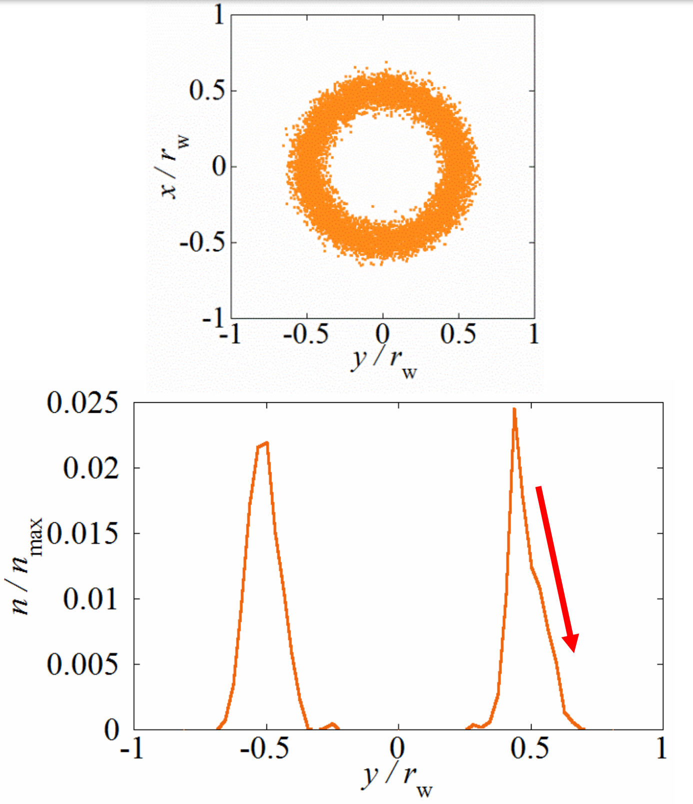
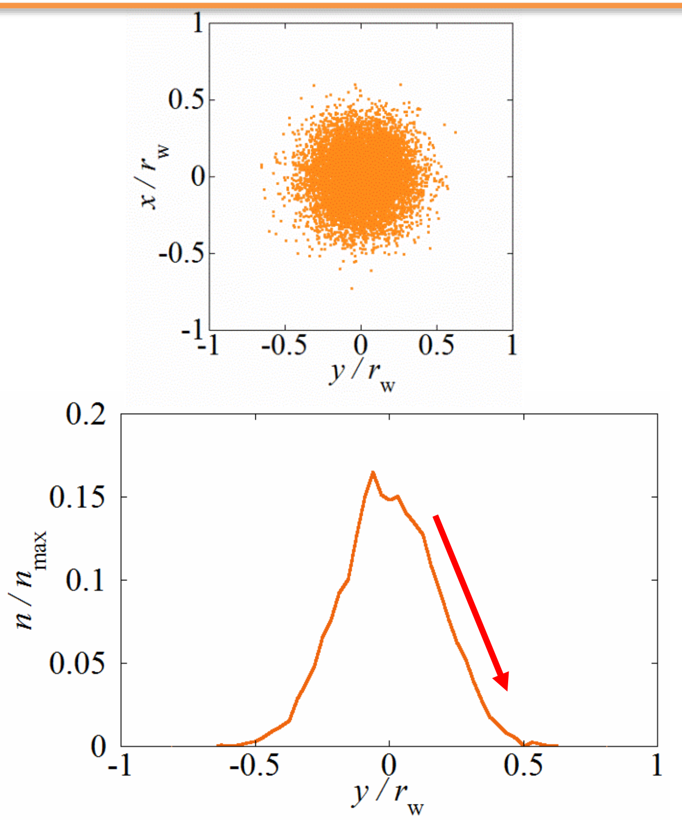
Faraday's law $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$ Ampere's law $\mu_0 \mathbf{j} = \nabla \times \mathbf{B}$

