n=1 Mode Motion on Field
Reversed Configuration Plasmas

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n=1 mode motion of plasma column

A field-reversed configuration (FRC) plasma deviates from its equilibrium position and moves slowly around it at an equilibrium phase.

\[ r_s(z, \theta) = r_{s0}(z) + \xi(z) \exp(i(\omega t - n\theta)) \quad \omega = \omega_r + i\gamma \]

- \( \xi(z) = \text{const} \): shift motion
- Rotational mode: wobble motion
- \( \xi(z) = \psi z \): tilt motion
Effect of the n=1 mode motion
  • Low reproducibility on a translation experiment (FIX, FRX-C/T)
  • Particle loss from X-points
  • Low efficiency on a neutral particle beam heating

  **Physics issue**
  Source and Driving Mechanism

  **Technology issue**
  Control method
    a multipole field (NUCTE)
    a neutral beam injection (FIX)
Purpose of this subject

A source of the \( n=1 \) mode motion is investigated from the point view of a magnetic structure of the confinement field.

Contents

1. Magnetic Structure of the confinement field for a field reversed configuration
2. Experimental set up
3. Experimental results
   • Behavior of \( n=1 \) mode motion
   • Source of \( n=1 \) mode
4. Summary
1. Structure of Magnetic Field for FRC

(a) Mirror coil

*Negative field gradient of a radial direction*

*Shaping of a magnetic field line*

(b) Mirror coil with conducting rings, cusp bias field (Non-Tearing reconnection)
Structure of Magnetic Field in $\theta$-Pinch Coil

Radial distribution of magnetic field strength averaged along the line of magnetic force

$$\Delta = \frac{\partial}{\partial r} \left( \frac{\overline{B}}{\overline{B}_w} \right) \approx \frac{\overline{B}(r_w) - \overline{B}(r_s)}{\overline{B}(r_w)} \frac{r_w}{r_w - r_s}$$

Radial gradient of the averaged Field

$$\overline{B} \equiv \frac{2}{l_c} \int_0^{l_c/2} B_e dl$$
Magnetic Structure w/o and with FRC Plasma

w/o FRC Plasma

with FRC plasma

(\(l_s=37.5\text{cm}, r_s=5.0\text{cm}\))

\[
\frac{\partial}{\partial r} \left( \frac{B}{B_W} \right) < 0
\]

negative gradient of magnetic field strength
Magnetic structure \( \Delta \)

Magnetic field gradient \textit{at the outside of the separatrix is negative}. 

\textit{Plasma elongation, Mirror ratio, Coil aspect ratio}
2. Experimental Set up

1. Installation of a conducting ring
2. Control of coil aspect ratio
3. Control of plasma elongation

1. Optical diagnostics
2. $B_\theta$ magnetic probe array
Equilibrium Plasma Parameters

- $B_b = 48 \text{ mT}$
- $B_e = 0.5 \text{ T}$
- $r_s = 0.057 \text{ m}$
- $l_s = 0.33 \text{ m}$
- $n_e = 2.1 \times 10^{21} \text{ m}^{-3}$
- $T_i + T_e = 280 \text{ eV}$
- $\beta_s = 0.7$
- $\rho_i = 0.0041 \text{ m}$, $w = 4$
- $\tau_{\text{life}} = 70 \mu\text{s}$
- $\tau_{\text{onset}} = 35 \mu\text{s}$
- $\omega^* = 4.2 \times 10^5 \text{ rad/s}$
- $V_A = 170 \text{ km/s}$ (94 km/s)
Typical Plasma parameter with C. R.

- All field lines are pulled out through the discharge tube from narrow regions near the coil ends due to the conducting rings.
- Closed field configuration is quickly formed at the coil ends as soon as the confinement field is applied.
- A long FRC is generated without tearing at the mirror regions.

- Oscillation of $r_s$, $l_s$, and $n_e$ decrease.
- Life time will be prolonged
- Onset of n=2 will be delayed
- Improvement of symmetry for FRC formation
Observation of n=1 mode motion by visible optical diagnostics

Bremsstrahlung

\[ I_\lambda \propto \frac{z^2 n_e n_i}{T_e^{1/2} \lambda^2} \quad (\lambda = 550 \pm 5 \text{ nm}) \]

- \text{amplitude} = \left( \xi_x(t), \xi_y(t) \right) \quad \xi_x(t) = \sqrt{\xi_x^2(t) + \xi_y^2(t)}

- \text{asymmetry} = \frac{S_R - S_L}{S_R + S_L}

\[ S_L = \int_{r_w}^{r_w} I(x) \, dx, \, dy \]
\[ S_R = \int_{r_w}^{r_w} I(x) \, dx, \, dy \]
x-y profiles of line integrated light intensity at z=0

Radial compression

Axial contraction

n=1 mode motion

n=2 rotational instability
After the *axial contraction*, \( n=1 \) mode motion is appeared.

