Control of Global Behavior of FRC Plasmas

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Outline

Feature of FRC plasmas
Parameter range
FIX apparatus
Translation
Axial Compression
Neutral Beam Injection
Low Frequency Wave
Feature of FRC Plasmas

Closed magnetic configuration in open magnetic geometry

Good confinement
Direct Energy Converter

High beta value

$$\langle \beta \rangle = 1 - \frac{x_s^2}{2} \approx 90\%$$

$$x_s = \frac{r_s}{r_w}$$

No material structure are linking the plasma

Can be moved along machine axis ;
TRANSLAION
FRC plasma configuration

$R$ magnetic axis radius
$r_s$ separatrix radius
$r_w$ conductive wall radius
$l_s$ length

profiles

$n(r)$

$B(r)$
Magnetic field strength to sustain burning plasma

\[ \beta = \frac{\text{plasma pressure}}{\text{magnetic pressure}} \]

beta limit : stability

<table>
<thead>
<tr>
<th>Tokamak (ITER)</th>
<th>FRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ITER equivalent</td>
</tr>
<tr>
<td>( n_e (10^{20} \text{m}^{-3}) )</td>
<td>1.5</td>
</tr>
<tr>
<td>( T_i (\text{keV}) )</td>
<td>17</td>
</tr>
<tr>
<td>( \beta (%) )</td>
<td>6</td>
</tr>
<tr>
<td>( B (\text{T}) )</td>
<td>5.7</td>
</tr>
</tbody>
</table>
Parameter Range of FRC Plasmas

FRX-C/LSM compression

B  FRX-B
C  FRX-C
T  TRX-2

T (eV)

500  1000  2000

n (m⁻³)

2  5  10³  2  5  10²¹  2
Empirical scaling law

\[ \tau_N(\text{sec}) = 6.4 \times 10^{-5} \frac{R^2}{\rho_i(m)} \]

Change of plasma length by translation

Particle Inventory
\[ N = \pi r_s^2 l_s \langle n \rangle \]

Total Energy
\[ E = \frac{5}{2} N k T + \pi r_w^2 l_w \frac{B_v^2}{2 \mu_0} \]

Trapped Flux
\[ \Phi = \frac{\alpha}{2 \sqrt{2}} x_s^3 \pi r_w^2 B_w \]

Conservation/Loss
\[ Q_f = (1 - \epsilon_f) Q_i \]
\[ (Q = N, E, \Phi) \]

Change of plasma length
\[ \frac{l_{sf}}{l_{si}} = \frac{1 - \epsilon_E}{(1 - \epsilon_\Phi)^2} \left( \frac{\beta_f}{\beta_i} \right)^{-1} \left( \frac{\alpha_f}{\alpha_i} \right)^2 \left( \frac{r_{wf}}{r_{wi}} \right)^2 \left( \frac{x_{sf}}{x_{si}} \right)^4 \]
Translation Dynamics

Confinement region
**REThermalization**

\[ E_b = \frac{2}{2} N \kappa T \]  (equilibrium in a straight solenoid)

\[ E_p = \frac{3}{2} N \kappa T \]

**Energy Conservation**

\[ \frac{5}{2} N \kappa T + \frac{1}{2} m N v^2 = const \]  (no loss)

if \( v = 0 \) and \( N = const \)

then \( T = const \)
Change in temperature with time

![Graph showing the change in temperature with time, with points indicating 1st and 2nd reflections and passes.](image-url)
Density after Translation

![Graph showing the relationship between density and magnetic field strength](image)
Dependence of Confinement Times on Bias Field
Compression Schemes

3-D

2-D

1-D
# Compression Schemes

<table>
<thead>
<tr>
<th></th>
<th>3-D</th>
<th>2-D</th>
<th>1-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{max}}$</td>
<td>$\frac{2}{C^\gamma}$</td>
<td>$\frac{2}{C^\gamma}$</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{tot}}$</td>
<td>$C^{\left(\frac{1}{\gamma} - \frac{1}{7}\right)}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho_i$</td>
<td>$C^{-\frac{1}{\gamma}} \left(\frac{r_i}{r_f}\right)^{\frac{1}{2}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X_i$</td>
<td>$C^{-\frac{1}{\gamma}} \left(\frac{\langle\beta\rangle_i}{\langle\beta\rangle_f}\right)^{\frac{1}{2}}$</td>
<td>$C^{-\frac{1}{\gamma}} \left(\frac{\langle\beta\rangle_i}{\langle\beta\rangle_f}\right)^{\frac{1}{2}}$</td>
<td>Eq.</td>
</tr>
<tr>
<td>$l_i$</td>
<td>$C^{2+\varepsilon} \left(\frac{\langle\beta\rangle_i}{\langle\beta\rangle_f}\right)^{-1}$</td>
<td>1</td>
<td>$\frac{l_f}{l_i}$</td>
</tr>
<tr>
<td>$V$</td>
<td>$\frac{2}{C^\gamma}$</td>
<td>$C^{-\frac{2}{\gamma}} \left(\frac{\langle\beta\rangle_i}{\langle\beta\rangle_f}\right)^{-1}$</td>
<td>$C^{-\frac{2}{\gamma}} \left(\frac{\langle\beta\rangle_i}{\langle\beta\rangle_f}\right)^{-1}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$C^\varepsilon \left(\frac{r_f}{r_i}\right)^{\frac{1}{2}}$</td>
<td>$C^{-\frac{1}{\gamma}} \left(\frac{\langle\beta\rangle_i}{\langle\beta\rangle_f}\right)^{-1} \left(\frac{r_f}{r_i}\right)^{\frac{1}{2}}$</td>
<td>$\frac{X_{sf}^2}{X_{si}^2} C^\gamma \left(\frac{r_f}{r_i}\right)^{\frac{1}{2}}$</td>
</tr>
</tbody>
</table>

