Thomson Scattering Measurements of Non-Tearing-Mode Temperature Fluctuations

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Results of two novel Thomson-scattering-based fluctuation measurements on the MST RFP will be presented. We seek to understand anomalous electron heat transport in the RFP when stochastic magnetic fields are no longer the dominant contributor to transport, such as during improved confinement (PPCD). Previous measurements on MST relied on correlations between the temperature and the edge magnetic signals, demonstrating 15±5 eV temperature fluctuations correlated with the dominant core-resonant tearing mode in 400kA standard plasmas, with similar or smaller amplitudes for other modes as well. By correlating between nearly-simultaneous Thomson scattering electron temperature measurements (made using a tandem laser system), low amplitude plasma electron temperature and density fluctuations can be detected, without reference to the tearing modes. Total fluctuations of up to 35 ± 5 eV are observed in the plasma core during standard MST plasmas. This confirms that activity correlated with tearing modes composes a large share of the electron temperature fluctuations. In PPCD plasmas, the core-resonant tearing modes are known to be reduced by about a factor of three in amplitude, resulting in a corresponding reduction in relative electron temperature fluctuations. Since the equilibrium temperature rises from 350eV in standard plasmas to 1100eV in PPCD (each at 400kA), the absolute fluctuation levels remain similar. Total fluctuations in the core in PPCD are up to 40 ± 20 eV, whereas the tearing-mode correlated fluctuations are up to 30 ± 10 eV. A second novel measurement is the correlation between the Thomson scattering electron temperature and a high-frequency, small-scale density fluctuation detected by the FIR interferometry diagnostic. An upper limit on the FIR-correlated electron temperature fluctuation of 5 eV was found in the edge region where the mode is localized.

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Key Results

- **TS burst-covariance measures $T_e$ fluctuation with frequency resolution**
  - Possible signature of localized 400 kHz $T_e$ fluctuation
  - Core fluctuations in standard plasmas are predominantly low-frequency
  - Total $\tilde{T}_e/T_e$ is lower in PPCD

- **Tearing mode analysis has been extended to higher spatial harmonics**
  - Some fluctuation power exists in higher harmonics
  - Not sufficient to account for remaining low-frequency $\tilde{T}_e$ from burst-covariance

- **TS-FIR correlation attempted**
  - FIR interferometer shows edge-localized density fluctuation
  - Correlation length & mode number spectrum uncertain
  - Correlation to TS $T_e$ yields 3+/- 3 eV
  - Does not set a clear upper limit on the local $T_e$-$n_e$ correlation
MST RFP device parameters

- $R = 1.5 \text{ m}$
- $r = 0.52 \text{ m}$
- Circular cross-section
- $I_p < 0.6 \text{ MA}$
- $n_e \sim 1 \times 10^{19} \text{ m}^{-3}$
- $|B(0)| < 0.6 \text{ T}$
- $T_e \leq 2 \text{ keV}$
RFP marked by presence of global tearing modes

- Helical current/magnetic field perturbation
  - Electron temperature perturbation reflects magnetic structure
- Driven by natural current gradients
- Erupt spontaneously at ‘sawteeth’
- Mode overlap causes stochastic field lines
  - Limits confinement severely
- Suppressed by auxiliary current drive (PPCD)
Thomson Scattering Process Provides $n_e, T_e$ Measurements

- Plasma electrons oscillate under incident E-field
- Accelerating charge re-emits at same frequency
- Electron thermal velocity $\rightarrow$ Doppler broadening $\rightarrow$ temperature
- Total signal $\rightarrow$ density
MST TS Diagnostic Has High Spatial, Temporal Resolution

- 21 radial points, ~1cm resolution
- 2 Laser systems
  - Spectron: 25kHz burst (8 pulses each)
  - Fast Laser: 100 kHz burst (15 pulses)
- See W. Young, Fri @ 10:30am
Pulsed Parallel Current Drive (PPCD) reduces tearing mode amplitudes

