MHD simulation on pellet injection in LHD

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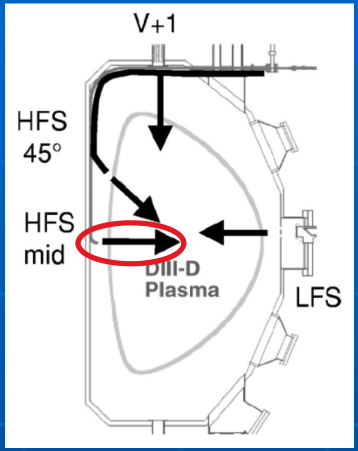
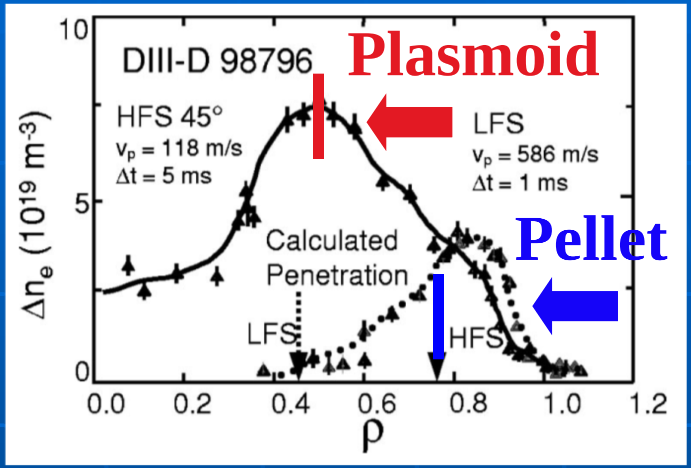
Introduction

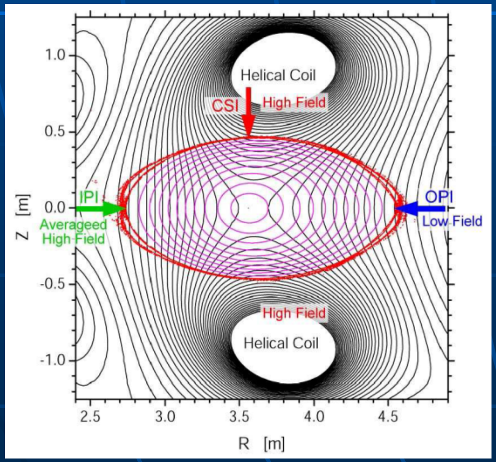
1. It is observed in tokamak experiments that the ablation cloud drifts to the lower field side.

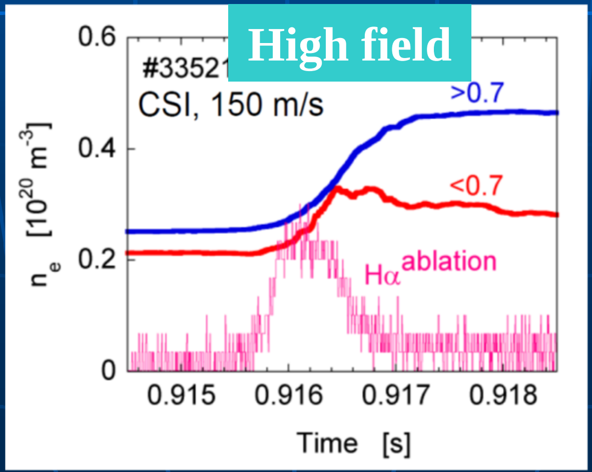


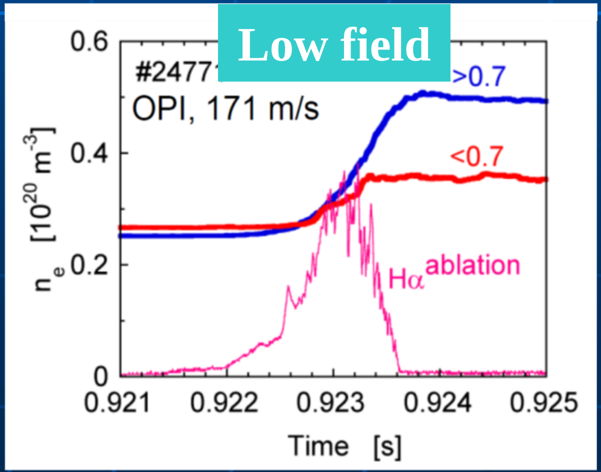


Baylor, Phys. Plasmas **7**, 1878 (2000)

2. The ablation cloud dose not approach the core plasma in LHD even if the pellet is injected from the high field side.







Sakamoto, 29th EPS conference on Plasma Phys. and Contr. **26B**, P-1.074 (2002)

The other works on motion of the ablation cloud.

Topics : Drift motion

1. P.B.Parks and L.R.Baylor, Phys. Rev. Lett. 94, 125002 (2005).
   - Theory, no resistivity, constant B-field
2. R.Samtaney et al., Comput. Phys. Commun. 164, 220 (2004).
   - Ideal MHD simulation, pellet is point source with ablation model
3. V.Rozhansky et al., Plasma Phys. Control. Fusion 46, 575 (2004).
   - No resistivity, constant B-field, pellet is point source, mass and moment equations
4. H.R.Strauss and W.Park, Phys. Plasmas 7, 250 (2000).
   - Ideal MHD simulation, pellet is plasmoid, no heating

1. In order to clarify the drift motion in LHD plasmas, MHD simulation has been carried out.
2. The plasmoid motions are evaluated in various configurations (LHD, tokamak, RFP and vacuum field) in order to obtain the universal understanding.

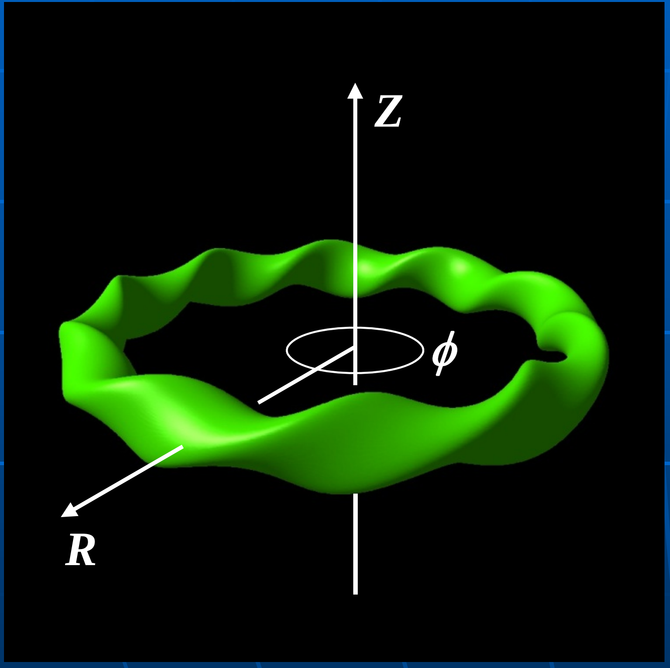
CAP code and numerical scheme.

1. **We are developing the CAP code in order to investigate the dynamics of the pellet ablation. (Multi-phase code)**
   R. Ishizaki et al, Phys. Plasmas, 11 4064 (2004).

2. **MHD version of the code has been developed in order to investigate the plasmoid motion in torus plasmas.**
   R. Ishizaki and N. Nakajima, J. Plasma and Fusion Res. SERIES 8, 995 (2009).

3. **A plasmoid induced by pellet ablation has locally and extremely large perturbation, namely nonlinear one, in which the plasma beta is > 1. Therefore, Cubic-interpolated pseudoparticle (CIP) method is used in the code in order to solve such a large perturbation stably.**
   T. Yabe and P.Y. Wang, J. Phys. Soc. Jpn 60, 2105 (1991).

