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

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in collaboration with

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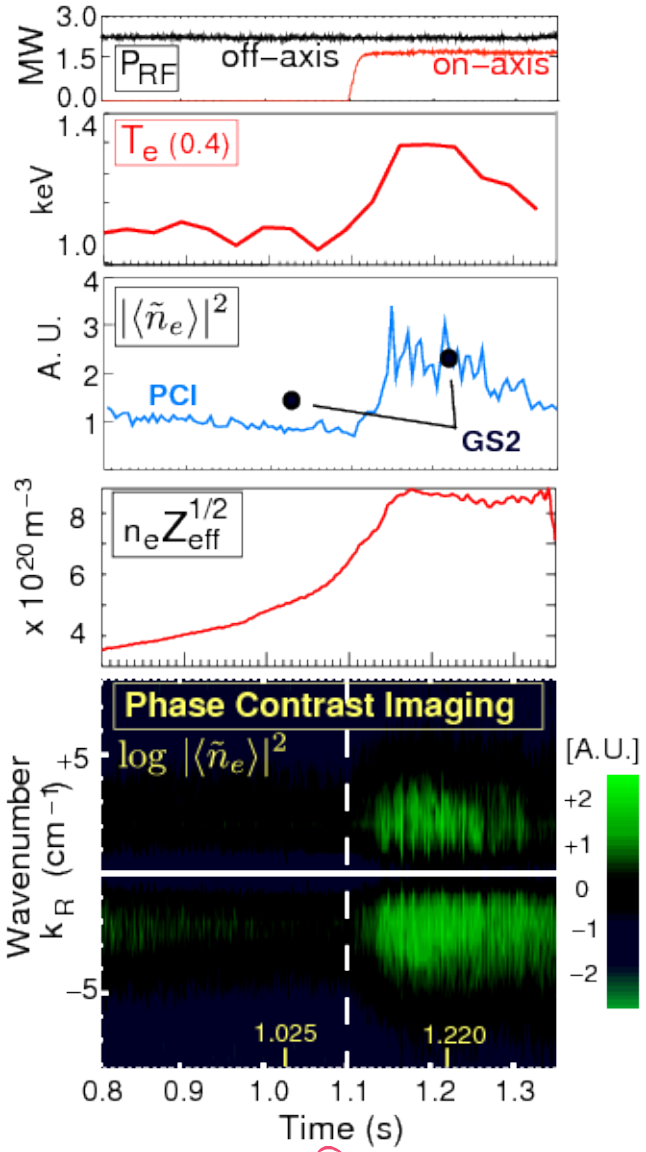
Strong density fluctuations observed during on-axis heating of C-Mod ITB

- 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 estabilished 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.**