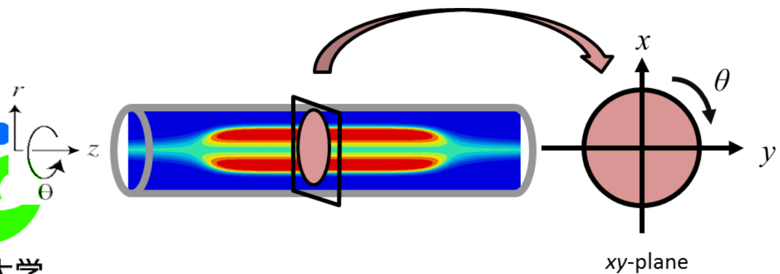
Definition of current density $\mathbf{j} = en_\mathrm{e}(\mathbf{u}_\mathrm{i} - \mathbf{u}_\mathrm{e})$

Thermal energy equation for electron fluid

$$\frac{\partial p_\mathrm{e}}{\partial t} + \gamma\, p_\mathrm{e}(\nabla \bullet \mathbf{u}_\mathrm{e}) + \mathbf{u}_\mathrm{e} \bullet \nabla p_\mathrm{e} = (\gamma - 1)(\mathbf{u}_\mathrm{e} - \mathbf{u}_\mathrm{i}) \bullet \mathbf{R}_\mathrm{ei}$$

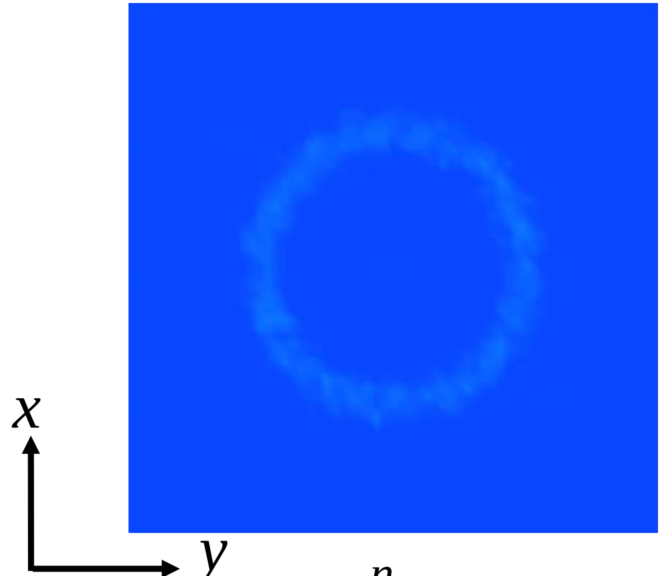
Tested particle fueling model

Ring fueling	Circular fueling
	

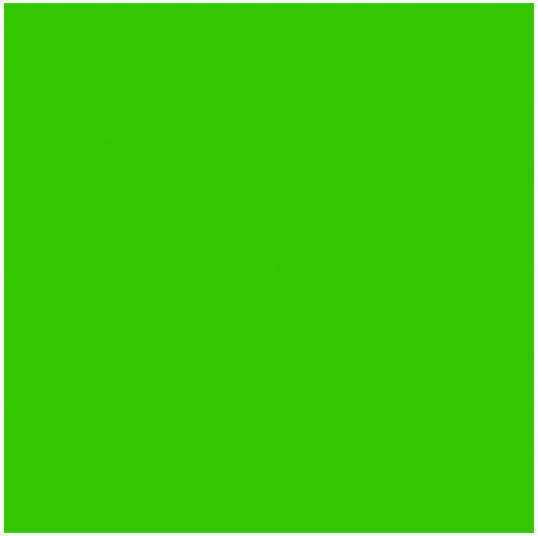


- Particle loading is done by using pseudo random number
- Normal distribution is used for spatial profile
- Velocity distribution is Maxwellian

