Controlling H-Mode Particle Transport with Modulated Electron Heating in DIII-D and Alcator C-Mod via TEM Turbulence

EX/2-3

by

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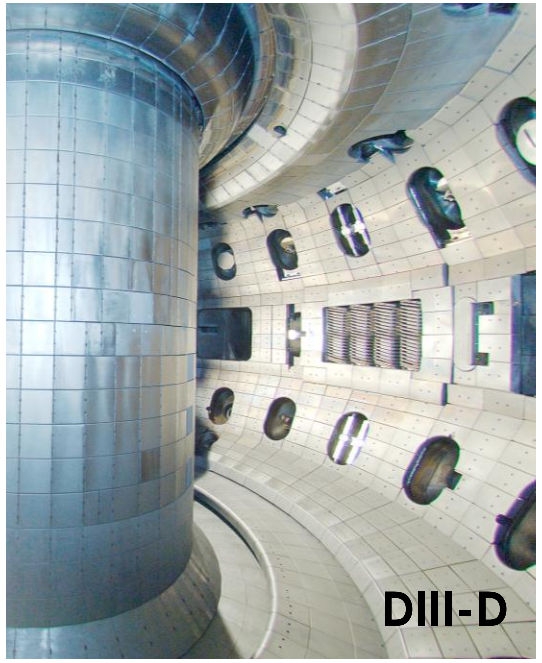

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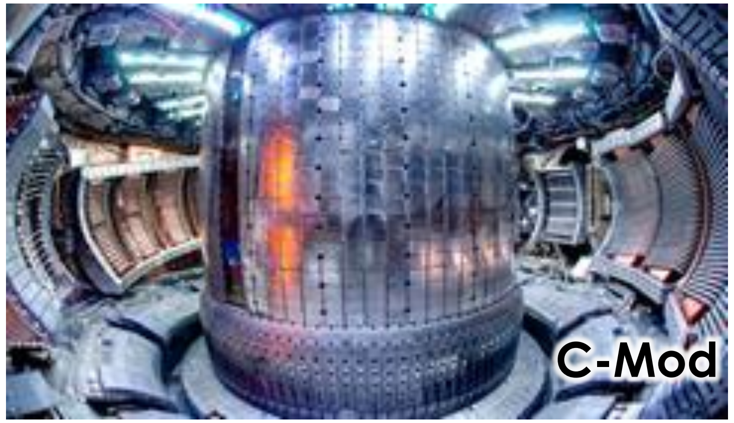

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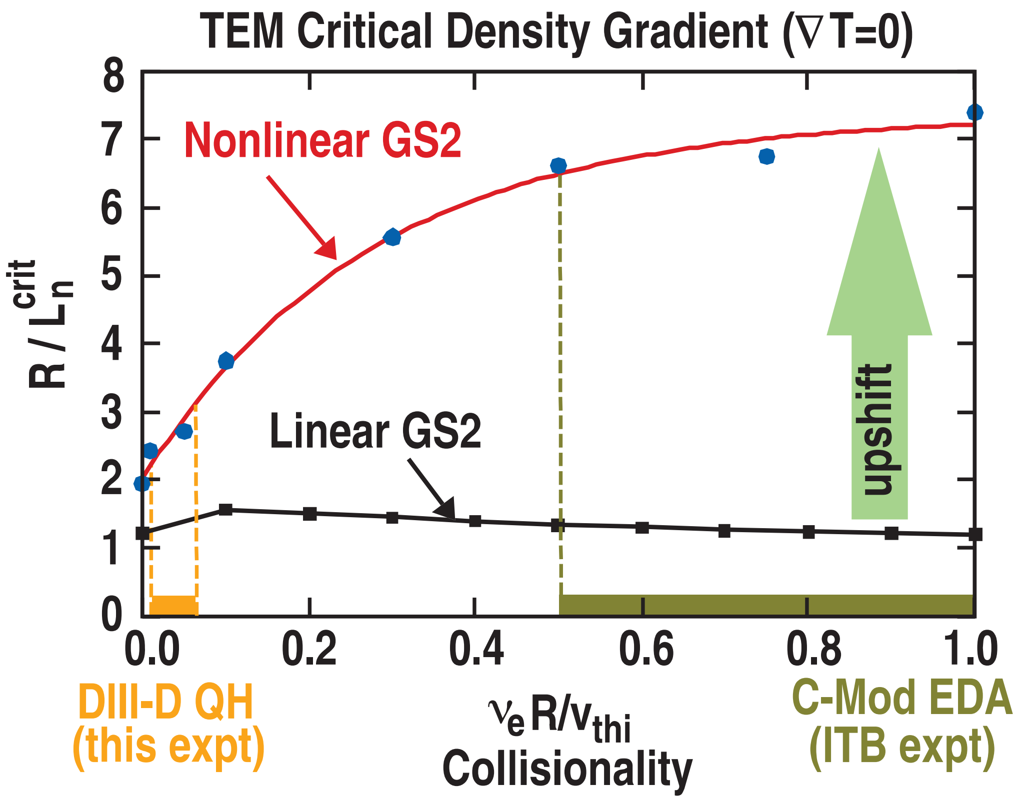
DIII-D NATIONAL FUSION FACILITY | NERSC National Energy Research Scientific Computing Center | SciDAC Scientific Discovery through Advanced Computing | MIT | Alcator C-Mod

