High $\beta$, High Density Improved Confinement RFP Plasmas


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RFP confinement limited by current driven tearing modes

- Current-driven tearing modes lead to stochasticity, degrading confinement
By inductively altering the current profile, these fluctuations are reduced.
Confinement was improved but with limitations

- Old results:
  - $T_e$ increases (<2 keV)
  - Higher $\beta$ (15% compared to 9% in standard discharge)
  - Improved $\tau_E$ (10 ms vs 1 ms), but ...

- Limited to relatively low density ($n_e \sim 10^{19} \text{ m}^{-3}$) due excitement of $m=0$ activity during edge-fueling

- Can capture high ion temperatures during improved confinement but $T_i$ doesn’t increase

- Even though beta is increased, stability isn’t challenged
Energy and particle content increased through pellet injection

- Now during improved confinement:
  - Density quadrupled
  - $T_e$ and $T_i$ increase
  - Total $\beta$ increases to 26%
  - Pressure large enough to challenge stability
Outline

• Introduction
  ‣ The RFP
  ‣ Pellet Injection
• Improved confinement at high density
• Stability at high beta
• Summary
RFP is characterized by high magnetic shear

- Strong shear allows high beta
- Resonant modes are primarily current driven
Pellet Injector

- Deuterium pellets
- \(N_{\text{pellet}} \sim 10^{20}\) particles (\(\sim N_{\text{mst}}\))
- Four barrels with diameters ranging from 1.0 to 2.0 mm
- Formed \textit{in situ}
- Accelerated by mechanical punch and/or high speed gas valve (\(\text{H}_2\) propellant)
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Improved confinement is the result of auxiliary current drive not pellet injection

Thermal equilibration time drops 10-fold
During improved confinement, density profiles are stationary

- No measurement during injection/ablation of pellets
- For similar pellet fueled discharges, $\tau_P = 5-6$ ms
- In non-improved discharges, $\tau_P = 1$ ms
Highest $\beta$ achieved in high density, improved confinement discharges

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<th>Case</th>
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- Standard (non-improved) plasmas: $\tau_E \sim 1$ ms, $\beta_{\text{tot}} \leq 9\%$
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- Standard (non-improved) plasmas: $\tau_E \sim 1 \, \text{ms}, \beta_{\text{tot}} \leq 9\%$
- $\beta_{\phi} \propto \langle p \rangle / B_{\phi}^2(a) \sim 70\text{-}120\%$
- Titan RFP reactor study assumed $\beta \sim 20\%$
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Mercier criterion likely violated in core

If violated, local interchange modes unstable

\[ \nabla p_{\text{critical}} = -\frac{rB_z^2q'^2}{32\pi q^2(1-q^2)} \]

\[ \nabla p_{\text{measured}} \]

\[ \beta_{\text{tot}} = 26\% \]
At highest betas, calculations predict pressure-driven instabilities.

Mercier criterion violated

\( n = 21 \)
\( n = 24 \)

\( \gamma \tau A \) - \( r/a \)

☐ - \( m = 3 \), resistive, pressure driven (Mercier-like)

(F. Ebrahimi)
At highest betas, calculations predict pressure-driven instabilities

Mercier criterion violated

- $m = 3$, resistive, pressure driven (Mercier-like)
- $m = 1$, resistive, pressure driven

(F. Ebrahimi)
During improved confinement, fluctuations are reduced.

Measured fluctuation spectrum

\( b_n \sqrt{B_\theta(a)} \text{ (\%)} \)

Toroidal mode number, \( n \)

6  8  10  12  14

High \( \beta \) (no pellet)

non-improved confinement

(m=1 magnetic fluctuations)
Smaller decrease in fluctuations could be from increase of pressure drive.

- Drop in $\tau_E$ could be related to rise in fluctuations from High $\beta$ to Higher $\beta$.
Although instabilities predicted, no disruptive effects are observed

- Pressure profile measured at 19 ms ($\beta_{\text{tot}} = 26\%$)
- Electron temperature still increasing at 19 ms
Summary

- Previous results
  - Improved energy confinement and higher beta with application of current profile control
  - Generation and confinement of hot thermal ions during improved confinement
Summary

• Previous results
  ‣ Improved energy confinement and higher beta with application of current profile control
  ‣ Generation and confinement of hot thermal ions during improved confinement

• New Results
  ‣ Can achieve higher beta with good confinement ($\beta_{\text{tot}} = 26\%$ - record for improved confinement RFP)
  ‣ Have not reached a disruptive $\beta$-limit