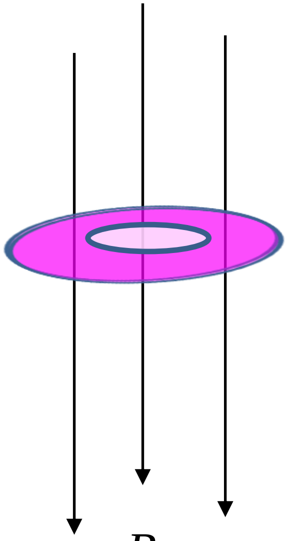
Ring fueling results



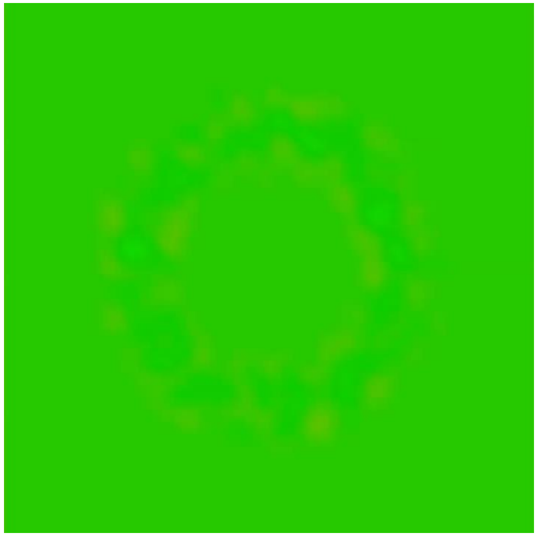
n_i



j_θ



B_z



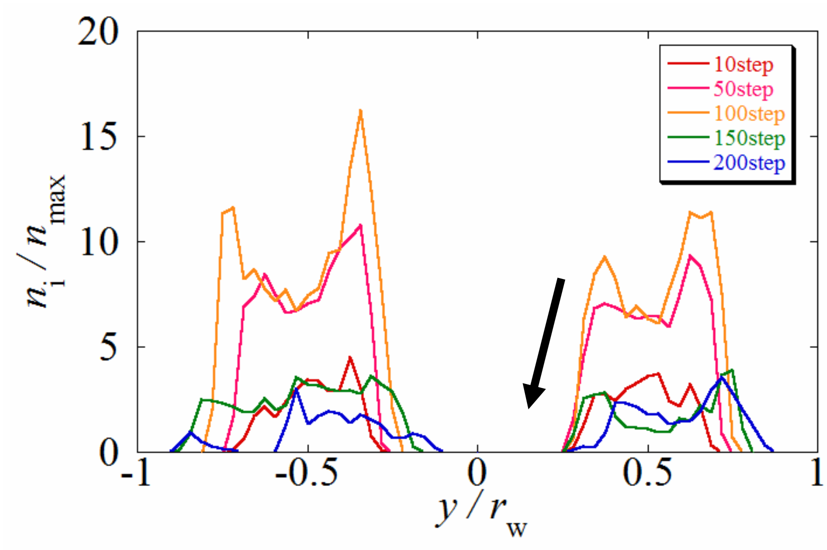
B

External field: B_{ex}=0.4 T
Ion temperature: T_i=50eV
Ion fueling time 5 μs
Calculation time 15 μs

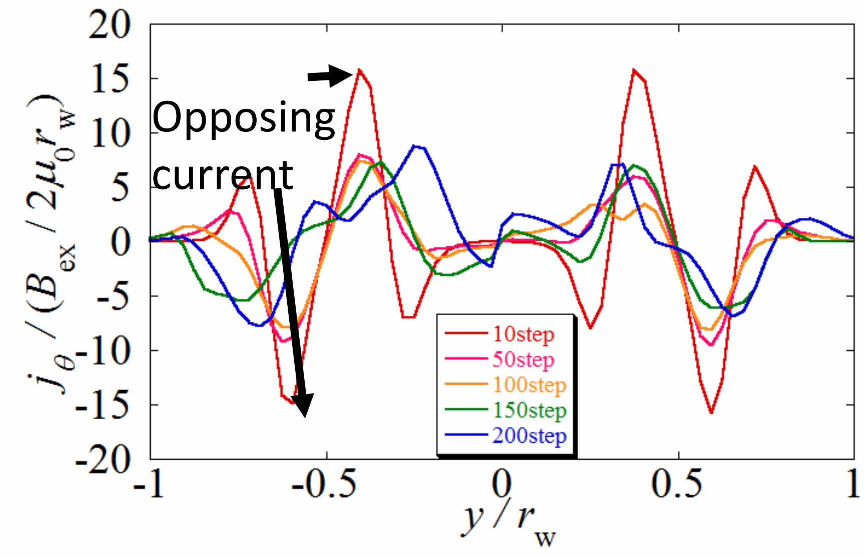
As soon as fueling stops, ring configuration destroys due to axial diffusion.