Density Gradient Driven Trapped Electron Mode Turbulence Regulates H-Mode Inner Core as $T_e \rightarrow T_i$ and at Low Torque

- **Dedicated H-Mode experiments on Alcator C-Mod and DIII-D demonstrate local control of density peaking with strong electron heating**
- **TEM is only unstable mode in H-Mode inner core with moderately peaked density**
  - When $T_e \rightarrow T_i$ at low torque & collisionality (similar to burning plasmas)
  - Long wavelength; drives strong particle and electron heat fluxes
- **Discovered and confirmed a new nonlinear TEM threshold that increases strongly with collisionality**
- **New coherent TEMs observed and reproduced by GYRO with new synthetic Doppler Backscattering diagnostic**
- **TEM provides new mechanism for burn self-regulation:**
  - a-heating would flatten density profile, reducing fusion power

New Nonlinear TEM Critical Density Gradient Increases Strongly with Collisionality



- **220 nonlinear GS2 simulations find effective *nonlinear* TEM critical density gradient.**

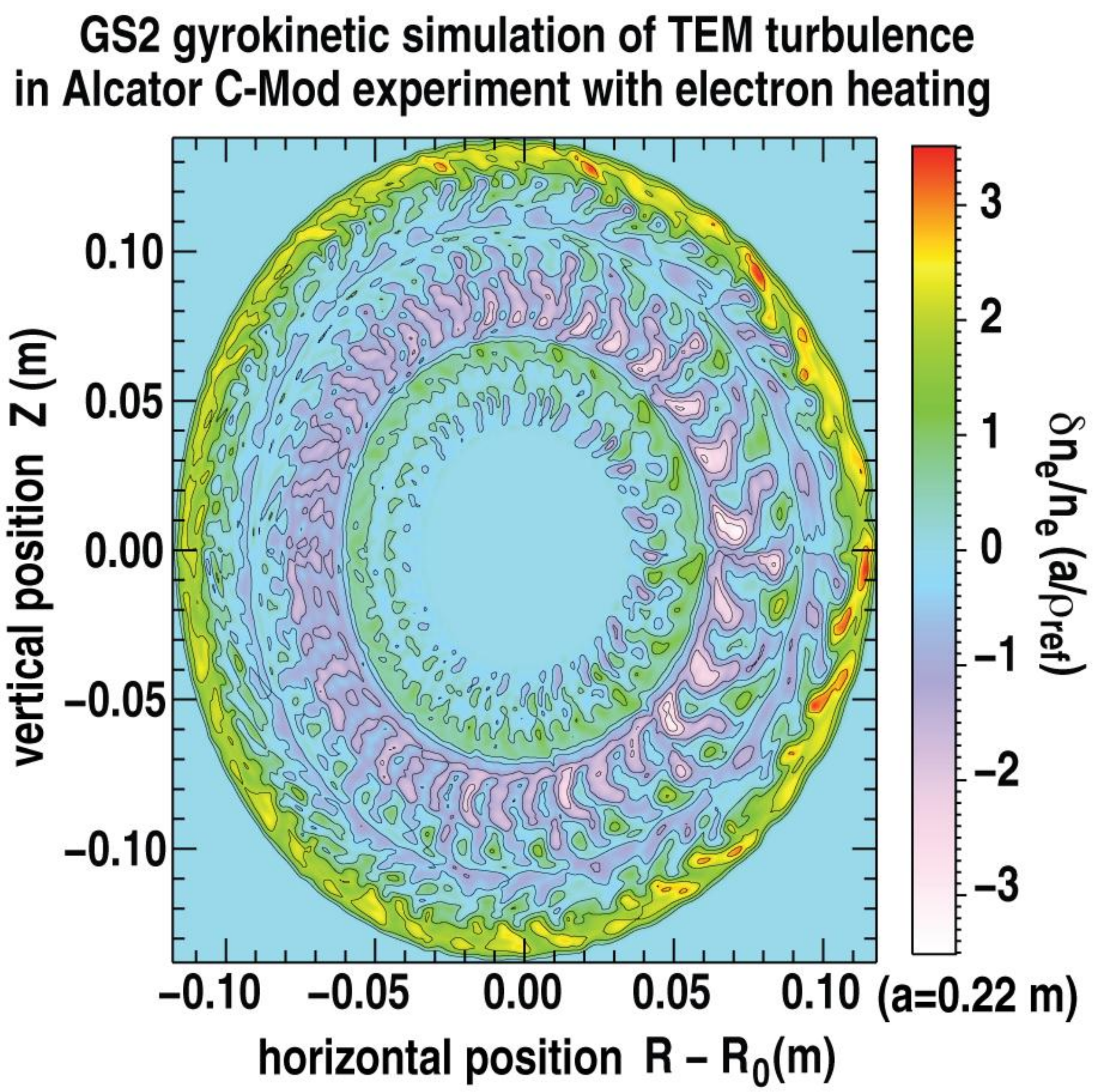
  [Ernst PoP (2004), IAEA (2006), APS Inv. (2012)]