Geometry and basic equations.



$$\frac{d\rho}{dt} = -\rho \nabla \cdot \boldsymbol{u}$$

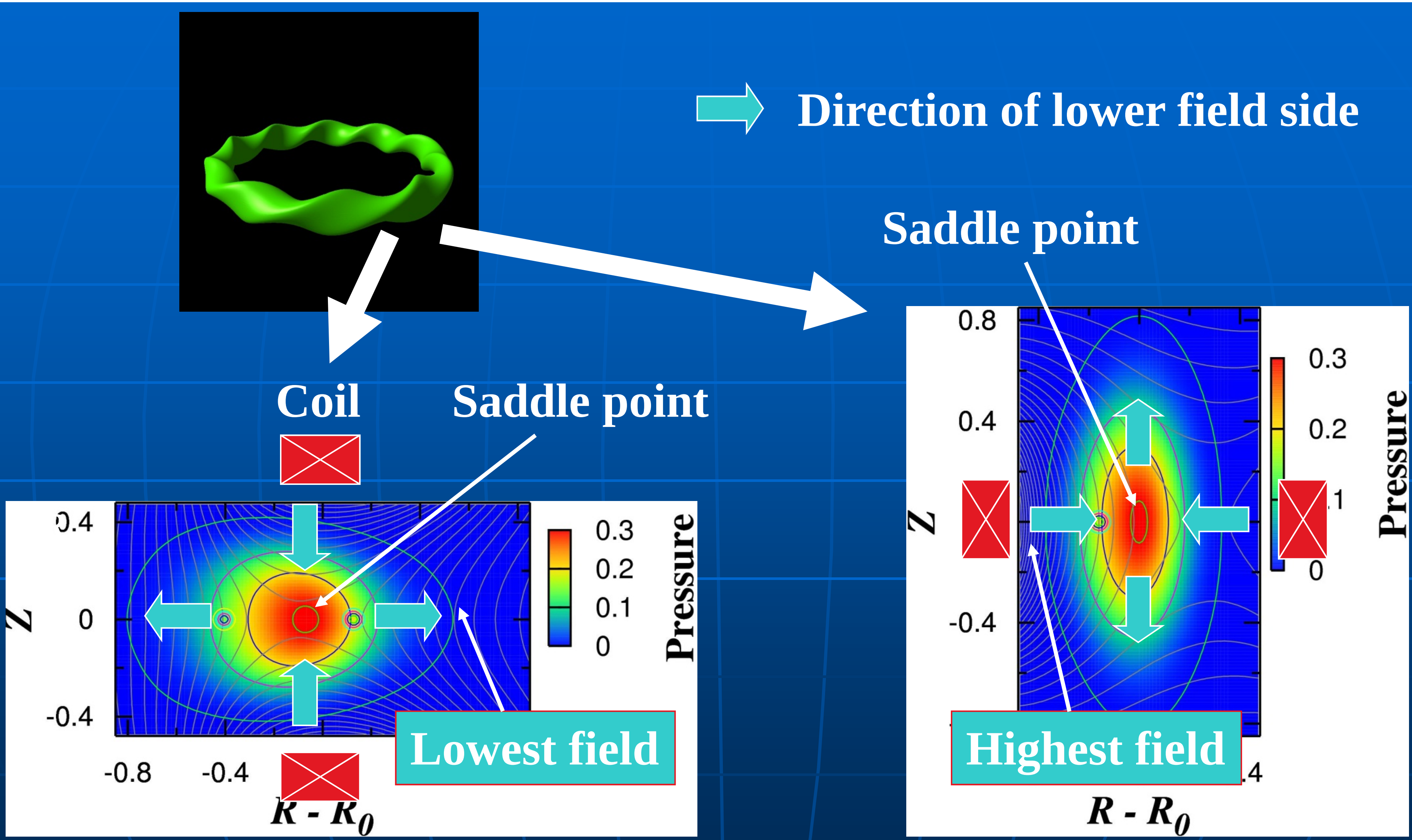
$$\rho \frac{d\boldsymbol{u}}{dt} = -\nabla p + \frac{1}{\mu_0}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + \nu\rho\left(\frac{4}{3}\nabla(\nabla \cdot \boldsymbol{u})^2 - \nabla \times \boldsymbol{\omega}\right)$$

$$\frac{dp}{dt} = -\gamma p \nabla \cdot \boldsymbol{u} + (\gamma - 1)\left[\nu\rho\omega^2 + \frac{4}{3}\nu\rho(\nabla \cdot \boldsymbol{u})^2 + \eta J^2 + H\right]$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B} - \eta \boldsymbol{J})$$

$$\boldsymbol{\omega} = \nabla \times \boldsymbol{u}$$

Poloidal cross sections in LHD.

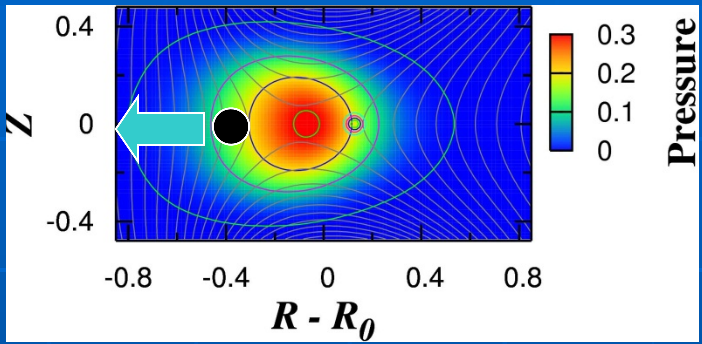


Horizontally elongated cross section

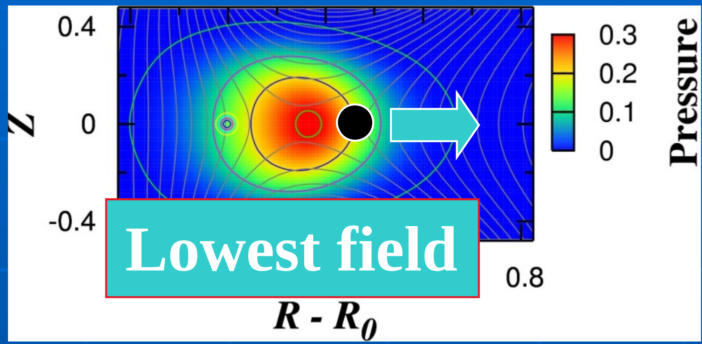
Vertically elongated cross section

Configurations and plasmoid locations.