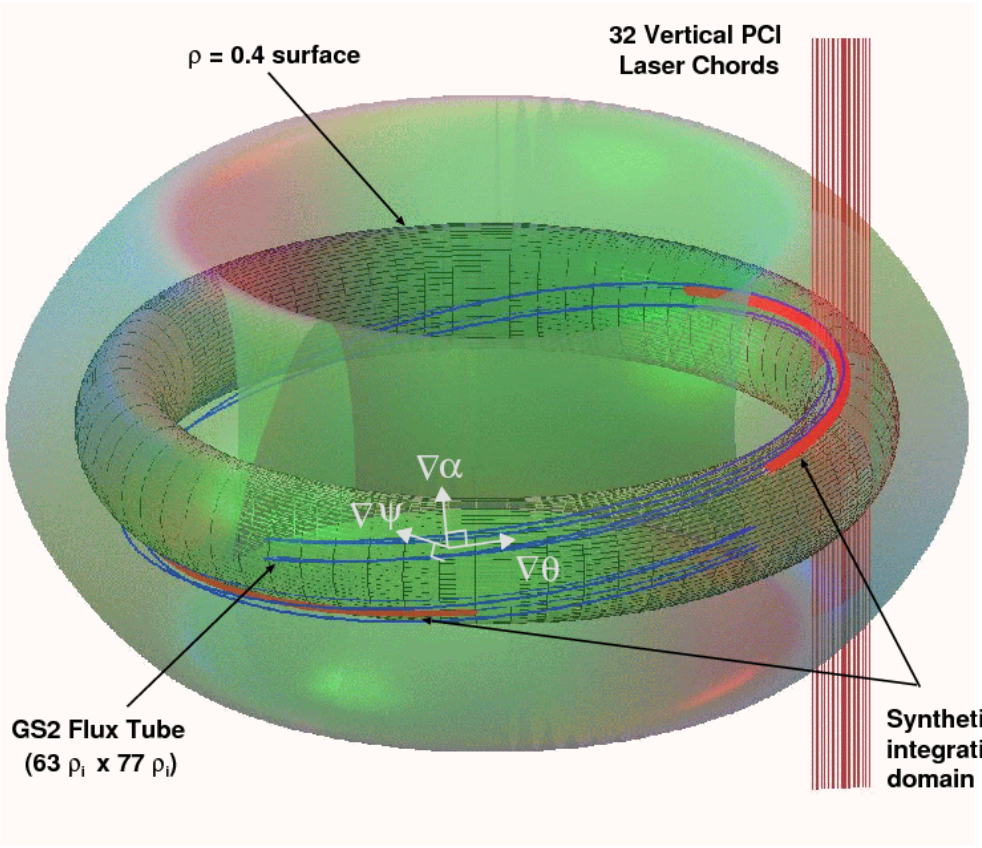
- **Mainly geometric effect**

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

Non-orthogonal

$$\mathbf{B} = \nabla\alpha \times \nabla\psi$$
$$\alpha = \zeta - q(\psi)\vartheta$$

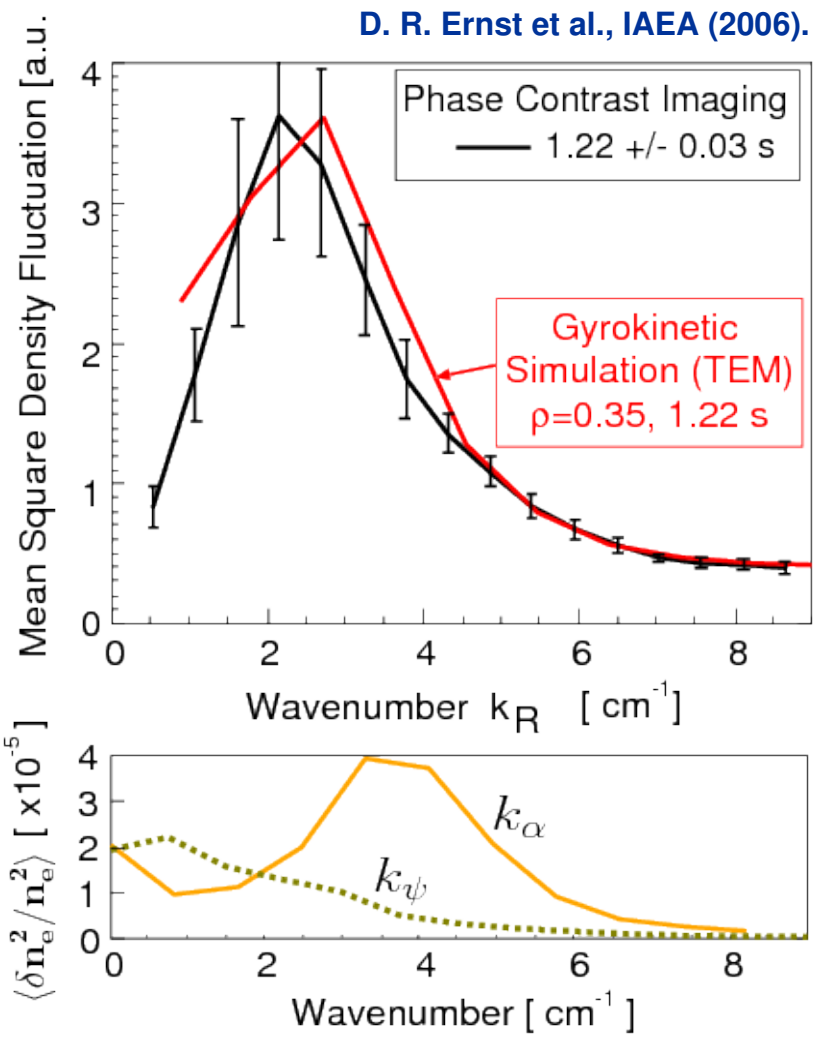
ψ labels flux surface
α labels field line
θ measures distance along field line



- Transform $\mathbf{k}_R = (\nabla\mathbf{R}\cdot\nabla\psi/|\nabla\psi|)\mathbf{k}_\psi + (\nabla\mathbf{R}\cdot\nabla\alpha/|\nabla\alpha|)\mathbf{k}_\alpha$
- Instrument function: Gaussian beam, finite aperture, reference beam $k_R \sim 0$