- **Low collisionality limits density gradient**
- **~2x upshift with realistic ion temperature gradients**

- **Dedicated H-Mode TEM experiments in C-Mod and DIII-D test the TEM nonlinear upshift over an order of magnitude variation in collisionality**

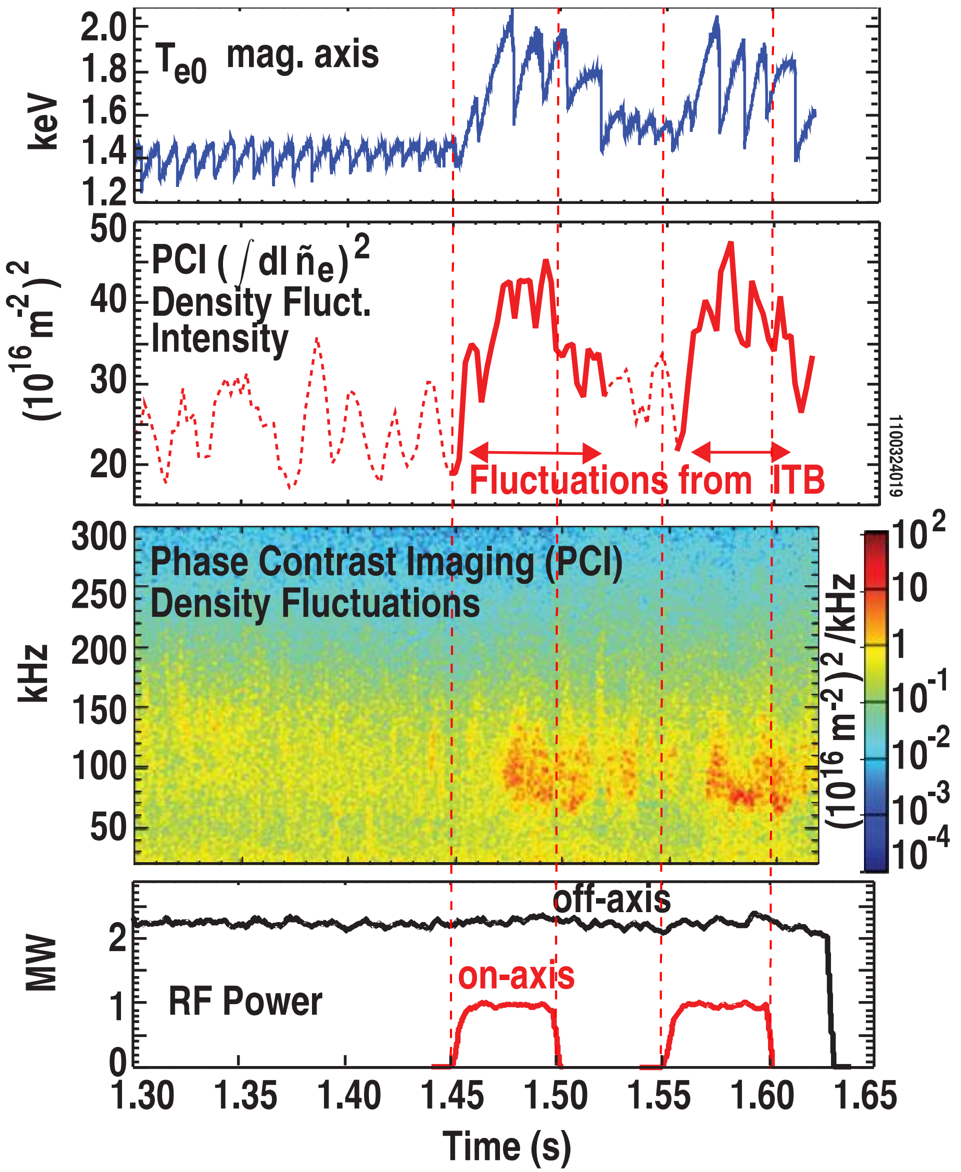
Density Gradient Driven TEMs Produce Strong Ion-scale Density Fluctuations