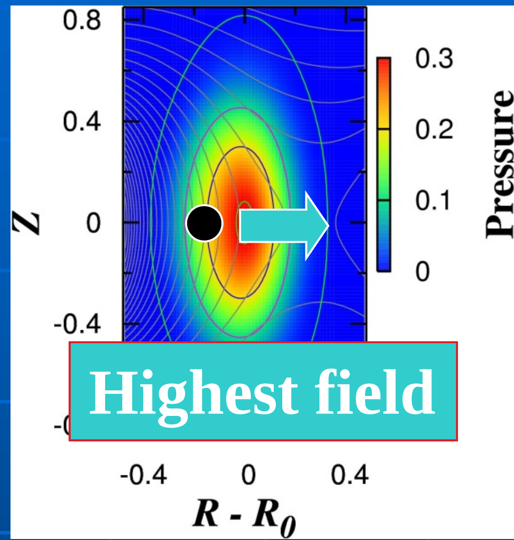
LH-i : LHD



LH-o : LHD

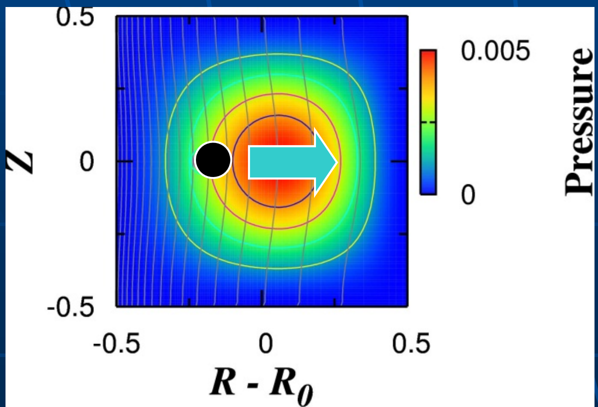


LV-i : LHD

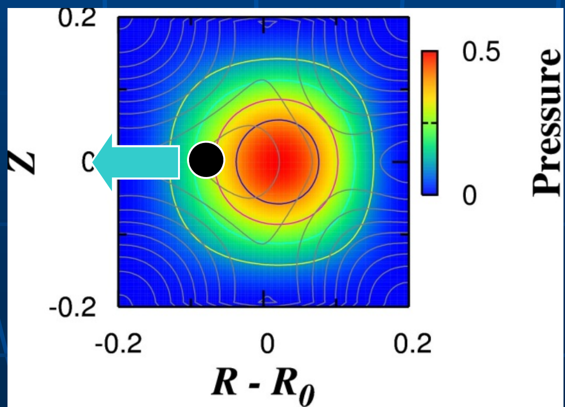


Direction of lower field side

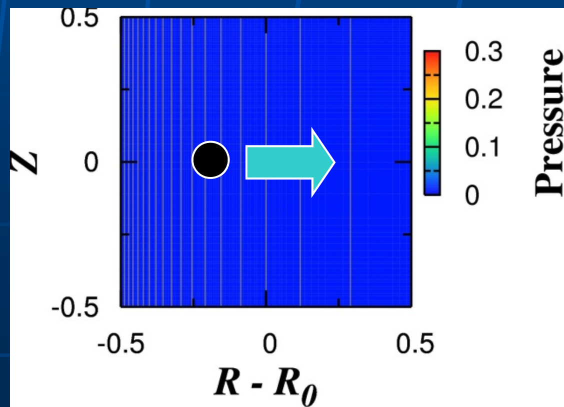
T-i : Tokamak



R-i : RFP

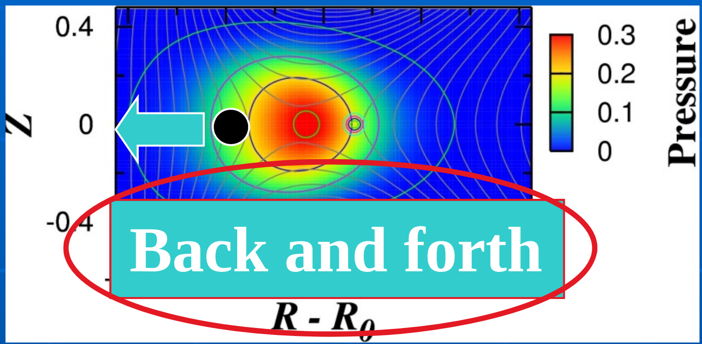


V : Vacuum field

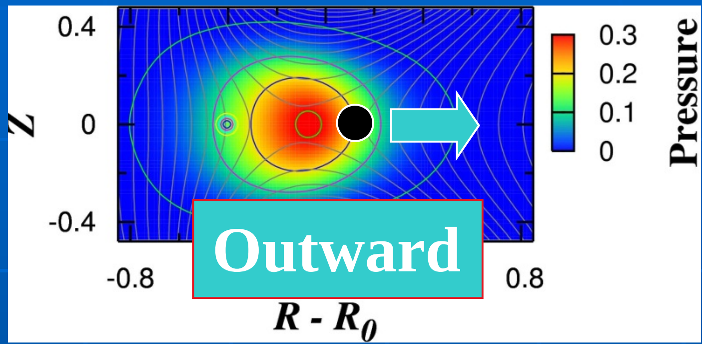


Simulation results.

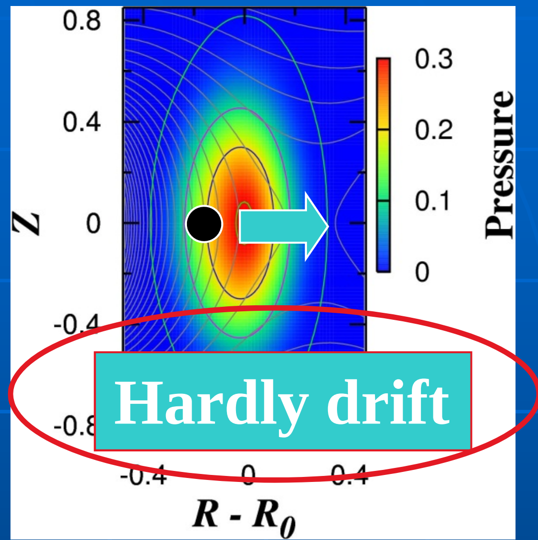
LH-i



LH-o

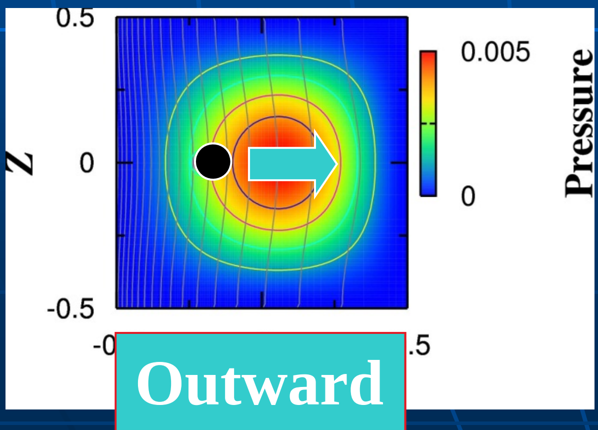


LV-i

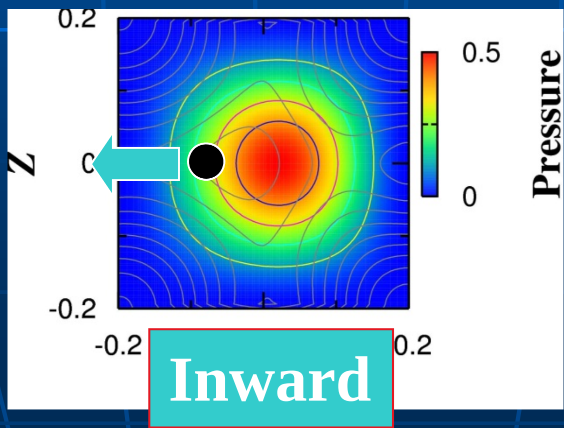


→ Direction of lower field side

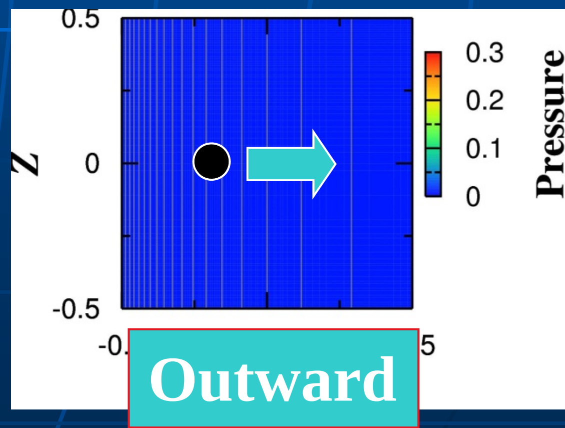
T-i



R-i



V



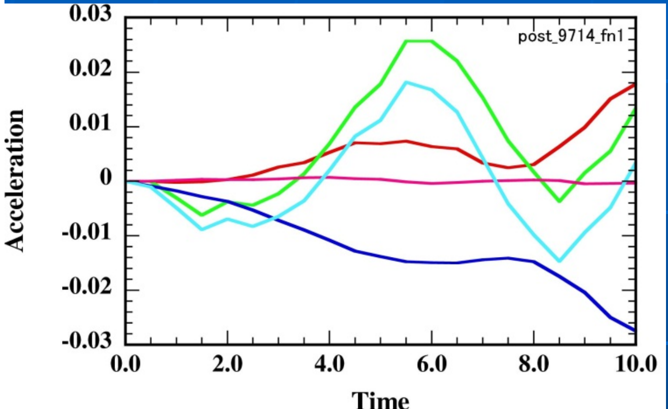
Outward/inward : positive/negative direction of major radius

$B_0 \cdot \nabla B_1$ is dominant among forces in all cases.