Ring fueling results

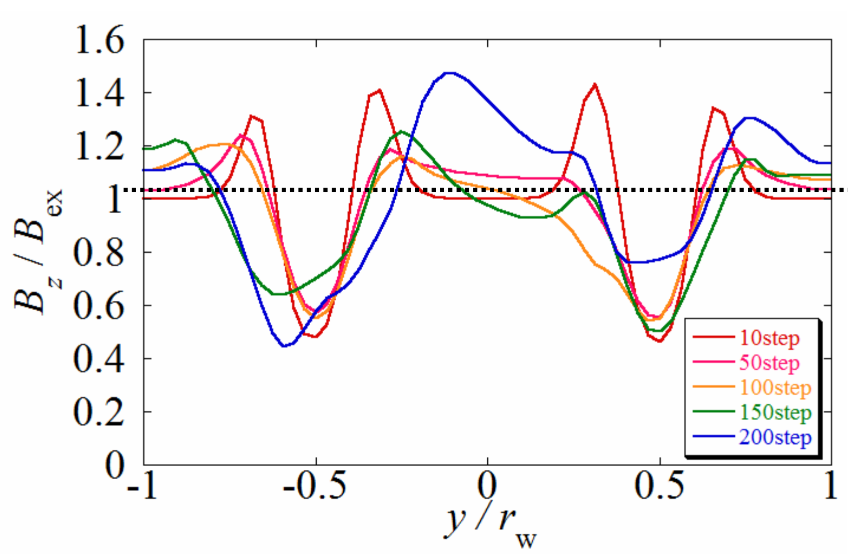
1step $=5.0\times10^{-8}$[s]