- **Density gradient driven TEM is long wavelength**
  - Strong particle transport
  - Strong electron thermal transport
- **Transport and density fluctuation spectra closely match gyrokinetic simulations with synthetic diagnostics**
- **TEM is sole instability for ρ<0.5 in all cases shown**

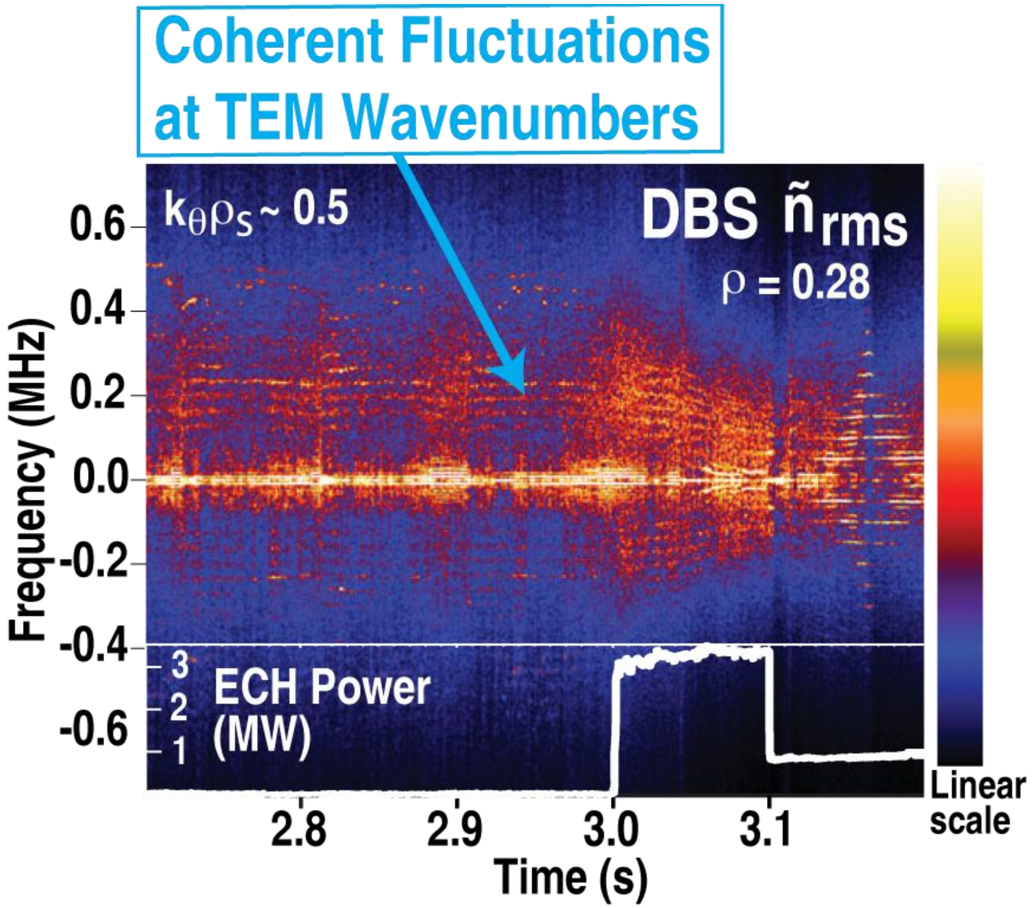