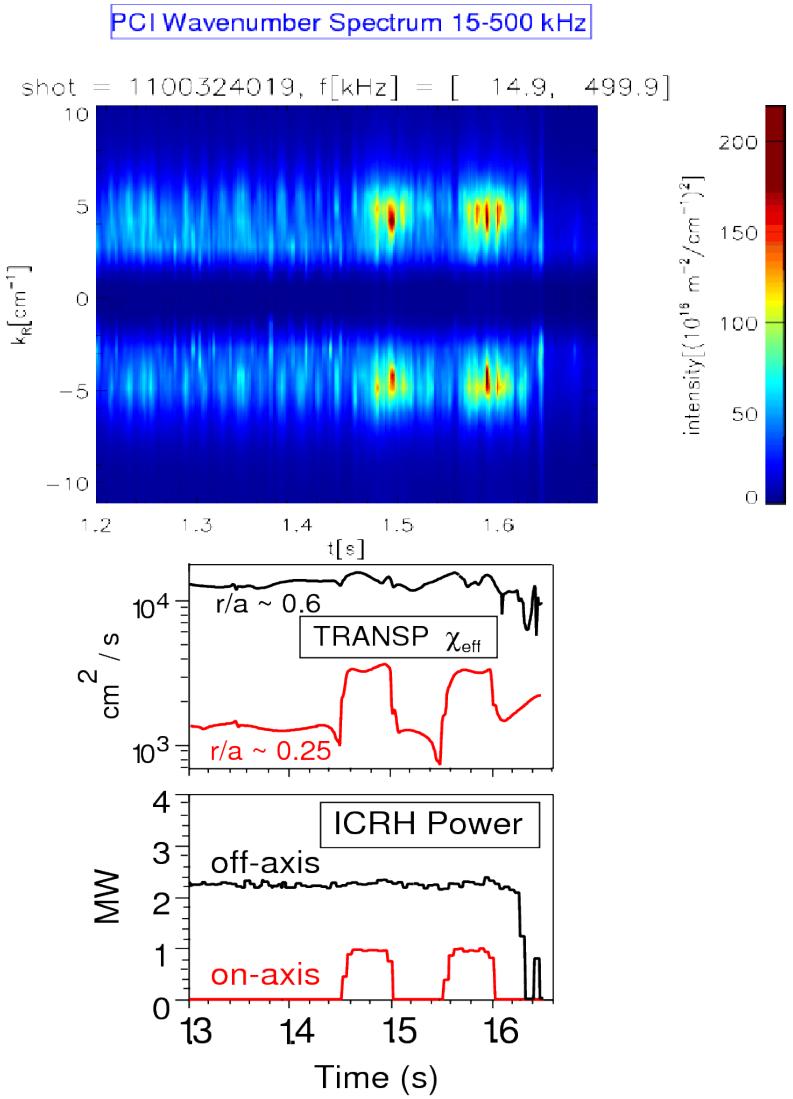
Simulations reproduce measured wavelength spectrum of TEM density fluctuations in the ITB

- 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?



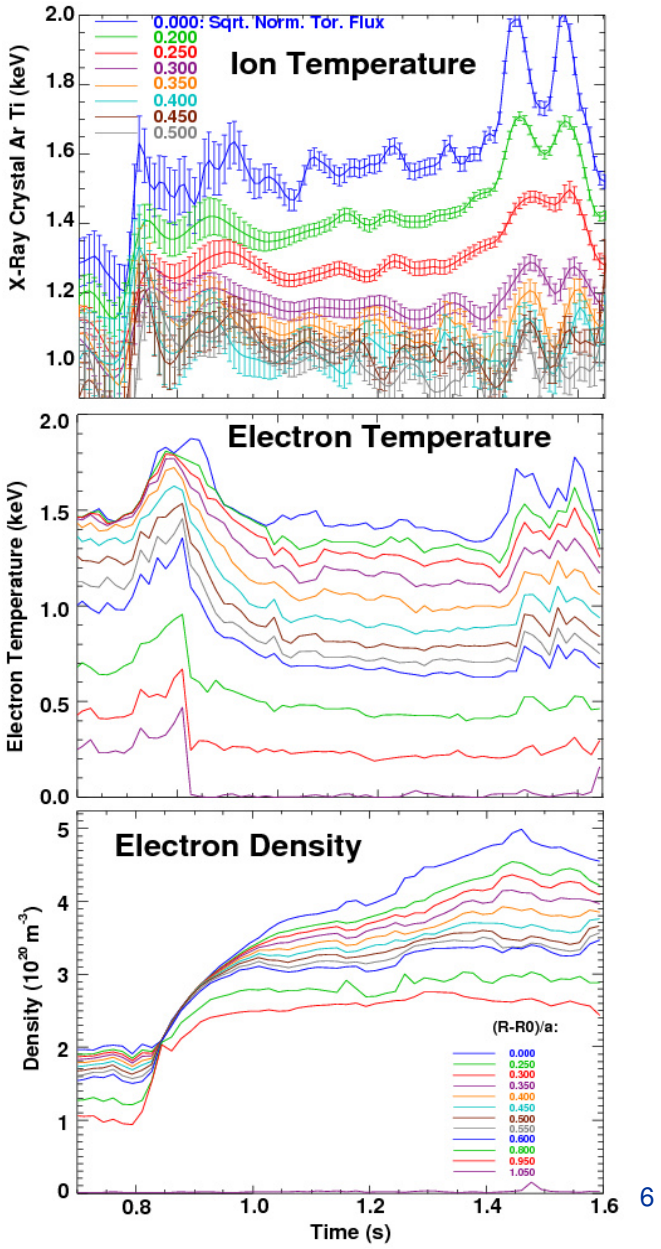
Our latest C-Mod ITB experiments utilized modulated ICRH to separate core and edge fluctuations