- Dynamo ordinarily sustains edge $J_{||}$
  - Higher $\eta$, lower $q$ in edge $\rightarrow$ edge current drive needed

- Poloidal induction causes edge parallel current drive
  \[ E_{||} = E_\theta B_\theta + E_\phi B_\phi \]
  - Poloidal Induction
  - PPCD
  - Toroidal Induction
  - Primary Current Drive

- Tearing mode activity reduced
Tearing mode temperature fluctuations due to magnetic topology

- Closed helical flux surfaces short-circuit temperature gradient
  - Profile flat at X-point, steep at O-point
- Produces fluctuation in phase with rotating mode
- Radial structure informative

H.D. Stephens et al, PoP 17, 056115 (2010)
Modeling tearing mode $T_e$ structure to capture total fluctuation power

- 32 magnetic coils in toroidal array used to resolve toroidal mode numbers
  
  - $B_\phi(\phi) = \sum_{n=0}^{16} B_n \cos(n\phi - \delta_n)$
  
  - Assuming poloidal mode number $m=1$, total phase at TS location is $\Phi_{n,TS} = n\phi_{TS} + \theta_{TS} + \delta_n + \pi/2$
    
    - $\frac{\pi}{2}$ accounts for radial component of magnetic mode leading toroidal component
  
  - $\Phi_{n,TS} = 0$ when mode O-point is facing TS measurement location

- Fluctuations assumed to have a form $T_e = F(\Phi_{n,TS}) + \cdots$
  
  - Linear model: $T_e = T_{e,0} + \tilde{T}_e \cos \Phi_{n,TS}$
    
    - To first order, the fluctuation should be in phase with radial component
  
  - Amplitude & phase: $T_e = T_{e,0} + \tilde{T}_e \cos(\Phi_{n,TS} + \delta)$
    
    - Captures Shafranov shift, other sources of phase shear

  - Higher harmonics: $T_e = T_{e,0} + \tilde{T}_{e,2} \cos(2\Phi_{n,TS} + \delta_2)$
    
    - Test for more fluctuation power associated with tearing modes
    
    - Harmonics are orthogonal, so we can analyze them independently
Tearing correlation works well in standard plasmas

- Phase & amplitude clearly defined
  - Captures both in & out-of-phase $T_e$
- Mode width may be determined
- Phase flip & zero amplitude at resonant surface → q-profile constraint
  - See E. Parke, P2.036, this conference
- Shafranov shift evident in phase ($z/a<0.2$)
Higher harmonics of n=6 have measurable amplitude

- First results on the higher harmonic content for MST
- Amplitude strongest outside mode rational radius
- Consistent with picture of temperature flattening within island
  - PC de Vries et al, PPFC 1997
\( n=5 \) mode is predominantly sinusoidal

- Higher harmonics do not contribute to fluctuation power
- Clearly not a gradient-flattening island
- Hot island may be indistinguishable from helical axis (SHAx)
  - MHD/thermal transport modeling desired

![Graph showing amplitude vs. z/a for 400kA Standard, n=5 tearing mode 1-3ms post-sawtooth.]](attachment:graph.png)
Burst-Covariance measures $\widetilde{T_e}^2$, insensitive to diagnostic errors

- Take covariance of $T_e$ from Laser 1, 2 in pair-burst mode
  - $C = \frac{1}{N-1} \sum_i^N [T_{e1,i} - \overline{T_{e1}}] \cdot [T_{e2,i} - \overline{T_{e2}}]$

- Mean of covariance reflects only true temperature fluctuations
  - Diagnostic errors have no covariance, average to zero

- Mean of covariance taken over large ensemble of similar shots
  - Error bars based on standard error in the mean
Burst-covariance allows probing of high-frequency fluctuations