Alcator C-Mod

Local Core Density Fluctuations Increase Strongly with Electron Heating in Both C-Mod and DIII-D



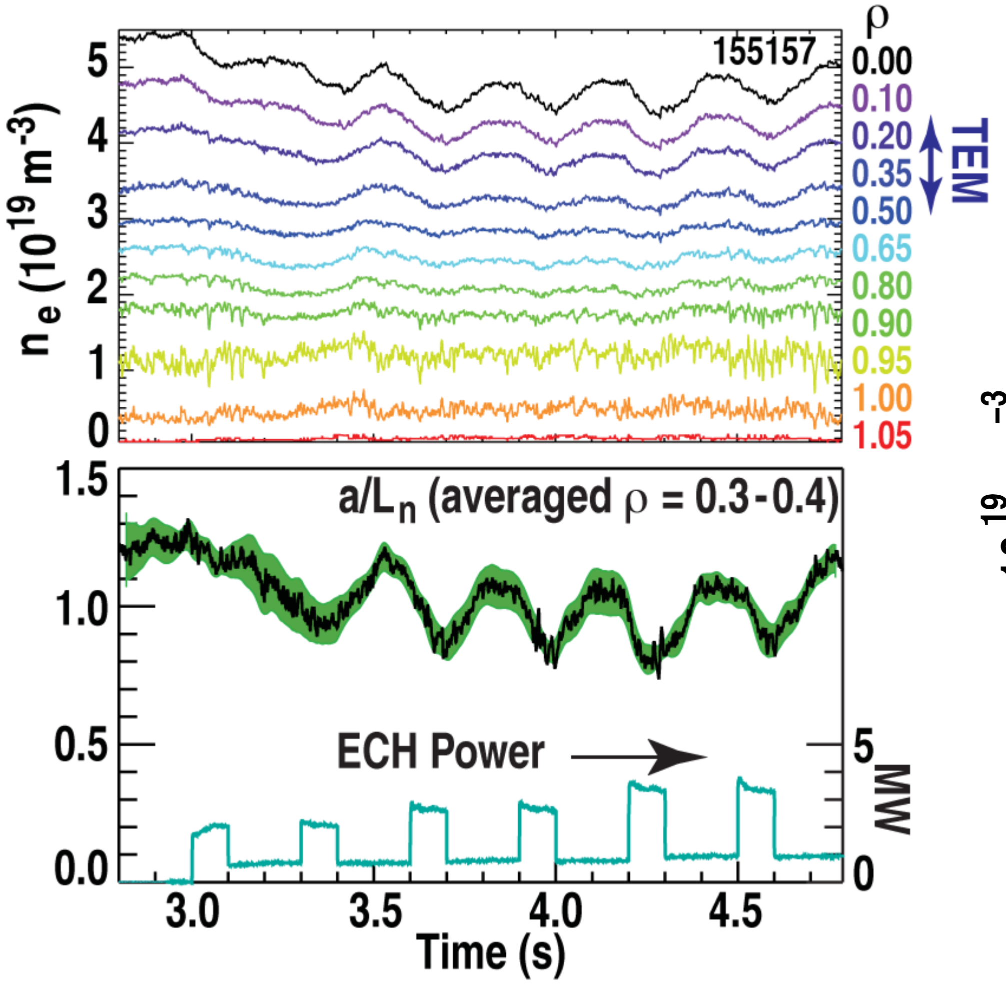
- **Phase contrast imaging on C-Mod shows density fluctuations track temperature**



- **New coherent modes observed on Doppler Backscattering in DIII-D at TEM wavelengths**