- **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**



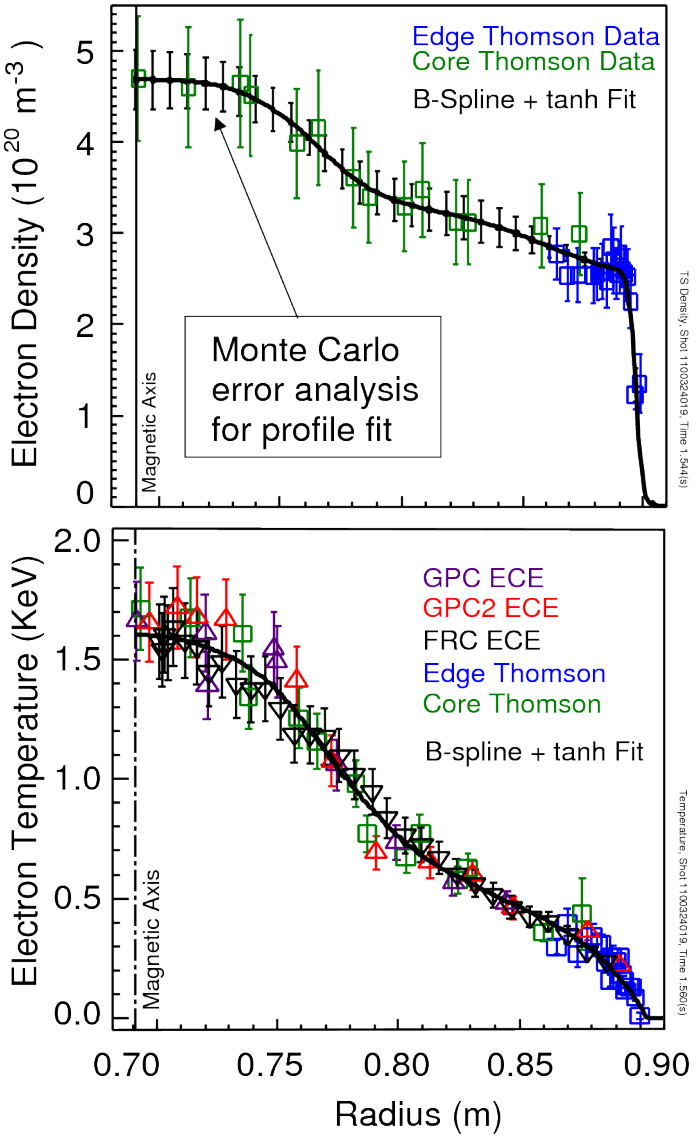
On-axis pulses produce strong, localized perturbations