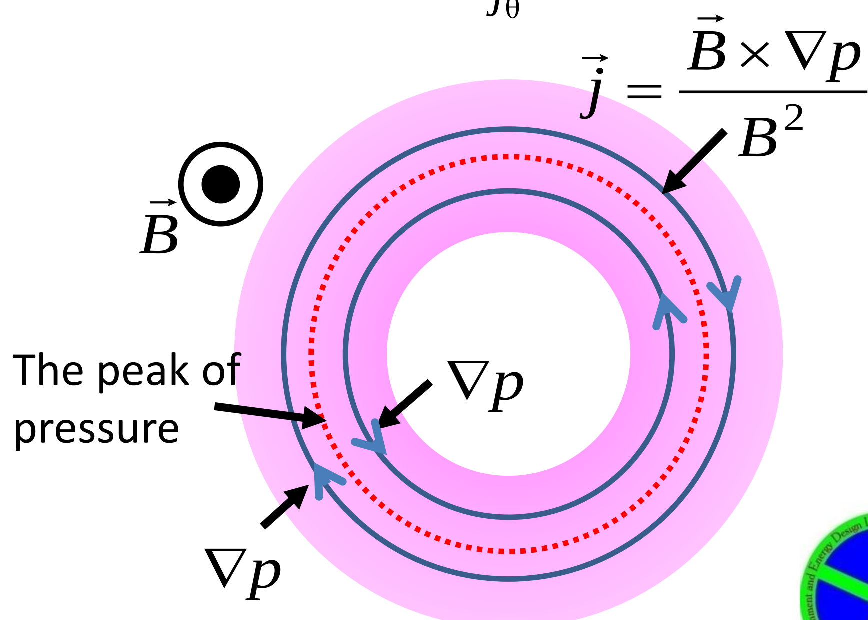
n_i



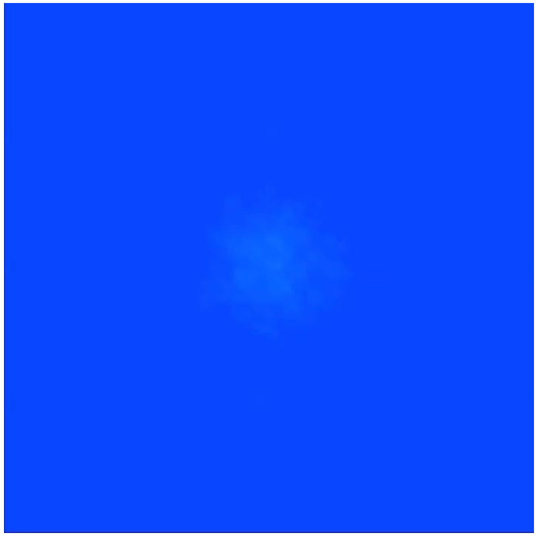
j_θ



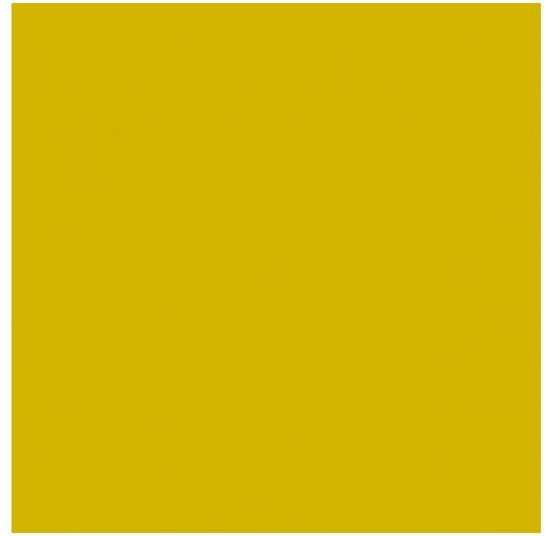
B_z



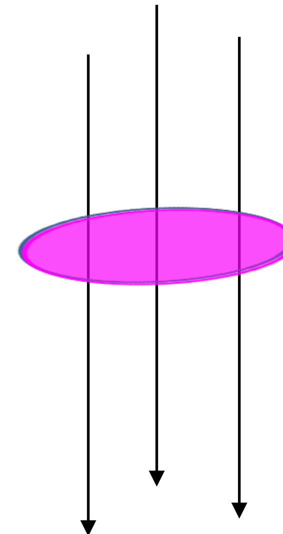
Circular fueling



n_i



j_θ



B_z

B_z

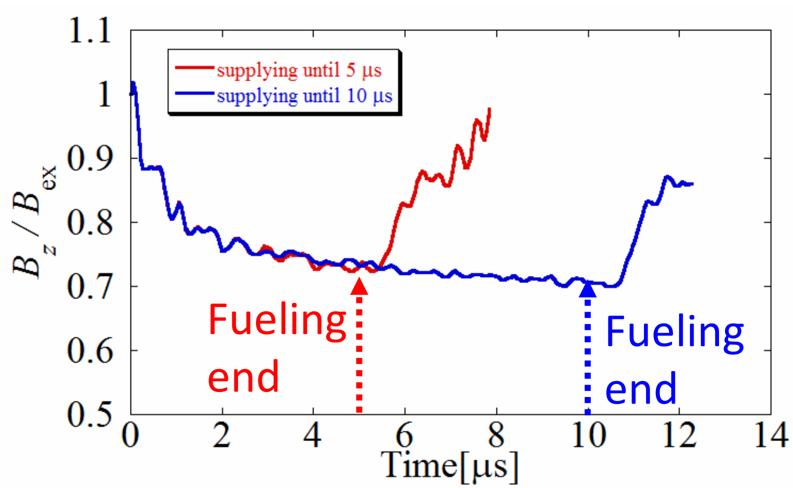
External field: B_{ex}=0.4 T
Ion temperature: T_i=50eV
Ion fueling time 5 μs
Calculation time 10 μs