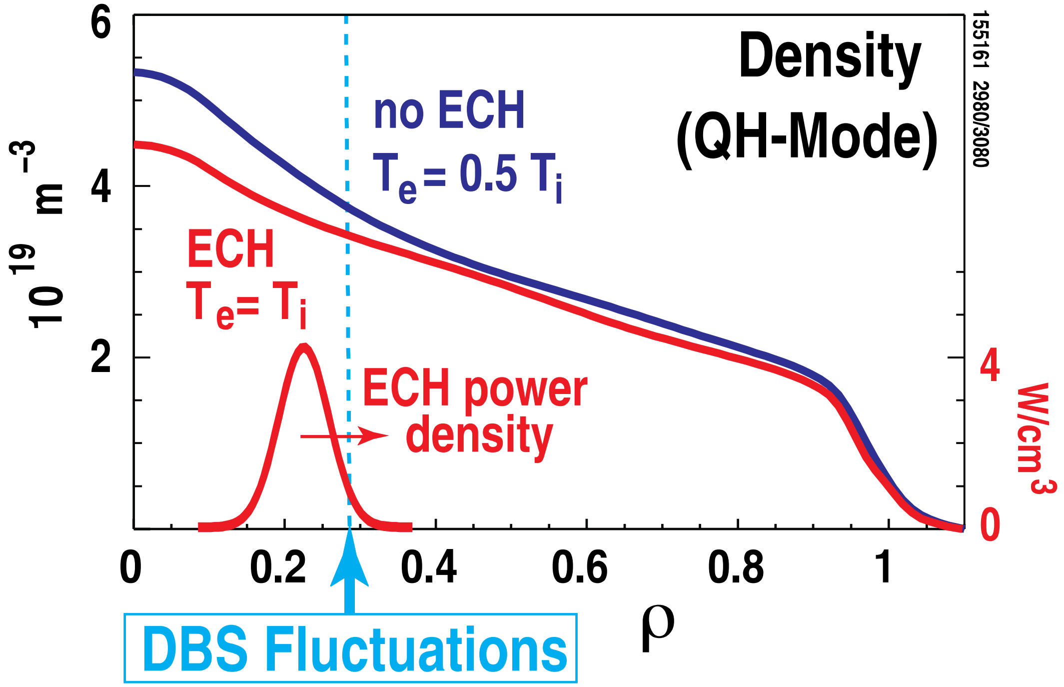
Alcator C-Mod DIII-D NATIONAL FUSION FACILITY

