Density and $\beta$ limits in the Madison Symmetric Torus Reversed-Field Pinch

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On behalf of the MST Team
Outline

• Motivation and Key Results
• Overview of Experimental Hardware
  – The RFP and MST
  – Pellet injection fueling on MST
• High $\beta$ Experiments (Pellet fueling + Improved Confinement)
  – Ohmically heated experiments
  – Experiments with NBI heating
• Density Limit Experiments
  – Pellet triggered terminations
  – Impact of reversal
Motivation and Key Results

What mechanism limits $\beta$ on the RFP?

- Pellet fueling of improved confinement discharges
  - Scans density, temperature, Ohmic heating power
- Electron $\beta$ remains constant
- Strong scaling of magnetic activity
- Additional NBI heating achieves higher $\beta$
  - Due in part to fast ion population

What governs the density limit on MST and the RFP?

- Develop pellet fueling technique to study density limit
- Establish density limit scaling up to 600kA
- Explore the role of edge reversal and $m=0$ modes on limit
  - Higher density limit in reversed discharges
- Density up to twice the limit in improved confinement experiments
The Reversed Field Pinch (RFP)

- $B_\theta \sim B_\phi$ with $B_\phi$ reversing direction in the edge
- $q < 1$, tearing modes resonant
- High shear, high $\beta$ ($> 10\%$)
  - Record $\beta$ of 26% achieved with pellet fueling
The Madison Symmetric Torus (MST)

\[ R = 1.5 \text{ m} \]
\[ a = 0.5 \text{ m} \]
\[ I_p = 200 - 600 \text{ kA} \]
\[ |B| = 0.2 - 0.6 \text{ T} \]
\[ n_e < 1 \times 10^{20} \text{ m}^{-3} \]
\[ T_e, T_i < 2.0 \text{ keV} \]
MST's Pellet Injector Provides Unique Capabilities

Collaboration with ORNL pellet fueling group
4-barrel pipe gun injector
Flexible pellet hardware

- 1.0 – 4.0* mm diameter
- Particle Content $10^{20} - 10^{21}$
- $v_{\text{pellet}} = 100 - 1200 \text{ m/s}$
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Improved Confinement Achieved with Pulsed Parallel Current Drive (PPCD)

- Inductively drives current in the plasma edge to flatten the current profile, reducing the tearing mode drive
- Limited to low density (< 1x10^{19} m^{-3}) with edge fueling alone
The Recipe for Achieving High $\beta$ on MST

- Pellet injection prior to the onset of PPCD
- Density increased while $m = 0$, $m = 1$ activity reduced
- $T_e$ Increases
- $T_i$ increases along with $T_e$ (only observed at high density)
High $\beta$ Region of Interest from 17-20 ms

- $T_e$ measured at 2 kHz
- Density and other quantities averaged over 0.5 ms window
- $\beta$ peaks at the end of the improved confinement period
Saturation of $\beta_e$ at High Density

- Estimate of electron $\beta$ obtained from experimental measurements of $n_e$ (CO$_2$) and $T_e$ (Thomson Scattering)

- Line averaged $T_e$ derived from Thomson profile measurement

\[
\langle \beta_e \rangle = \frac{2\mu_0\langle n_e \rangle\langle T_e \rangle}{|B(a)|^2}
\]

\[
N_{GW} = \frac{\langle n_e \rangle}{n_{GW}}
\]

\[
n_{GW} = \frac{I_p}{\pi a^2}
\]
Increases in \( \beta \) are mostly due to an increased contribution from ions.