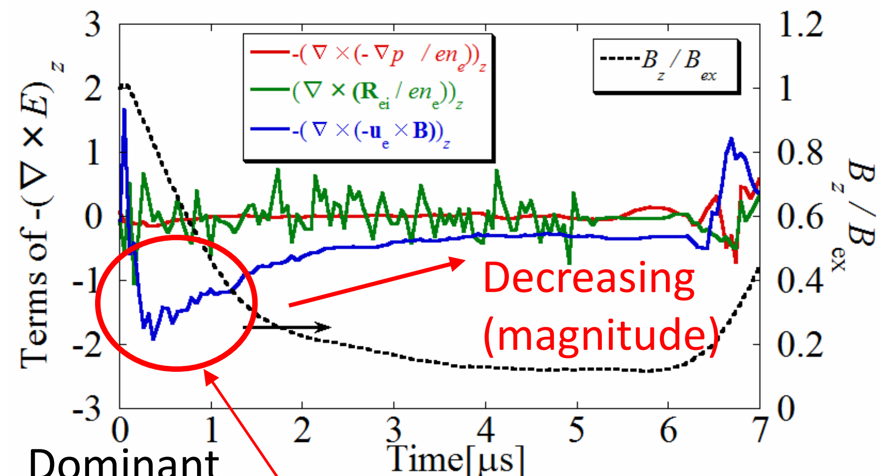
As soon as fueling stops, ring configuration destroys due to axial diffusion and instability.

Magnetic field weakening

External field: B_{ex}=0.4 T
Ion temperature: T_i=50eV
Electron temperature: T_e=50eV
Ion fueling rate: S=1.4*10^{26}[1/s]

External field: B_{ex}=0.4 T
Ion temperature: T_i=50eV
Electron temperature: T_e=50eV
Ion fueling rate: S=1.4*10^{27}[1/s]





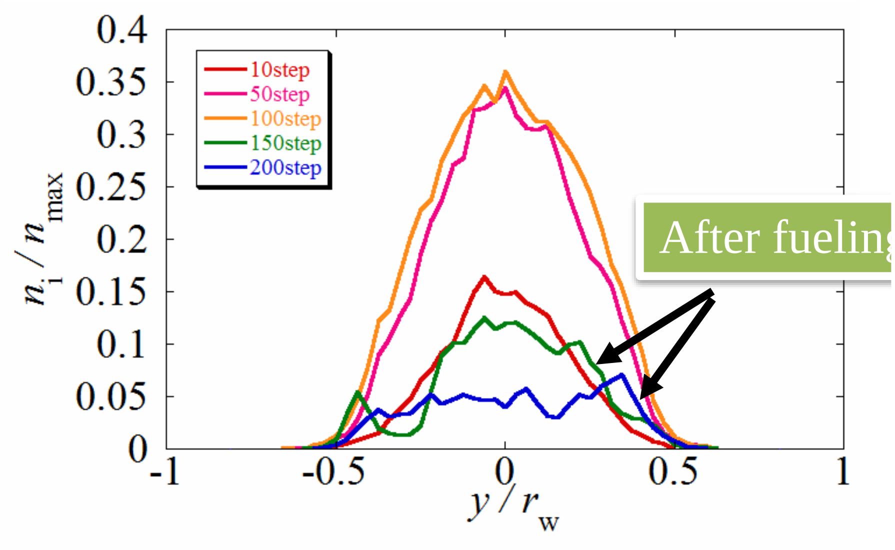
Dominant component

$$\mathbf{E} = \boxed{-\mathbf{u}_e \times \mathbf{B}} - \frac{\nabla p_e}{en_e} + \frac{\mathbf{R}_{ei}}{en_e}$$

1. Magnetic field weakening stops just after the end of fueling.
2. As the ion fueling rate increases, magnetic field weakening enhances. However, it can never produce the field-reversal.