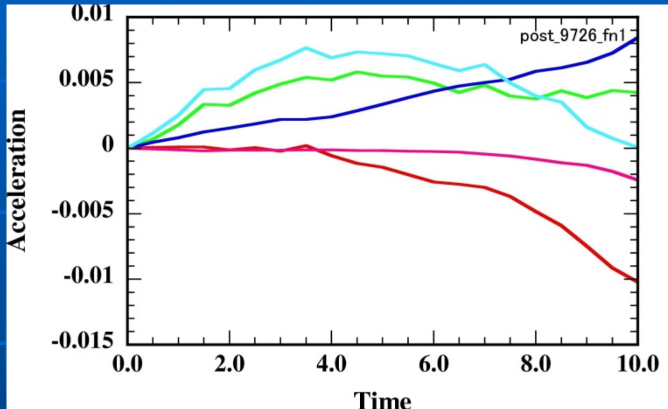
$$F_1 = -\nabla\left(p_1 + B_0 \cdot B_1 + B_1^2/2\right) + B_0 \cdot \nabla B_1 + B_1 \cdot \nabla B_0 + B_1 \cdot \nabla B_1$$

0 : equilibrium
1 : perturbation

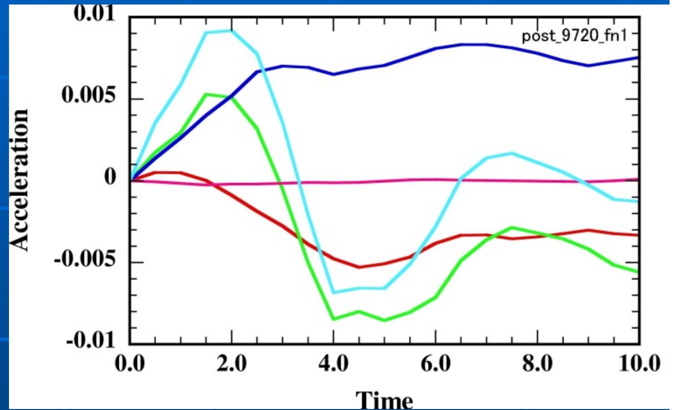
LH-i : LHD



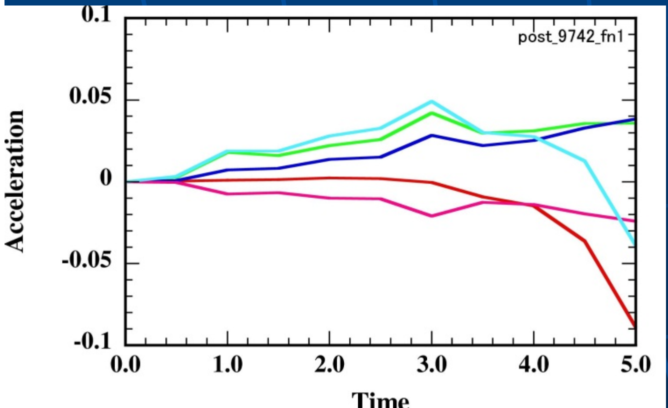
LH-o : LHD



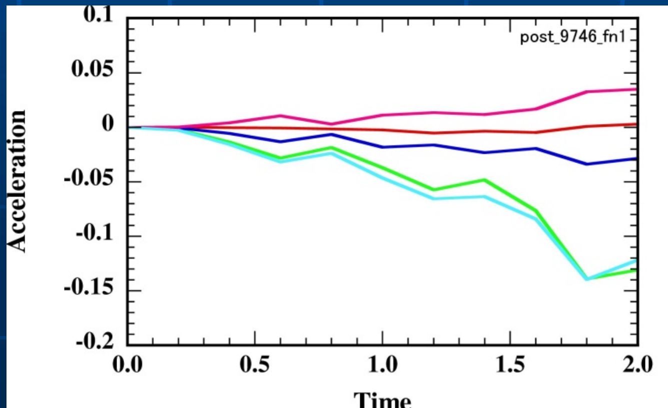
LV-i : LHD



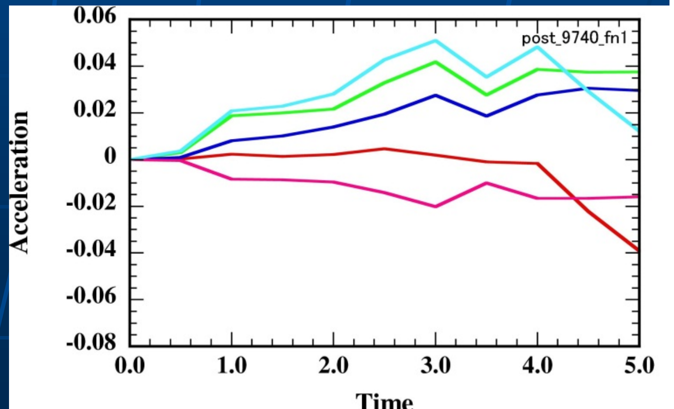
T-i : Tokamak



R-I : RFP



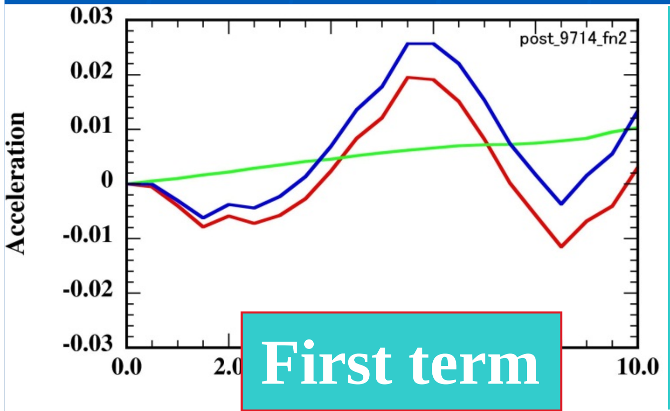
V : Vacuum field



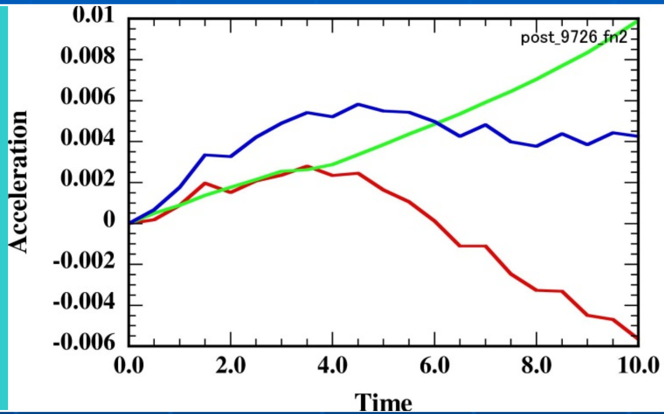
F_R consists of two forces.

$$F_R = e_R \cdot (B_0 \cdot \nabla B_1) = B_0 \cdot \nabla B_{R1} - \frac{B_{\varphi 0} B_{\varphi 1}}{R} = B_0 \frac{\partial B_{R1}}{\partial \ell} - \frac{B_{\varphi 0} B_{\varphi 1}}{R}$$