- 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



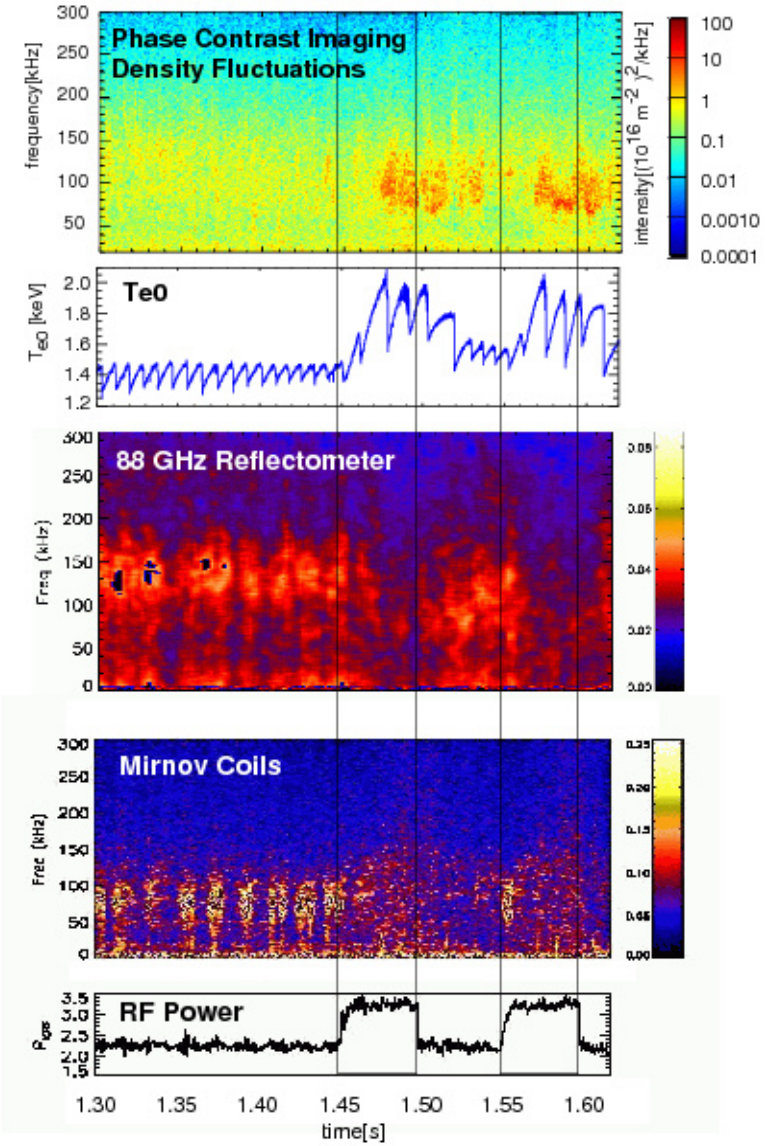
Profile fitting upgraded to include Monte Carlo error analysis

- **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**

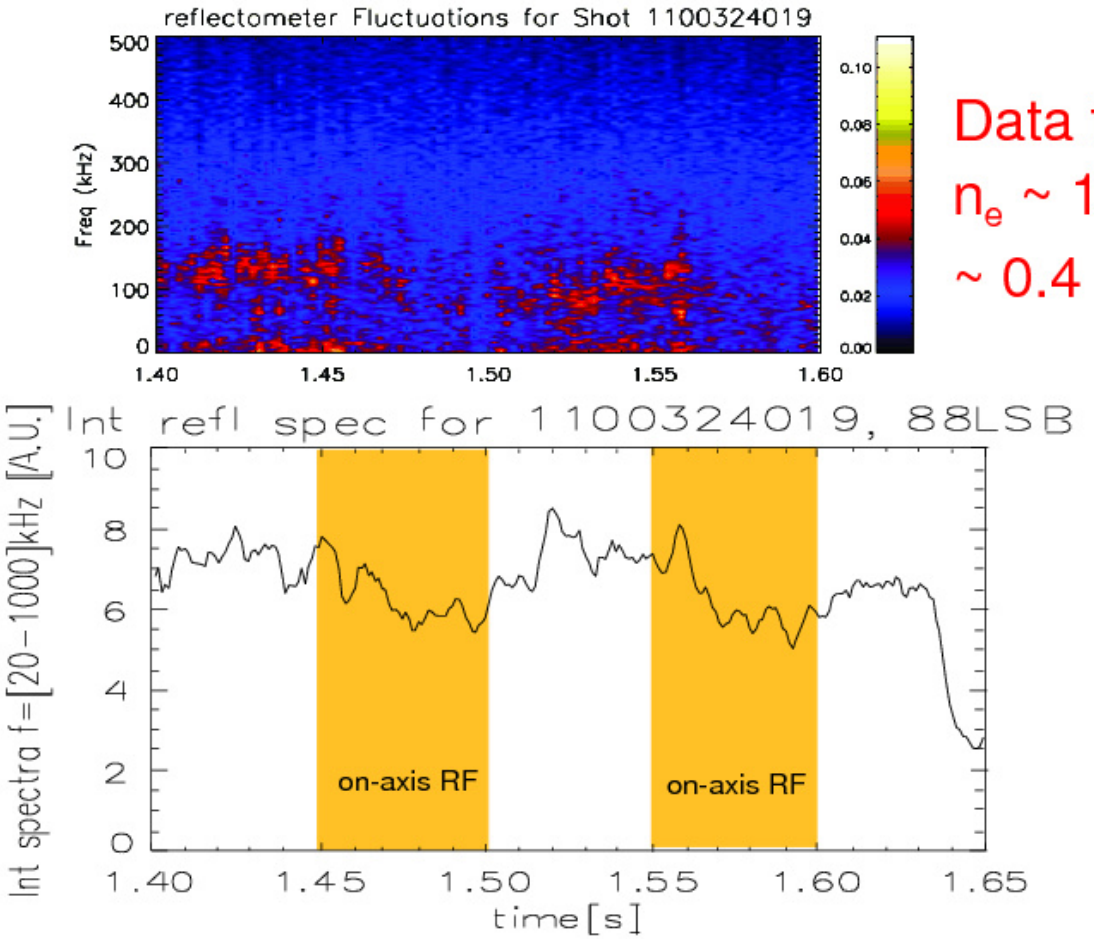


Are the strong PCI density fluctuations from the edge or the core?