| compression ratio     | $C = \frac{B_{w2}}{B_{w1}}$, $C = R^{\frac{1}{2}}$ |
| density ratio         | $R = \frac{n_{\text{max,2}}}{n_{\text{max,1}}}, R = C^{\frac{1}{\gamma}}$ |
| temperature ratio     | $r = T_i/T_{\text{tot}}$ |

Eq. \[
1 - X_{sf}^2 = \left(\frac{\langle\beta\rangle_i X_{sf}^2 l_f}{\langle\beta\rangle_i X_{si}^2 l_f}\right)^{\frac{1}{2}}
\]

Eq. \[
1 - X_{si}^2 = \left(\frac{\langle\beta\rangle_i X_{si}^2 l_f}{\langle\beta\rangle_i X_{sf}^2 l_f}\right)^{\frac{1}{2}}
\]
Axial Compression

Confinement Coil

Upstream mirror

Axial Compression coil

diamag probe

B

0.13T

0.04T

0.17T

Z
Change of $x_s$ by axial compression
Heating by axial compression

$T_f/T_i$

$x_{si} = 0.5$

$x_{si} = 0.4$

$x_{si} = 0.3$

$L_{sf}/L_{si}$
Confinement improvement by axial compression
Change of Separatrix radius with Time

![Graph showing the change of Separatrix radius with time. The graph has a y-axis labeled $r_s (cm)$ and an x-axis labeled time ($\mu$sec). The graph includes two lines: one solid line labeled "compression" and one dashed line labeled "no compression." There is a note indicating "Axial Compression Started."}
Fig. 5 Particle confinement time $\tau_N$ at each instance of time plotted against the value calculated for the empirical scaling law with (solid line) and without (dotted line) axial compression. Confinement is improved by bringing the gradually decaying FRC back into a state with larger empirical scaling parameter and larger confinement time $\tau_N$. For example, the point with the time marker 330 $\mu$s on the compressed case has larger empirical scaling parameter and therefore larger $\tau_N$ than that of the uncompressed case.
Experimental Arrangement for
Neutral Beam Injection

Schematic diagram of the FRC confinement chamber with NB injection system.
Time Evolution of Stored energy

- with NBI
- w/o NBI

total energy (J)

<table>
<thead>
<tr>
<th>Time (μs)</th>
<th>Energy Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>48 J</td>
</tr>
<tr>
<td>150 μs</td>
<td>0.3 MW</td>
</tr>
<tr>
<td>200 μs</td>
<td>390 J</td>
</tr>
<tr>
<td>250 μs</td>
<td>2.3 MW</td>
</tr>
<tr>
<td>300 μs</td>
<td>640 J</td>
</tr>
<tr>
<td>400 μs</td>
<td></td>
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</tbody>
</table>
Dependence of Confinement

/ Confinement Improvement on Mirror Ratio

![Graph showing the relationship between confinement lifetime ($\tau_E$) and mirror ratio ($R_M$) with and without NBI.]

- **With NBI** (filled circles)
- **Without NBI** (open circles)
Arrangement for
Low Frequency Wave Experiment

- Quartz tube
- theta-pincho coil
- Formation Region
- Upstream Mirror Coil
- Confinement Coil
- Downstream Mirror Coil
- RF Antenna (small)
- Magnetic Probe Array (2D)
- Vacuum Chamber
- Power Source
- Confinement Coil
Time Evolution of Stored Energy

The graph shows the time evolution of stored energy over time in microseconds. The energy is plotted against time, with two curves distinguished by the labels "with RF" and "w/o RF."
Effects of RF Heating

(a) $T_i + T_e$ (eV)

(b) $T_i$ (eV)

(c) $n_i \times 10^{19}$ m$^{-3}$

- Dashed line: w/o pulse
- Solid line: with pulse

Time (μs)

-20 0 20 40 60 80 100
Induced Magnetic Field disturbance

antenna current

Br
Bθ
Bz

260  280  300  320μsec
Propagation of Magnetic Disturbances
Dispersion Relation of $B_\theta$ Disturbance

$r=275$

- Frequency (kHz) vs. $k_\parallel (1/m)$

The graph shows a linear relationship between frequency (kHz) and $k_\parallel (1/m)$ with a gradient of $r=275$. The data points are marked with error bars, indicating the variability or uncertainty in the measurements.
Spatial Variation of $v_z$