Characteristics of non-collisional ion heating in the MST RFP

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An unknown mechanism transfers a large amount of energy from the B field to the ions

- Magnetic reconnection liberates energy from the magnetic field
- Heating is much faster than i-e collision time (>10 ms)
Ion heat can be captured by improving energy confinement

- Magnetic fluctuations degrade confinement
- By suppressing magnetic fluctuations after a few reconnection events, ion heat can be captured
- An understanding of the ion heating mechanism may lead to further performance enhancements
Outline

• Magnetic reconnection ion heating in MST

• New experimental observations
  - mass dependent heating efficiency
  - density dependent anisotropy
  - evidence of suprathermal ions

• Summary
The Reversed Field Pinch is a low B toroidal confinement device.

- Low magnetic field allows for self-organization
- Susceptible to tearing instability
The Madison Symmetric Torus is a large, moderate current RFP!

\[ R = 1.5 \, \text{m} \quad I_p \leq 600 \, \text{kA} \quad n_e = 0.4 - 4.0 \times 10^{19} \, \text{m}^{-3} \quad \beta \leq 26 \% \]

\[ a = 0.52 \, \text{m} \quad B = 0.5 \, \text{T} \quad T_{i,e} = 0.2 - 2 \, \text{keV} \]
Magnetic reconnection is impulsive and periodic

- Power liberated from equilibrium magnetic field is larger than Ohmic input power

\[ P_{\text{mag}} \sim 10 \text{ kJ/} \ 100\mu\text{s} = 100 \text{ MW} \]

\[ P_{\text{ohmic}} \sim 5 \text{ MW} \]
Rutherford scattering measures the bulk ion temperature

- Measures $T_{\text{perp}}$ only
- Spatial resolution $\sim 15$ cm
- Temporal resolution $\sim 10$ $\mu$sec

- Can vary fuel gas to look for species dependent ion heating

Neutral particle energy analyzer

20 keV He$^0$ beam
Bulk ion heating efficiency, $\epsilon \sim m^{1/2}$

- Efficiency defined as,

$$\epsilon = \frac{\Delta E_{\text{thermal}}}{\Delta E_{\text{mag}}}$$

- H, D, He fuel gases used

- D and He both have $q/m = 1/2$

Fiksel et. al. PRL 103, 145002 (2009)
CHERS can measure both $T_{\text{perp}}$ and $T_{\text{par}}$ locally!

- **CHarge Exchange Recombination Spectroscopy** measures $C^+6$ impurity ion temperature.

- Good simultaneous spatial (1-4 cm$^2$) and temporal (10-100 $\mu$s) resolution.

- Plasma reproducibility allows a direct comparison of $T_{\text{perp}}$ and $T_{\text{par}}$.
Density dependent anisotropy is observed during reconnection heating.

- Anisotropy persists for many collisional isotropization times, $\tau \sim 0.1$ ms.
- This observation is not yet understood.
Density dependence observed wherever $T_{\text{par}}$ is measured

- $T_{\text{par}}$ at the reversal surface shows similar behavior to $T_{\text{par}}$ in the core.
Neutron flux depends on ion density and energy

- Deuterium plasmas produce fusion neutrons,
  \[ D + D \rightarrow He^3 + n \rightarrow T + p \]

- We can calculate neutron flux based on measured values of \( n_i \) and \( T_i \), assuming a Maxwellian distribution,
  \[ \Phi \sim n_i^2 \sigma v(T_i) \]
Neutron flux measurements do not agree with predictions using Maxwellian assumption!

- 3 differences between data and Maxwellian model:
  - data show low density neutron flux x10 higher than model
  - data show neutron flux decreasing with density
  - data show a longer decay constant
Measured neutron flux is consistent with suprathermal ion population

- Small number of suprathermal ions (E=17keV) can produce large neutron flux
  - $n_{fi} = 6\%$
    - = 1\%
    - = 0.1\%
NBI experiments show fast ions (E>7keV) are well-confined

\[ \tau_{\text{loss}}^{\text{fi}} = 1 \text{ ms} \]

\[ \tau_{\text{loss}}^{\text{fi}} = 20 \text{ ms} \]

Fiksel et. al. PRL 95, 125001 (2005)
Summary of new experimental observations of ion heating on MST

- The heating efficiency of the majority ion species $\sim m^{1/2}$

- The impurity ion temperature develops an anisotropy in higher density plasmas

- Neutron flux measurements indicate the presence of suprathermal ions

→ need to do more work to use experimental observations to constrain theoretical models
The End