Controlling fluctuations in an Internal Transport Barrier with on-axis ICRH

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in collaboration with

Strong density fluctuations observed during on-axis heating of C-Mod ITB

- Begin with strong density peaking inside ITB foot (half-radius)
- On-axis heating raises $T_e$ by 30%, destabilizing TEM
- Increased outward particle transport halts density rise
- Equilibrium established between TEM particle transport and Ware pinch
- GS2 reproduces strong relative increase in density fluctuation amplitude due to on-axis heating
GS2 Synthetic PCI diagnostic

- Could make multiple copies of flux tube, rotated toroidally, to cover flux surface
- Equivalent approach: integrate density fluctuations along flux tube, over range of angles subtended by PCI laser

- Result: radial and poloidal spectra are mixed, yielding apparent downshift in measured $k_R$ spectrum.

- Mainly geometric effect

D. R. Ernst et al., IAEA (2006).

- Transform $k_R = (\nabla R \cdot \nabla \psi / |\nabla \psi|)k_\psi + (\nabla R \cdot \nabla \alpha / |\nabla \alpha|)k_\alpha$
- Instrument function: Gaussian beam, finite aperture, reference beam $k_R \sim 0$
Simulations reproduce measured wavelength spectrum of TEM density fluctuations in the ITB

- GS2 with synthetic PCI diagnostic
- Shape of measured wavenumber spectrum in close agreement
- Wavelength of peak in close agreement
  - Synthetic diagnostic produced downshift from 4 cm\(^{-1}\) to 3 cm\(^{-1}\)
  - Largely due to geometric effects: PCI measures \(k_R\) spectrum (wrs to major radius)
- ITB in effect localizes chord-integrated fluctuation measurement
- PCI amplitude not absolutely calibrated in these prior 2004 experiments
- PCI is line-integrated: Do changes in the edge fluctuations matter?

D. R. Ernst et al., IAEA (2006).
Our latest C-Mod ITB experiments utilized modulated ICRH to separate core and edge fluctuations

- On-axis ICRH modulated 50ms on, 50ms off
- On-axis electron temperature increased 50% during heating pulses
- Again, strong bursts of density fluctuations accompany heating pulses
- Edge fluctuations diminish during on-axis heating
- Greatly improved diagnostic coverage; multiple fluctuation diagnostics; PCI calibrated
On-axis pulses produce strong, localized perturbations

- Large swings in core temperature
- Ion temperature measurements by high resolution x-ray crystal spectroscopy
- Ti coverage out to r/a ~ 0.3: ITB pinches Argon, depleting region of interest
- Fitted profiles for Te, Ne shown
- Ran experiments at higher toroidal field to eliminate ECE cutoff: full ECE coverage of ITB
Profile fitting upgraded to include Monte Carlo error analysis

- Profile fitting tools combine available profile data from multiple diagnostics into a fitted density and temperature profiles
- Significant recent upgrades to fitting software
- Monte Carlo error analysis of profiles and their gradients
- Trials can be saved for MC code runs
- Error bars on gradient
Are the strong PCI density fluctuations from the edge or the core?

- PCI in phase with core temperature
- 88 GHz reflectometer: $n_e \sim 0.4 \, n_e^{ped}$
  - Edge density fluctuations actually diminish during the on-axis heating
- Mirnov spectrum shows magnetic fluctuations associated with edge Quasi-Coherent mode diminish during heating pulses
Edge reflectometry in pedestal shows integrated edge density fluctuations also diminish during on-axis heating pulses.

Data from \( n_e \sim 1.0 \times 10^{20} \text{ m}^{-3} \sim 0.4 n_{e}^{\text{ped}} \)
Mirnov frequency spectra show QC mode disappears during on-axis heating; new feature appears on PCI

- During on-axis heating, PCI shows strong spectral feature (core or edge?)

- Simultaneously, magnetic fluctuations associated with the edge Quasi-Coherent mode disappear

- Reflectometry shows the edge QC mode magnetic fluctuations are not replaced by electrostatic fluctuations

- PCI appears to reflect increased core density fluctuations
Very recent experiments with more complete diagnostic set show similar behavior.

Core +

Edge

Edge fluctuations diminish during on-axis heating pulses.
Gas Puff Imaging Spectra in SOL and Pedestal

- Detailed wavelength and frequency spectra in 8 columns: $r \sim -1.6 \text{ cm to } +1.5 \text{ cm wrs to LCFS}$
- Mainly density fluctuations

Show density fluctuations in SOL diminish during on-axis heating
Possible small increase in QC mode amplitude
TEM expected in ITB during on-axis heating

- Density gradient should be strongly TEM unstable based on previous cases
- Monte Carlo error analysis of the profile fits yields a range of $a/L_n$.
- On-axis heating increases temperature, destabilizing TEM in presence of steep density gradient
- Detailed analysis in progress.
Summary

- We have used modulated on-axis heating to perturb local profiles in an ITB, with the aim of modulating TEM turbulence.

- The heating pulses drive strong bursts of density fluctuations.

- These experiments appear to have successfully ruled out edge fluctuations in the line-integrated PCI signal.

- Kinetic profiles are very well-documented, providing an ideal validation test-bed for comparison of gyrokinetic simulations with fluctuation measurements.

- Preliminary linear gyrokinetic results appear to support the role of TEM turbulence.

- Further analysis with synthetic diagnostics is planned.