- **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**

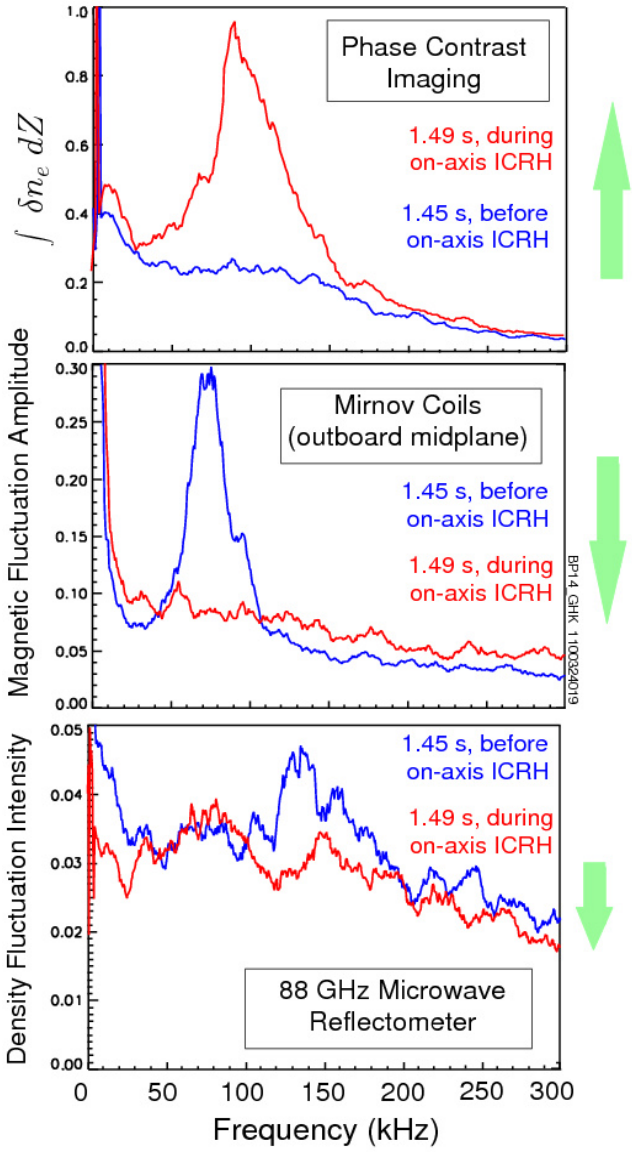


Edge reflectometry in pedestal shows integrated edge density fluctuations also diminish during on-axis heating pulses



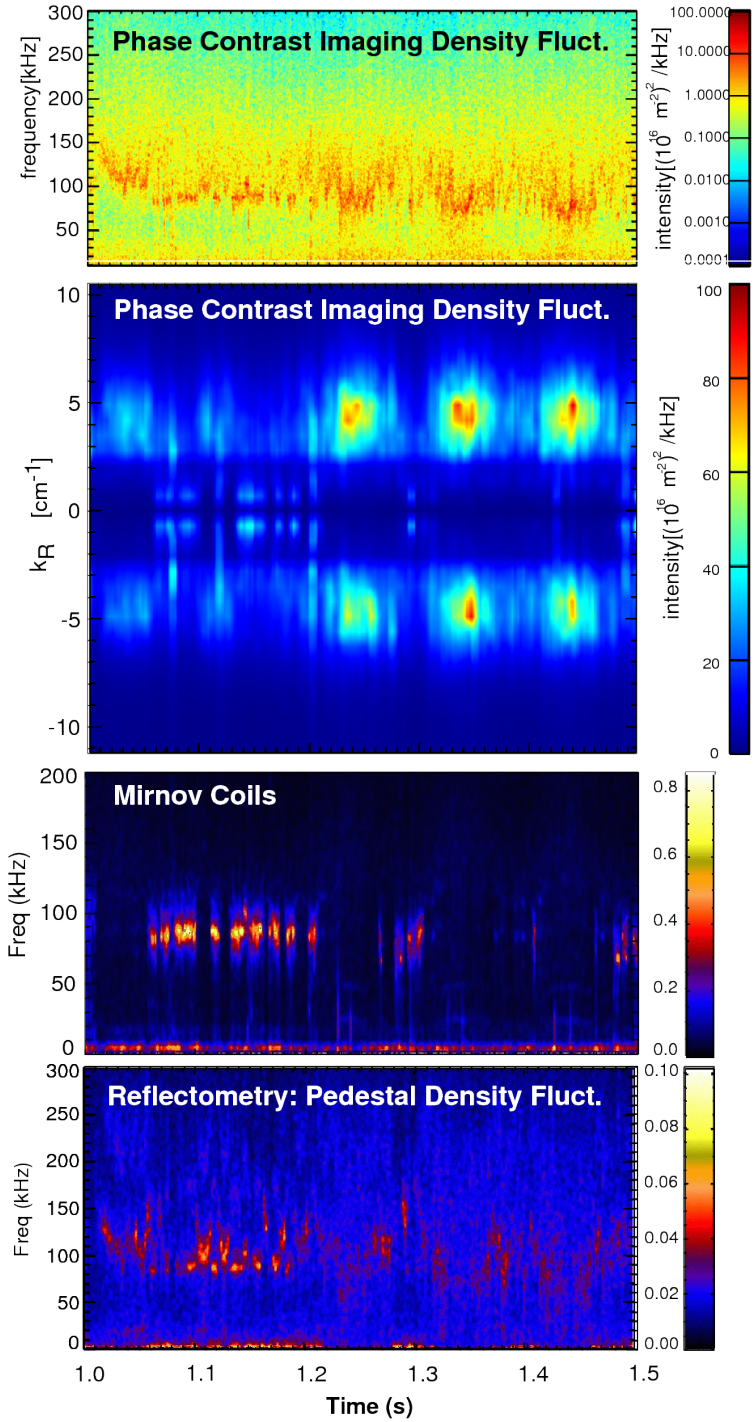
Data from
$n_e \sim 1.0 \times 10^{20}\ m^{-3}$
$\sim 0.4\ n_e^{ped}$