Density Profile Locally Flattened by Modulated ECH in DIII-D

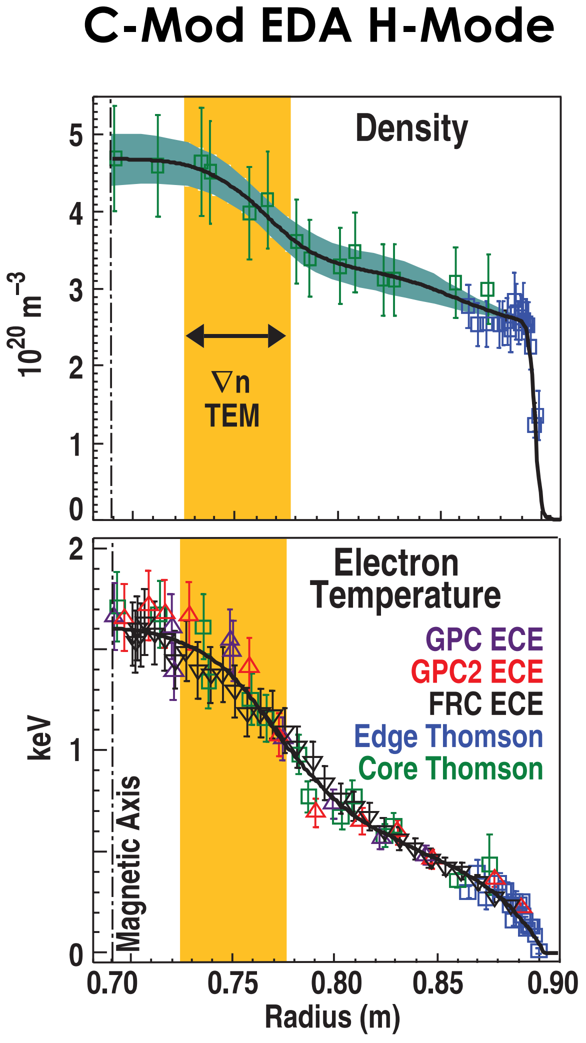


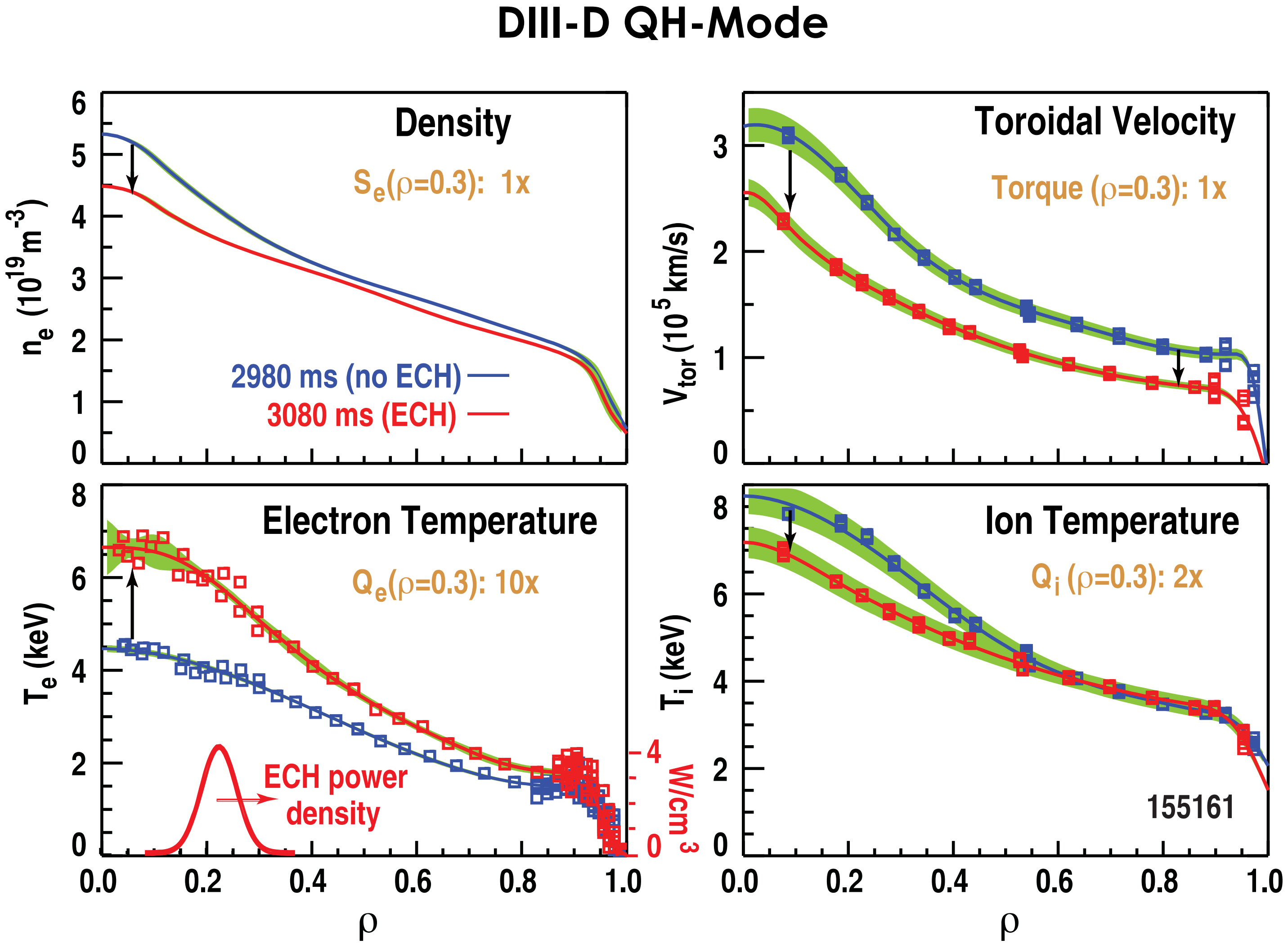
- Density is modulated by ECH only for ρ < 0.5, where GYRO analysis shows TEM dominant