1step =5.0×10^-8[s]

Circular fueling results



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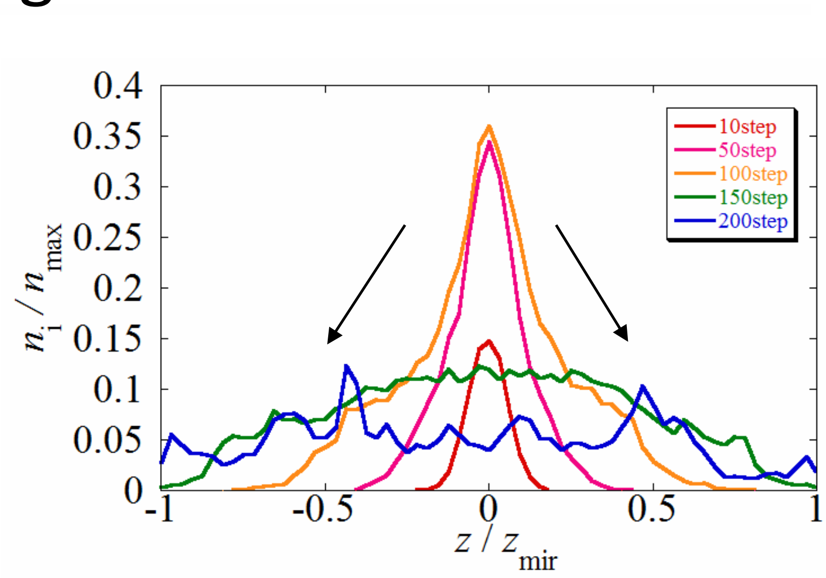
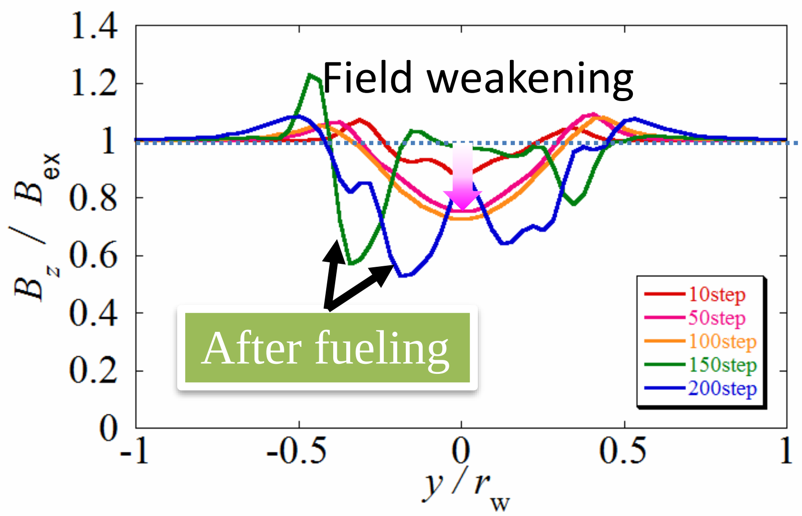


Dispersion by axial diffusion



B_z

- Due to no field-reversal and no magnetic reconnection event, the circular plasma configuration destroys by the rapid axial diffusion.

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Summary

- 2D Resistive MHD / Hall MHD simulation has been carried out to study two FRC collision process.
- 3D MHD simulation has also been done for ST merging. After a ballooning instability, the merging process is observed.
- From our high-resolution MHD simulation, the following effects are essential to reproduce FRC merging
  - ✓ Cross-field thermal conductivity
  - ✓ Anomalous resisitivity effect
    = requirement of full-particle simulation
- We can not succeed in producing an FRC plasma by giving only the pressure gradient.

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