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**

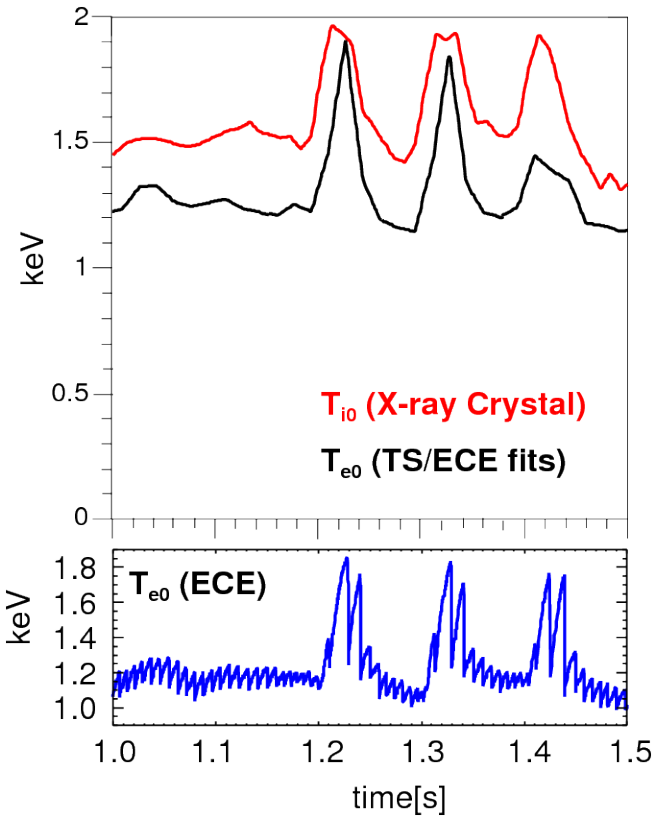
Very recent experiments with more complete diagnostic set show similar behavior