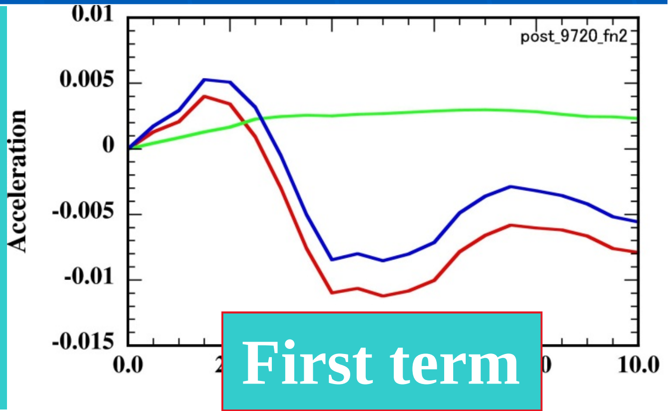
LH-i : LHD



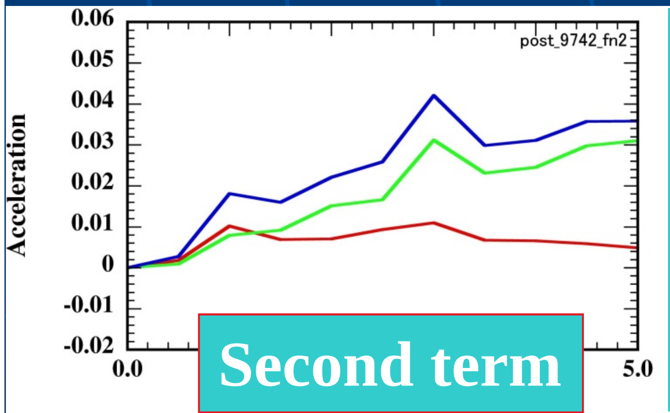
LH-o : LHD



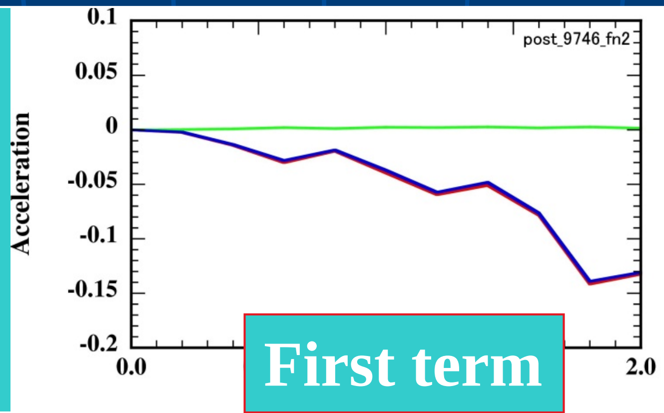
LV-i : LHD



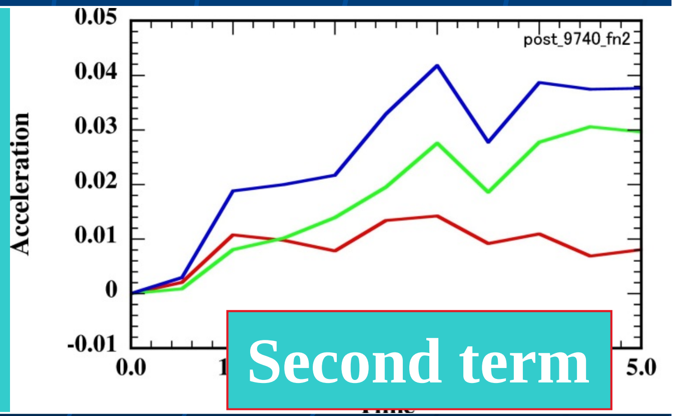
T-i : Tokamak



R-I : RFP



V : Vacuum field

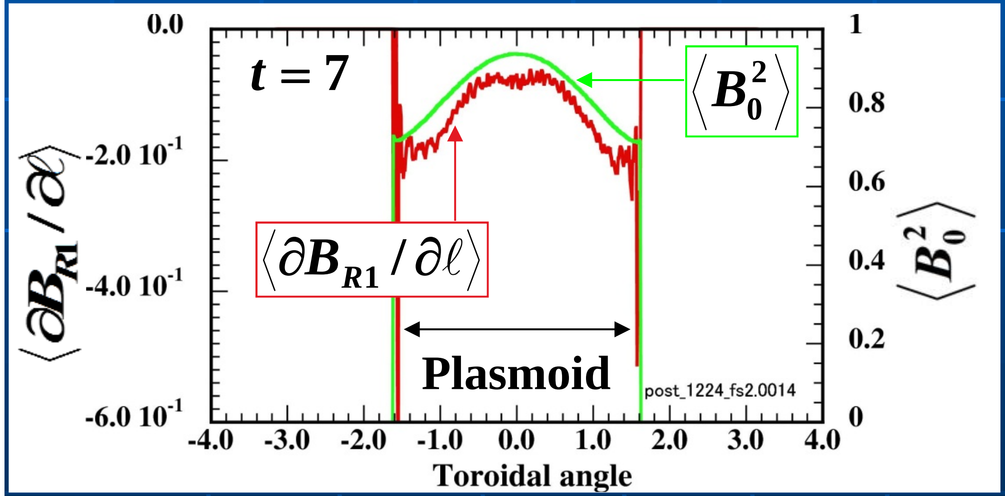


The first term in F_R depends on the connection length.

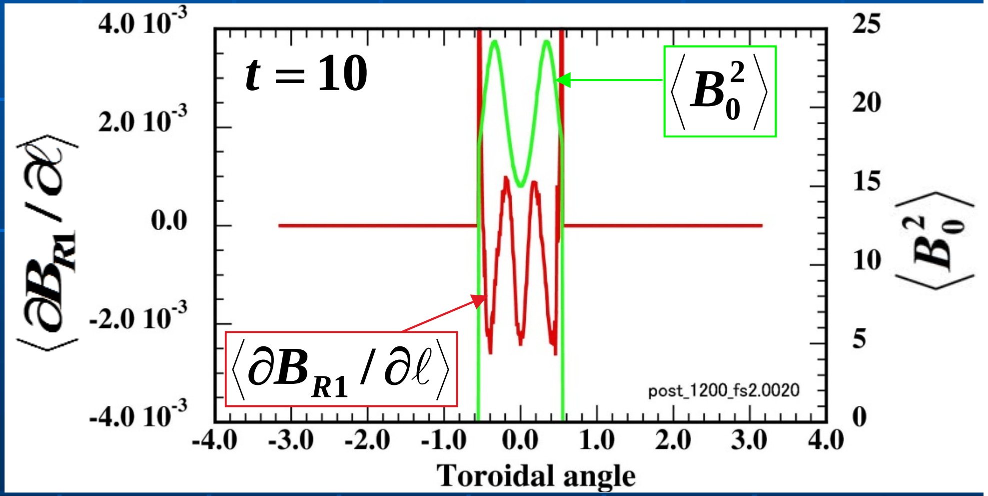
$$F_R = B_0 \cdot \nabla B_{R1} - \frac{B_{\varphi 0} B_{\varphi 1}}{R} = B_0 \frac{\partial B_{R1}}{\partial \ell} - \frac{B_{\varphi 0} B_{\varphi 1}}{R} \approx \frac{B_0 B_{R1}}{L_c} - \frac{B_{\varphi 0} B_{\varphi 1}}{R}$$

L_c : Connection length

T-i : Tokamak



LH-i : LHD



$\langle \ \rangle$: Average on the poloidal cross section within the plasmoid

A leading term in F_R is determined by the connection length.

$$F_R \approx \frac{B_0 B_{R1}}{L_c} - \frac{B_{\varphi 0} B_{\varphi 1}}{R}$$

L_c : Connection length

Tokamak

$$L_c \approx \pi q R \approx \pi R$$

$$F_R \approx -\frac{B_{\varphi 0} B_{\varphi 1}}{R} > 0$$

1/R force

Freidberg, Ideal MHD

LHD

$$L_c \approx \frac{\pi R}{\alpha M}$$

$$F_R \approx \begin{cases} B_0 B_{R1} / L_c & \text{LH-i, LV-i} \\ B_0 B_{R1} / L_c - B_{\varphi 0} B_{\varphi 1} / R & \text{LH-o} \end{cases}$$

Vacuum field

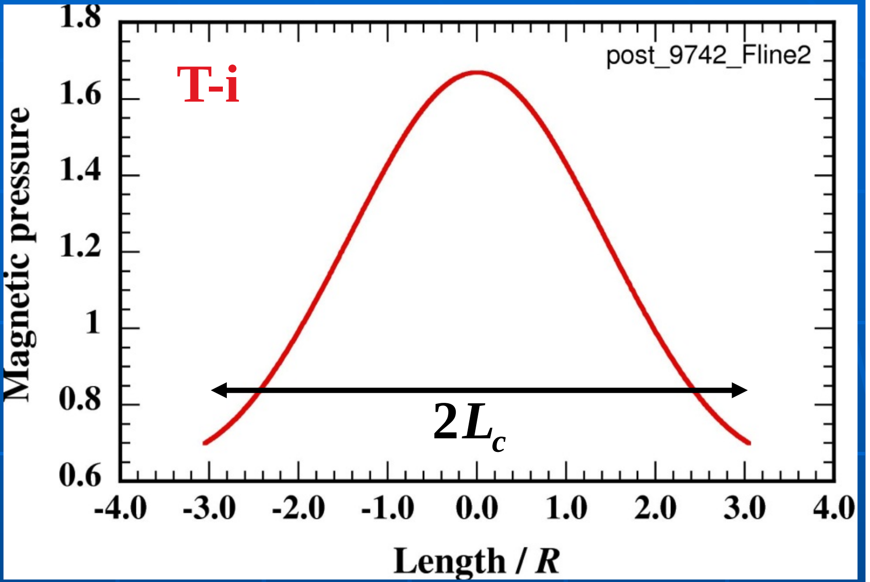
$$L_c \to \infty$$

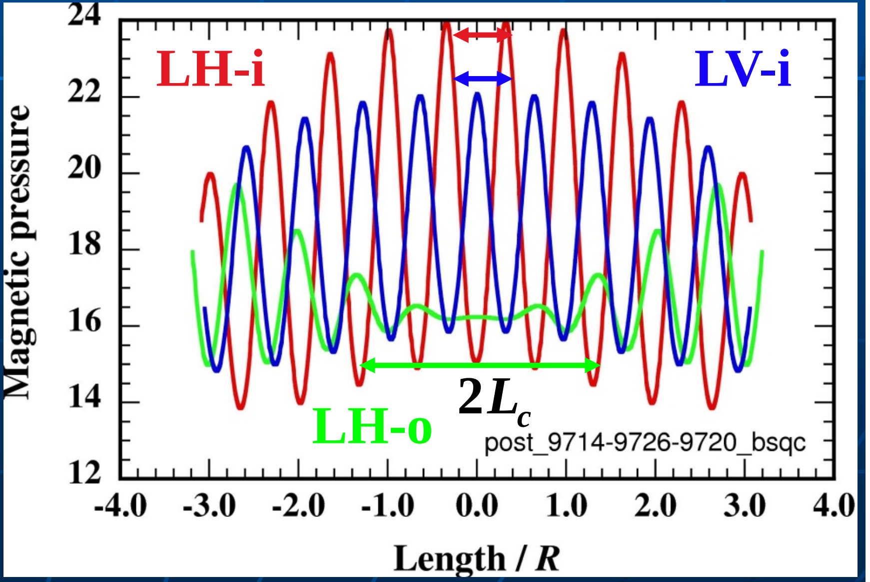
$$F_R \approx -\frac{B_{\varphi 0} B_{\varphi 1}}{R} \propto 1/R > 0$$