\[
\gamma = 0.36 \times 10^6 \quad (s^{-1})
\]

\[
\gamma^{-1} \geq \tau_A
\]

\[
\omega_r = 4.20 \times 10^5 \quad (s^{-1})
\]

\[
\omega_r \approx \Omega^*
\]
3-D trajectory of $n=1$ motion

Even mode (radial shift motion)
Dependence of $\xi_m$ on averaged magnetic field gradient

$\xi_m$ increases with the radial gradient of the confinement field
Typical Trajectory of Plasma column \( (r_s=5.7\text{cm}, l_s=37.5\text{cm}) \)

**combined**

\[
\gamma = 0.15 - 0.23 \times 10^6
\]
\[
\omega_r = 5.2 \times 10^5
\]

**Radial oscillation** *(Figure eight)*

\[
\gamma = 0.14 - 0.17 \times 10^6
\]
\[
\omega_r = 4.7 \times 10^5
\]

**Radial oscillation**

\[
\gamma = 0.36 \times 10^6
\]
\[
\omega_r = 4.2 \times 10^5
\]

**Rotation (counterclockwise)** *(diamagnetic)*

\[
\gamma = 0.10 - 0.15 \times 10^6
\]
\[
\omega_r = -4.8 \times 10^5
\]

**Rotation (clockwise)** *(paramagnetic)*

\[
\gamma = 0.24 \times 10^6
\]
\[
\omega_r = 6.3 \times 10^5
\]

\[
l_s/V_A \approx 2 - 4 \mu s << \gamma^{-1} \approx (5 - 10)\tau_A
\]

\[
|\omega_r|/\omega^* \approx 1.0 - 1.5
\]

\[v_r >> |v_\theta| \quad \text{radial oscillation}
\]

\[v_r << |v_\theta| \quad \text{Rotation}
\]
Estimation of the force acting on the plasma

$k$ (center force) is \( \sim 1000 \text{ N/m} \) (10N at \( \xi_m = 0.01 \text{ m} \))
Relation between $\xi_m$ and axial asymmetry

Relation between $\xi_m$ and asymmetry at $z=0$

Relation between $\xi_m$ and Axial asymmetry

Open symbol 6mTorr-2kV
Closed symbol 4mTorr-2kV

Weak correlation between $\xi_m$ and axial asymmetry
Mechanism of generation and saturation for n=1 mode motion

Asymmetry of formation

Magnetic structure of confinement field

Effect of conducting wall

Coil Aspect ratio

Conducting ring

Non tearing reconnection

Initial momentum (Energy) of n=1 mode motion at axial contraction

On set n=1 motion

Saturate Stabilization

$F_r \approx 10N$

($\xi_r \approx 0.01m$)
1. A source of $n=1$ mode motion is investigated from the point view of a magnetic structure of a confinement field.

- The source of $n=1$ mode motion is related to an negative field gradient of a radial direction. With the increase of the negative gradient, the amplitude of the motion becomes large.
- The gradient is controlled by a coil aspect ratio and a plasma elongation.
- By an installation of a conducting ring at the end of theta pinch coil, the amplitude decreases.
- Symmetry of a plasma formation is also related to the appearance of $n=1$ mode motion.
2. **Behavior of n=1 mode motion** is also investigated.

- The trajectory of n=1 mode motion depicts different orbits, for example, *a radial oscillation, an elliptic (or circler) rotation and a combined orbit* dependent on the initial velocity.
- The direction of the rotation is not only *clockwise* but also *counterclockwise*.
- *The axial mode structure is even.* The odd mode motion can not be observed.
Axial dependence of $B_\theta$ field

$n=1$ mode motion by $B_\theta$ field measurements

Odd mode of $B_\theta$ field  
Even mode deformation of Plasma column

$z=-0.175\,m$  
$\theta=-60^\circ$

$z=0$  
$\theta=90^\circ$

$z=0.175\,m$  
$\theta=-60^\circ$
Mode Analysis of $B_\theta$ field at $z=-0.175m$

$n=1$ mode $B_\theta$ is dominant mode during 15-25µs
Estimation of Trajectory by a center of force

\[ m \left( \frac{d^2 r}{dt^2} - r \left( \frac{d\theta}{dt} \right)^2 \right) = F_r = -kr \]

\[ \frac{d}{dt} \left( mr^2 \frac{d\theta}{dt} \right) = F_\theta = 0 \]

when \( \frac{d\theta}{dt} \approx \text{const} (F_\theta \approx 0) \), from energy conservation

\[ \frac{m}{2} \left( \left( \frac{dr(t)}{dt} \right)^2 - \left( \frac{dr(0)}{dt} \right)^2 \right) + \frac{k}{2} \left( r(t)^2 - r(0)^2 \right) - \frac{m}{2} \left( \left( \frac{d\theta}{dt} \right)^2 - \left( \frac{d\theta}{dt} \right)_0^2 \right) = 0 \]

\( \frac{dr}{dt} \approx 0 \) at a maximum of \( r(t) \),

\[ \frac{m}{k} = \frac{\left( r(t)^2 - r(0)^2 \right)}{\left( \frac{dr(t)}{dt} \right)^2 - \left( \frac{dr(0)}{dt} \right)} \]