CXRS/MSE/BES on the MST Reversed-Field Pinch

D. J. Den Hartog

University of Wisconsin – Madison
Center for Magnetic Self-Organization

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Measurement of fast plasma dynamics in MST requires innovative high-speed spectroscopic diagnostics.

- Plasma parameters change dramatically during fast reconnection events ("sawtooth crashes")
  - fluctuations increase, stored magnetic energy drops, ions are heated, ....
  - timescales of 10–100 µsec
- Detailed physics understanding requires spatially and temporally resolved measurements of temperature, flow, and $B$
  - energy and momentum transport
  - MHD dynamo ($\tilde{v} \times \tilde{B}$)
  - equilibrium reconstruction
  - ....
Key contributors to this work:

  - Department of Physics, University of Wisconsin–Madison
  - Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas
- M. G. O’Mullane and H. P. Summers,
  - University of Strathclyde, Glasgow, United Kingdom

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Outline

• Brief introduction to the Reversed-Field Pinch and MST
• Beam-based diagnostics
  – Charge-exchange recombination spectroscopy (CXRS)
  – Spectral motional Stark effect diagnostic (MSE)
  – Fast He beam emission spectroscopy (BES)
• Summary
The RFP: toroidal confinement at low $|B|$.

- Toroidal field $B_T$ is $\sim 10X$ smaller in RFP than same-current tokamak
  - $B_T \approx B_P$ with high total $\beta$ (typically $\geq 10\%$)
  - equilibrium substantially determined by plasma dynamics
MST is an ohmic RFP operated at moderate current.

\[ R = 1.5 \text{ m}, \quad a = 0.5 \text{ m} \]

\[ I_p \leq 600 \text{ kA}, \quad |B| \leq 0.6 \text{ T} \]

\[ n_e \leq 4 \times 10^{19} \text{ m}^{-3}; \quad T_e, T_i \leq 2 \text{ keV} \]
CXRS measurements can be made at 11 radial points on a poloidal cross-section of MST.

Both CX and background emission are recorded simultaneously.
Custom high throughput CXRS duo-spectrometer is the key to measuring fast ion dynamics in MST.

- Double-grating Czerny-Turner design provides required dispersion
  - each grating is a mosaic, 220 x 220 mm, 3600 g/mm
  - directly coupled fiber optic input and output

D. Craig et al., to be published in Rev. Sci. Instrum.
Ion heating (“self-heating”) occurs in ~0.1 ms throughout the plasma during a global reconnection event.
Spectral MSE
Spectral MSE technique measures $B \geq 0.2$ T.

- In MST, $v_{beam} \times B$ is small ($\sim 1$ MV/m), so Stark components overlap
- Solution: measure full Stark spectrum
  - Fit with model assuming statistical population of excited levels
  - From component separation derive local $|B|$ to 2% precision

- An atomic model is being developed for MSE at low $|B|$ as part of ADAS
  - Cause of small structural asymmetries in the MSE spectrum still not resolved
The spectral MSE system achieves 100 µsec time resolution with arrays of FLC shutters and CCD spectrometers.
Fast He BES
Fast He beam emission spectroscopy offers possibility of local measurement of $T_e$ and $n_e$ in plasma core.

- Thermal He or fast Li BES is a well-established diagnostic technique
  - record ratio of emission intensity of two visible lines
    - lines chosen such that ratio dependent on local plasma parameters
  - used to measure $T_e$ and $n_e$ in plasma edge
  - beam typically does not penetrate to plasma core

- Similar technique proposed for emission from fast He neutral beam
  - but fast neutral beams have *substantial metastable fraction*
    - result of neutralization following ion acceleration
  - metastable fraction alters beam emission ratios
    - either quantify metastable fraction (difficult)
    - or select emission ratios relatively insensitive to metastable fraction
Fast He BES has been tested in MST.

- He neutral beam
  - primarily used for Rutherford scattering diagnostic
  - He beam diameter ~5 cm at observation point
  - \( N_{\text{beam}} \sim 1.6 \times 10^{10}\text{cm}^{-3} \)
  - operated at ~16 keV for He BES

- Line of sight intersected beam at \( r/a = 0.12 \) (58 cm from beam entry to plasma)
  - oblique viewing angle Doppler shifted emission away from background
  - simultaneously recorded two emission lines
A collisional-radiative model has been applied to the He beam.

- $1^1S$, $2^1S$, and $2^3S$ populations
  - obtained by solving spatially dependent balance equations
- Other excited state populations
  - equilibrium solutions relative to the above three populations
The metastable fraction for the fast He beam was estimated to be 1.5%.

- Measured ratio of emission intensities for plasmas with different $T_e$
  - compare with theoretical values calculated for various initial fractions
Metastable fraction drops substantially as beam passes through MST plasma.

- Ground state atoms are relatively unaffected
  - ~80% pass across the whole cross section
Singlet line emission is not sensitive to the initial metastable fraction, particularly at the observation point in MST.
Triplet line emission is very sensitive to the initial metastable fraction.
If the initial metastable fraction is low enough (< 5%), singlet line ratios may yield measurement of local density.

- Ignore the relatively small effect on singlet emission from metastable populations
Comparison of measurement to modeling has not yielded conclusive results on MST.

- Modeling suggests that $I_{667}/I_{492}$ should have a strong $n_e$ dependence and a weak $T_e$ dependence.
- Measurements reproduce the qualitative feature of positive dependence on $n_e$.
  - The ratio from modeling is consistently twice that from experiment.
Summary

- Advanced CXRS and spectral MSE diagnostics are routinely operated on MST to measure fast plasma dynamics
  - ADAS is one of the keys to the success of spectroscopic diagnostics on MST
- Fast He BES has been tested on MST
  - He I singlet line intensities are weakly affected by metastable fractions
    - may be possible to use to derive local $n_e$

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Plasma parameters measured</th>
<th>Spatial and temporal resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHERS</td>
<td>Impurity (C) $T_i$ and $v_i$</td>
<td>2 cm, 100 kHz</td>
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<tr>
<td>Spectral MSE</td>
<td>$</td>
<td>B</td>
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