RFP-like

$$L_c \approx \pi \varepsilon R \approx \pi a$$

$$F_R \approx \frac{B_0 B_{R1}}{L_c} \propto 1/a$$

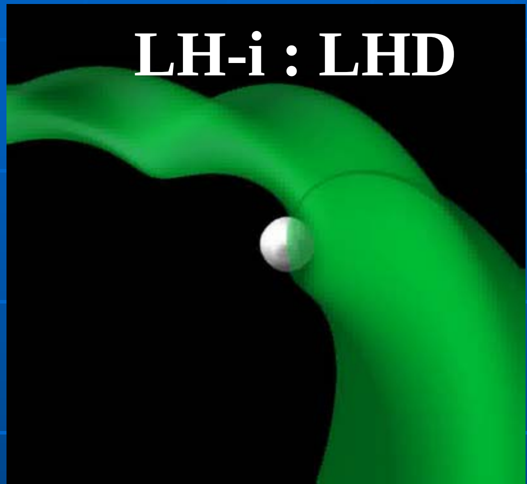




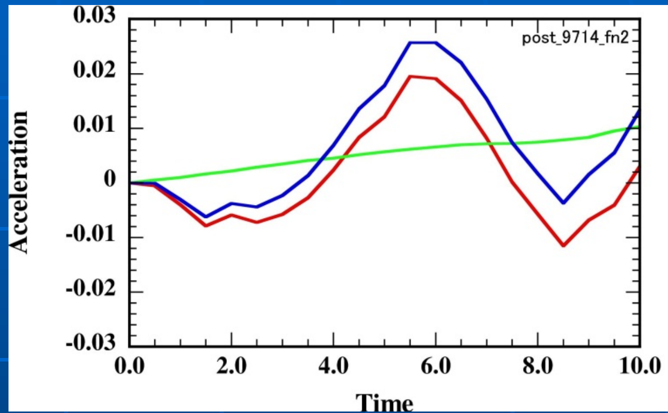
The dipole field is created around the plasmoid.

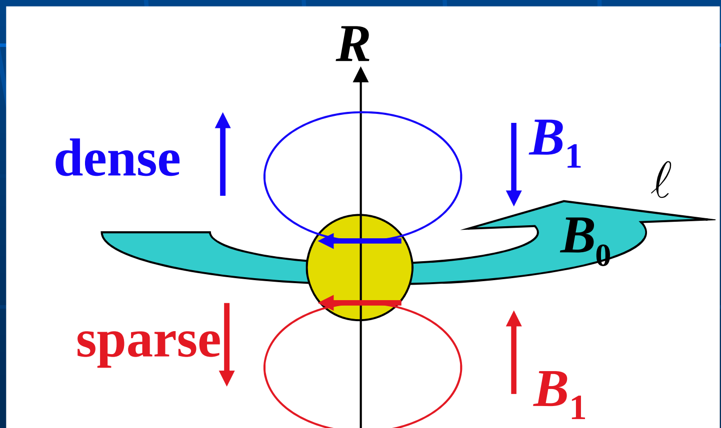
$$F_R = B_0 \frac{\partial B_{R1}}{\partial \ell} - \frac{B_{\varphi 0} B_{\varphi 1}}{R}$$

What is the first term?

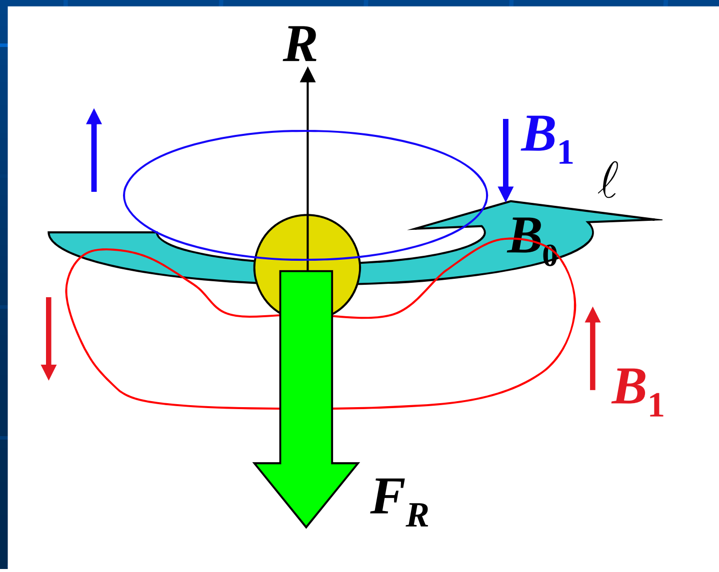


B_{R1} : **Perturbed magnetic field**



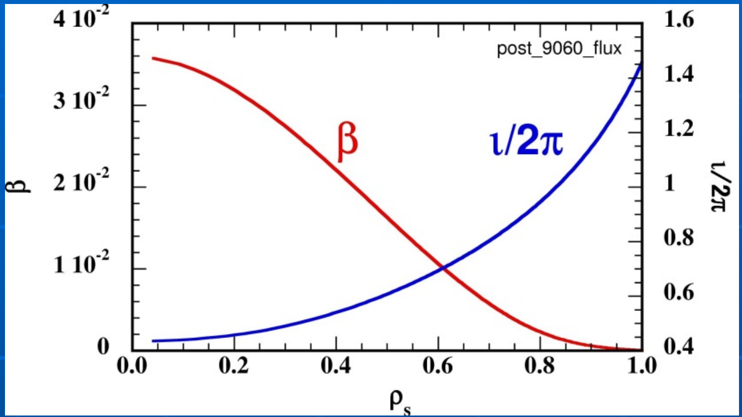


Perturbed magnetic field becomes Dipole field.



Initial conditions.