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Ohmically Heated 200 kA PPCD Experiments

- $T_e$ decreases as $n_e$ increases
- $\langle \beta_e \rangle$ constant
- $m=1$ and $m=0$ magnetic activity increases, reaching levels comparable to that observed in standard discharges
Increased Ohmic Heating at High $n_e$

- Spitzer like scaling of resistivity suggests a factor of 3-4 increase in $P_{\text{ohmic}}$
- Consistent with equilibrium reconstructions ($P_{\text{ohmic}} = \eta J^2$)
Evidence for a Soft $\beta$ Limit

- Density scan amounts to scan of Ohmic power
  - Spitzer like resistivity ($T_e^{-3/2}$) increases by factor of 3-4

- $\langle \beta_e \rangle$ constant despite $\sim 3x$ increase in $P_{\text{Ohmic}}$ ($\sim 1$ to $\sim 3$ MW)

- Magnetic activity increases by a factor of 4 or more
  - Stochastic transport in the core could provide an explanation

- What is the impact of additional NBI heating power?
200 kA PPCD Experiments with NBI Heating

- 1 MW NBI
- Comparable $I_p$, $n_e$
- There is a region where $\langle \beta_e \rangle$ is higher
- Decrease in magnetic activity
NBI Heating Aids in Achieving Higher $\beta$

- Possible explanations
  - Beam Heating
  - Mode reduction
  - Enhanced core deposition of pellet material

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n_{GW} = \frac{I_p}{\pi a^2}
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Impact of Fast Ion Population on $\beta$

- Thermal $\beta$ of 26% for discharge with NBI heating

- Estimates for the fast ion $\beta \sim 2\text{-}3\%$ lead to a total $\beta$ of 28%

\[
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RFP Density Limits

• Greenwald limit for Tokamak and RFP experiments with circular cross sections:

\[ n_{GW} = \frac{I_p}{\pi a^2} \]

• Symptoms include:
  – Increase in radiation
  – Edge cooling
  – MHD activity
  – Thermal quench
  – Shrinking of the current channel
  – Disruption (in tokamaks)
Goals of Pellet Triggered Density Limit Experiments

• Use large, fast deuterium pellet to provide a large edge fueling source when it collides with the far wall
  – 2.0 mm pellets used for 200 kA
  – 4.0 mm pellets used up to 600 kA

• Expand our understanding of density limit phenomenology

• RFX-mod model attributes the density limit to the formation of m=0 island, motivating a comparison of reversed and non-reversed discharges
  – F = -0.2 for standard operation
  – F = 0.0 for non-reversed

\[ F = \frac{B_\phi(a)}{\langle B_\phi \rangle} \]
Density Limit Termination

- Small changes in pellet mass (and density) impact plasma termination
- Varying degrees of plasma termination observed
- Loss of reversal ($F>0$) for full termination

\begin{align*}
\text{No Pellet} & \quad m = 0.127 \\
& \quad m = 0.154
\end{align*}

\begin{align*}
\langle n_e \rangle \left(10^{19} \text{ m}^{-3}\right) & \\
I_p \text{ (kA)} & \\
F & \\
\text{Time (ms)} &
\end{align*}
Impact of Reversal on the Density Limit

- $m=0.291$
- $F=0.0$
- $m=0.313$
- $F=-0.2$
- $m=0.317$
- $F=-0.3$

Deeper reversal appears more robust to limit

Magnetic activity increases
MST Density Space

- $|1/l_p(dl_p/dt)| > 5 \%/ms$
- Greenwald limit constrains density
- Small change based on reversal parameter

\[ n_{GW} (10^{19} \text{ m}^{-3}) \]

\[ \langle n_e \rangle (10^{19} \text{ m}^{-3}) \]
Highest Density Achieved So Far

Density limit is greatly exceeded in PPCD
- Core fueled
- Unsustained
- With NBI

![Graph showing density limit exceeded](image-url)
Summary

• Constant $\langle \beta_e \rangle$ scaling with increasing density
  – Ohmic power increases, as does magnetic activity
  – Consistent with soft $\beta$ limit

• NBI heating achieves a higher $\langle \beta_e \rangle$
  – Including fast ion population, $\beta = 28\%$

• Pellet triggered terminations represent a robust way to trigger density limit plasma terminations up to 600 kA
  – Rapid current decay, loss of reversal and increased magnetic activity
  – Partial termination as density limit is approached

• Varying F has an effect on the apparent density limit
  – Deeper reversal has higher terminating density
  – Edge modes grow despite lack of resonant surface