Core + Edge

Edge

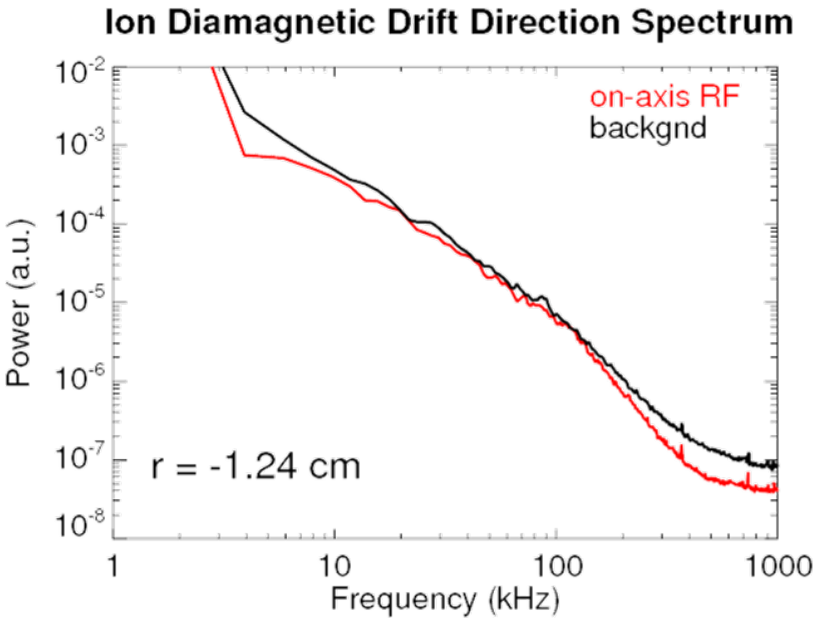
Edge

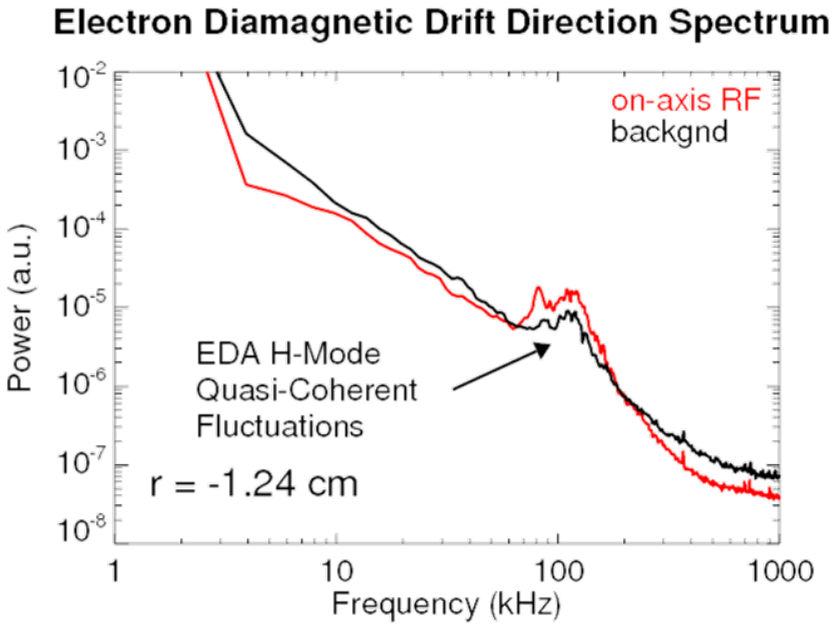


Edge fluctuations diminish during on-axis heating pulses

Gas Puff Imaging Spectra in SOL and Pedestal

- Detailed wavelength and frequency spectra in 8 columns: r ~ -1.6 cm to +1.5 cm wrs to LCFS
- Mainly density fluctuations



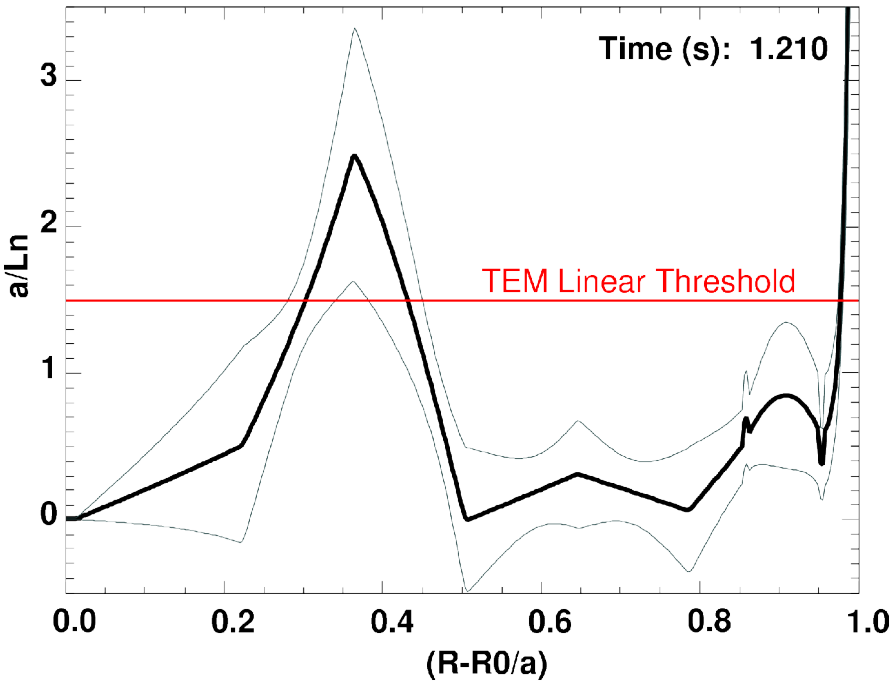


Shows density fluctuations in SOL diminish during on-axis heating

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.**