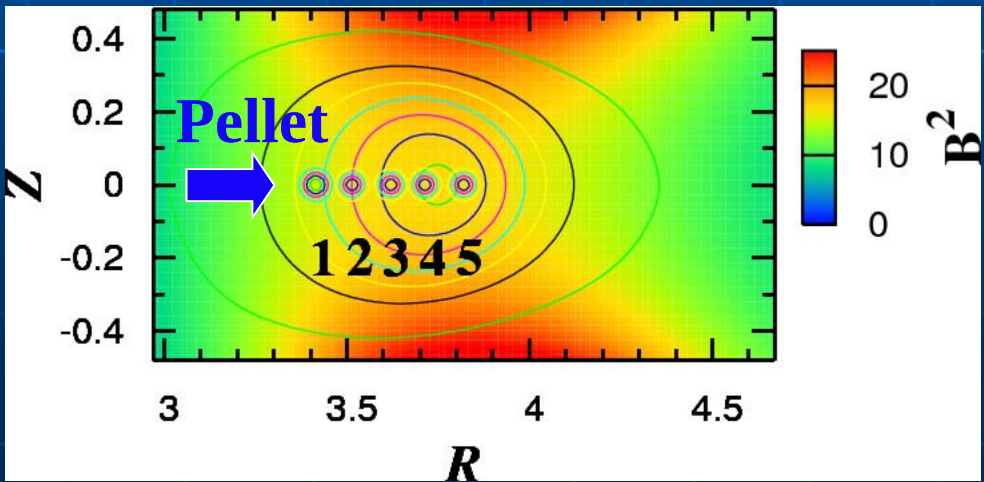
1. LHD plasma



$R_{axis} = 3.75\ \mathrm{m}$

$\beta = 3.6\ \%$

2. Initial conditions of plasmoids



Case 1 : $R_p = 3.42\ \mathrm{m}$

Case 2 : $R_p = 3.52\ \mathrm{m}$

Case 3 : $R_p = 3.62\ \mathrm{m}$

Case 4 : $R_p = 3.72\ \mathrm{m}$

Case 5 : $R_p = 3.82\ \mathrm{m}$

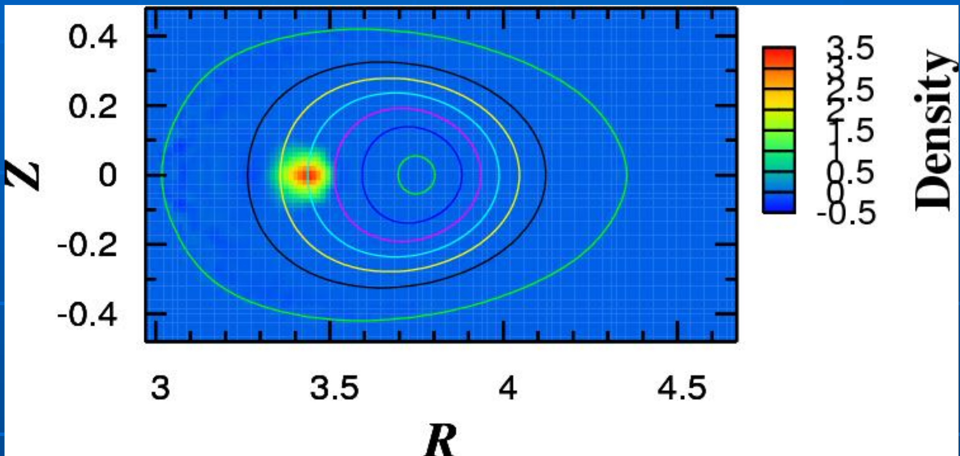
Case A : $V_p = 0.0\ \mathrm{m/s}$

Case B : $V_p = 3.6 \times 10^4\ \mathrm{m/s}$

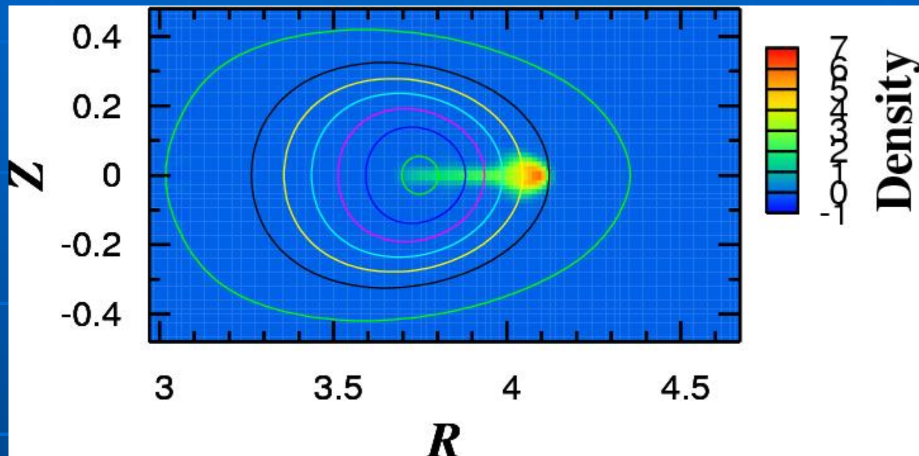
Plasmoid densities on the poloidal cross sections.

$t = 6.15\,\mu\text{sec}.$

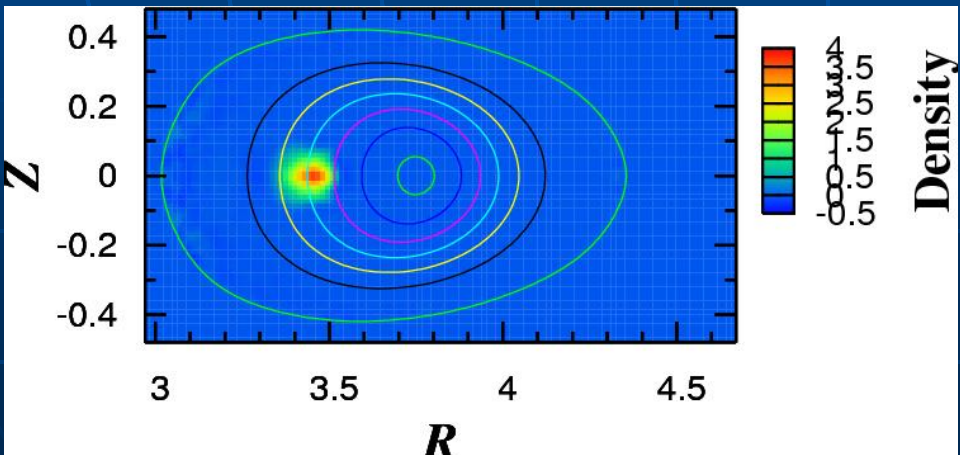
Case 1A : $R_p = 3.42\,\text{m}, V_p = 0.0\,\text{m/s}$



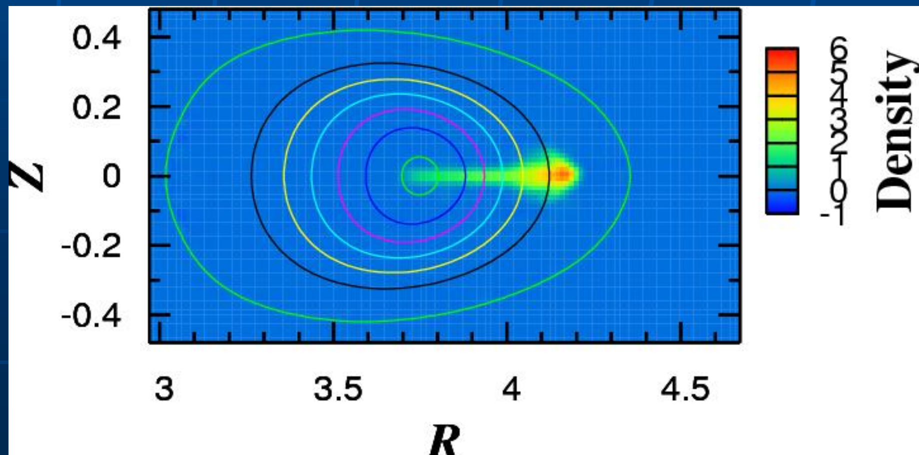
Case 5A : $R_p = 3.82\,\text{m}, V_p = 0.0\,\text{m/s}$



Case 1B : $R_p = 3.42\,\text{m}, V_p = 3.6 \times 10^4\,\text{m/s}$



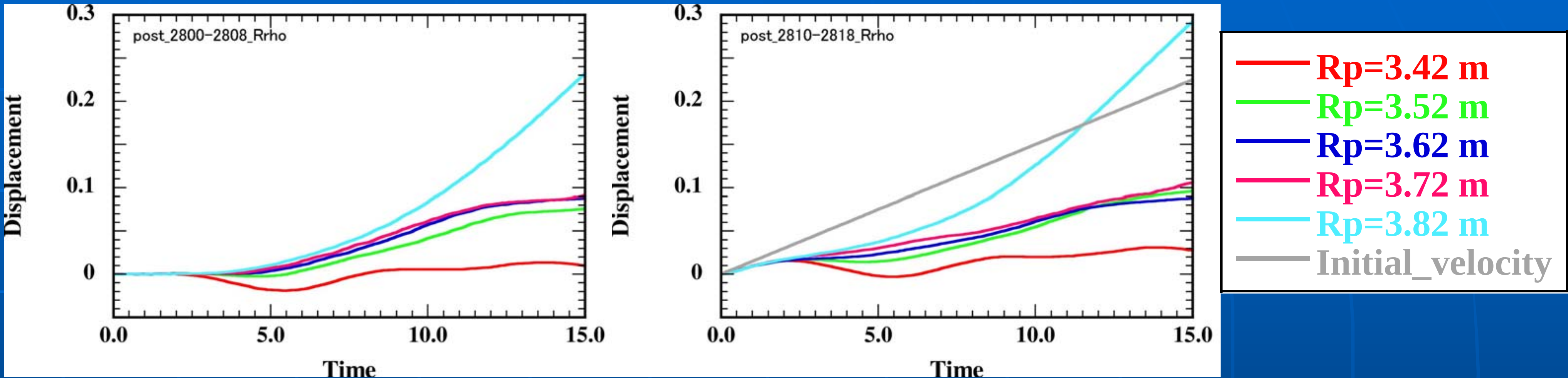
Case 5B : $R_p = 3.82\,\text{m}, V_p = 3.6 \times 10^4\,\text{m/s}$