- Possible to probe high frequencies by varying inter-laser spacing $\delta t$
  - High-Frequency response governed by $\delta t$
  - Low-Frequency response determined by $n$, $\Delta t$
- Existing data has $\delta t = 1 - 5 \mu s$
  - Positive sensitivity to tearing mode frequencies
  - Negative sensitivity only for frequencies >50kHz

\[
\langle C \rangle = \int_0^\infty A(\omega)S(\omega)d\omega
\]

\[
A(\omega) = \frac{N}{N-1}\cos(\omega \cdot \delta t) - \frac{1}{N(N-1)} \sum_{i,j}^{N,N} \cos[\omega \Delta t(i - j)]
\]
PPCD has less low-frequency $\tilde{T}_e/T_e$ than standard

- Lower tearing mode amplitudes probably responsible
- Absolute $\tilde{T}_e$ fluctuations comparable
  - Relative fluctuation proportional to equilibrium gradient
  - PPCD equilibrium $\nabla T_e$ larger

$$\left(\frac{T_e}{T_e}\right)^2$$

$$\left(\tilde{T}_e\right)^2$$
Standard: tearing modes account for most of total $\tilde{T}_e^2$

- **Possible explanations**
  - Other fluctuations at low frequency exist
  - Secular response of burst-covariance larger than expected
  - Tearing model not capturing all fluctuations associated with tearing mode
    - Harmonics not sufficient to account for difference
    - Errors in magnetic mode phase?
    - Radial motion of $r_s$?

$n=5$ & $6$ tearing fluctuations (up to 4th harmonic) account for most of the total core $\tilde{T}_e^2$
PPCD tearing-correlated $\tilde{T}_e$ does not exhibit clear mode structure

- Low mode amplitudes
  - Low SNR for TS
  - May exacerbate tearing mode phase errors from magnetics
- Small data set
- Large uncertainties
Possible localized 400 kHz $\tilde{T}_e$ fluctuation

- Most of profile consistent with $f < 50$ kHz
- Fluctuation at $r/a=0.6$ consistent with 400 kHz peak
  - Covariance vs $\delta t$ best fit by 400 kHz
- Suspicious
  - $\delta t = (2.0, 2.5, 5.0)$ taken on same day
  - $\delta t = (1.675, 3.325)$ taken on different days
  - Need fresh data: shuffle polychromators, $\delta t$ values

![Graph showing 400kA Std Plasma Covariance Profiles vs Time Delay $\delta t$](image1)

![Graph showing 400kA Std Plasma Covariance at $r/a=0.6$ vs Time Delay $\delta t$](image2)
FIR sees localized short-wavelength density fluctuation in edge

- See J. Duff P2.020
  - 200kA PPCD
  - Up to 10% relative fluctuation
  - 50-150 kHz
  - Edge-localized \((r/a \gtrsim 0.8)\)
Correlating FIR density to TS temperature is difficult

- TS and FIR separated by 20 degrees toroidally
- Correlation length is short (~10 degrees)
- Extrapolation of mode phase from FIR to TS location quadruples phase uncertainty
  - Toroidal mode number must be determined
  - Use cross-phase spectrum between FIR chords at 5 degrees separation
  - Must be done for each shot since rotation velocity matters
- Using magnetic signals as proxy does not work
  - Density fluctuation does not correlate well with magnetics
No significant TS-FIR correlation

- $T_e, n_e$ correlations small, within errors of zero
- Cannot conclude that the density mode has no temperature perturbation
  - Lack of significant $n_e$ correlation implies technique won’t detect $T_e$ fluctuation either
  - Need co-located measurements of $T_e, n_e$ fluctuations at high frequency
    - Fast laser system could address this in the near future
Future work

• Interpretation
  – What do harmonics tell us about tearing n=5 vs n=6?

• Expand datasets
  – Utilize existing datasets for tearing mode studies
  – Would like to take more data for TS burst covariance in PPCD, Standard, add F=0
    • Move edge polychromators to be sure high-frequency signal is real
    • Improve laser energy & alignment for edge diagnosis

• Analysis
  – Justify separate analysis of harmonics
  – Reconstruct power spectrum from burst covariance vs time delay
    • Or better yet, spectral estimation technique using non-uniform sampling