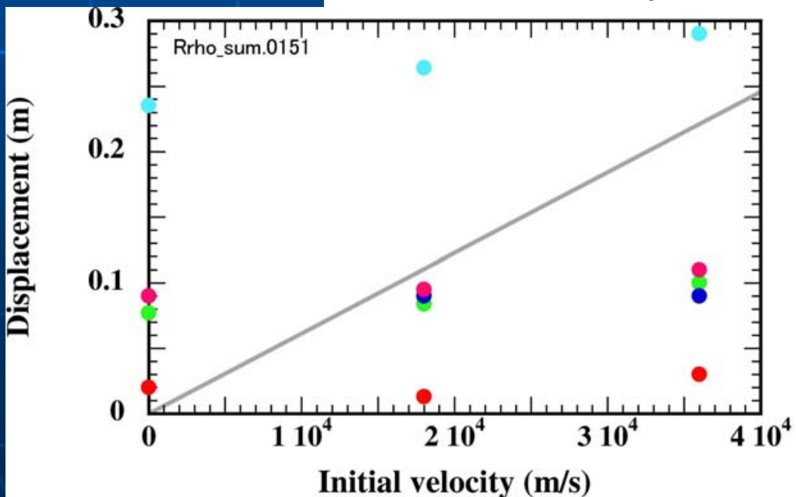
Displacements of the plasmoids.

Case A : $V_p = 0.0$ **m/s**

Case B : $V_p = 3.6\times10^4$ **m/s**



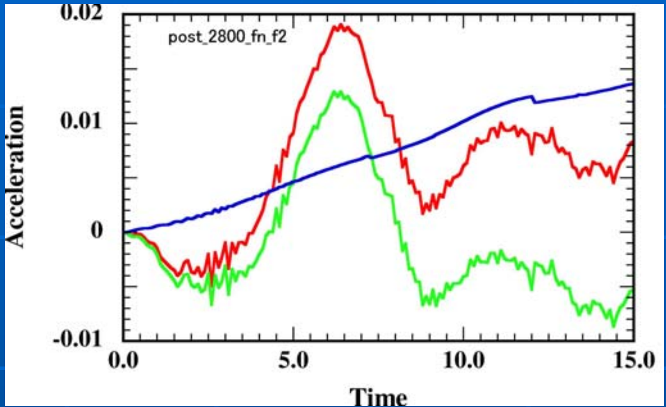
$t = 15\ (t = 6.15\mu\text{sec.})$



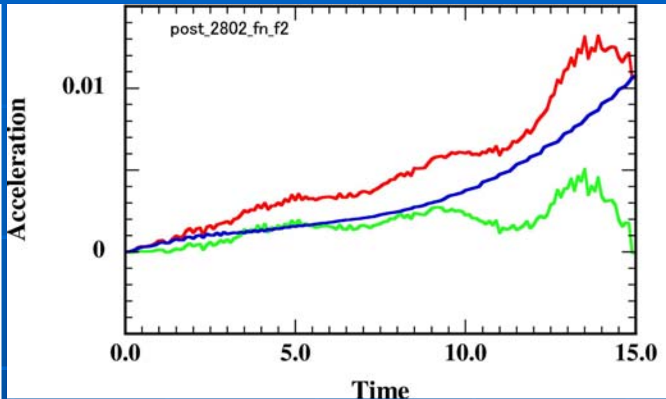
1. **The plasmoid drift with the initial velocity in the initial phase.**
2. **However, the effect of the initial velocity becomes small in the plasmoid motion because of deceleration due to the magnetic field.**
3. **The displacement hardly depend on the initial velocity.**

The force acting on the plasmoid is determined by the connection length.

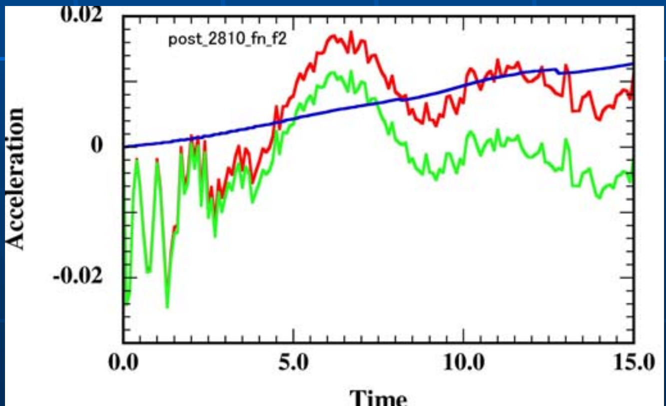
Case 1A : $V_p = 0.0$ m/s



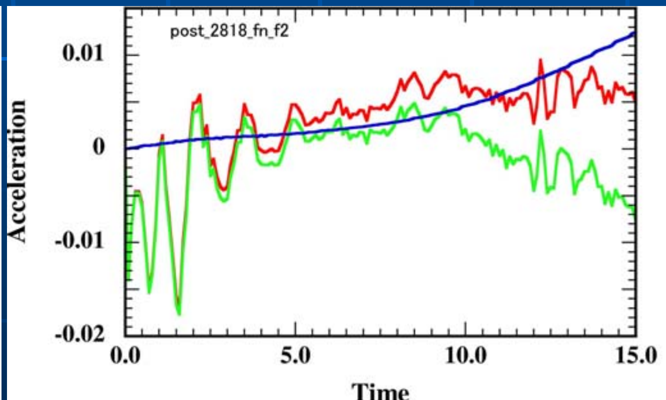
Case 5A : $V_p = 0.0$ m/s



Case 1B : $V_p = 3.6 \times 10^4$ m/s



Case 5B : $V_p = 3.6 \times 10^4$ m/s



Leading force

$$F_R \approx \frac{B_0 B_{R1}}{L_c} - \frac{B_{\varphi 0} B_{\varphi 1}}{R}$$

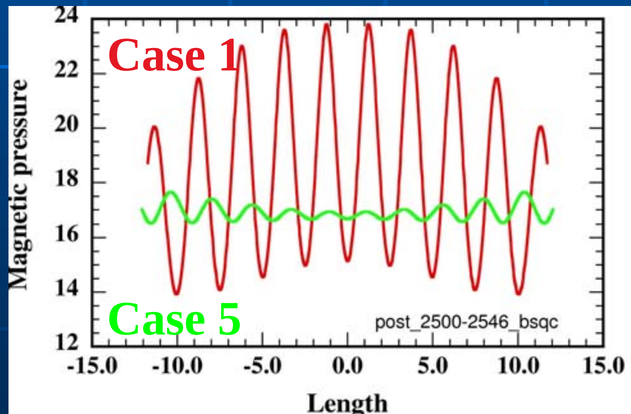
Dipole   1/R

L_c : connection length

B_0 : equilibrium

B_1 : perturbation

(R, φ, Z) : cylinder



The effect of initial velocity becomes small because the plasmoid is decelerated by the force due to dipole.

Summary and future work.

Summary

◯ **The drifts of the pellet plasmoid are summarized as follows:**

1. **It is found that the pellet plasmoid motions in various configurations can be explained by using the connection length.**
2. **Especially, the motions in LHD are different from one in tokamak. This fact qualitatively explains the difference on the experimental results between tokamak and LHD.**

◯ **Dependence of an initial velocity:**

1. **The effect of an initial velocity is small wherever an initial plasmoid is located on the horizontally elongated poloidal cross section.**
2. **That effect is small even if the initial velocity is 3.6×10^4 m/s because of deceleration due to the force by the dipole field.**

Future work

1. **The dependence on injection angle (e.g. tangential direction) will be investigated.**
2. **We will investigate behavior of a plasmoid which a pellet with an initial velocity induces, and clarify suitable condition of pellet injection in the LHD.**