- Profile reflectometer has 2-4 mm, 0.4 ms resolution



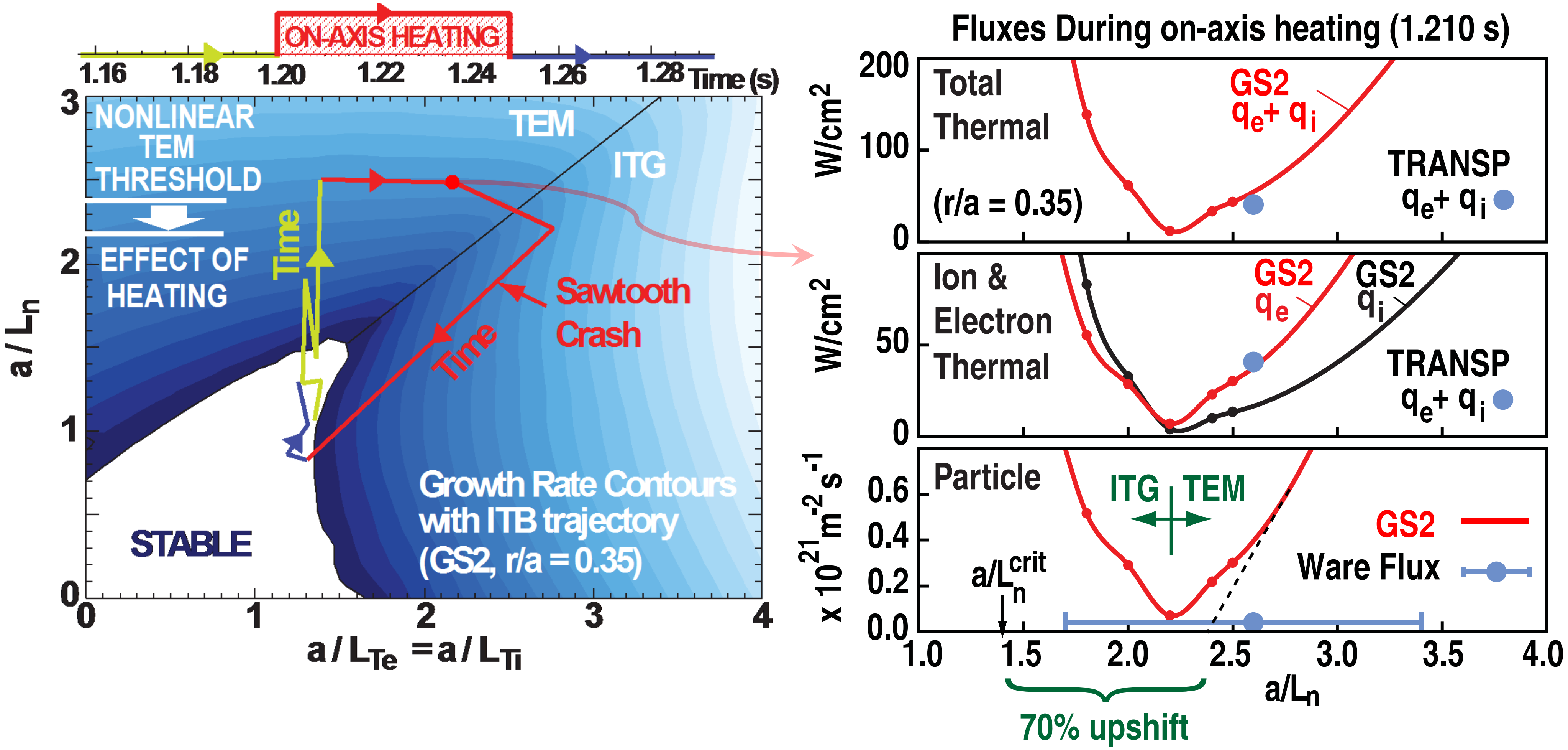
Electron Heating Raises T_e by ~50% in Both C-Mod and DIII-D Experiments





Increased Transport in C-Mod ITB During On-axis Heating Pulses is Consistent with GS2 Nonlinear Simulations of TEM

- Density gradient limited by effective nonlinear TEM critical density gradient
- Energy flux increases 5x during heating, dominated by electron energy flux

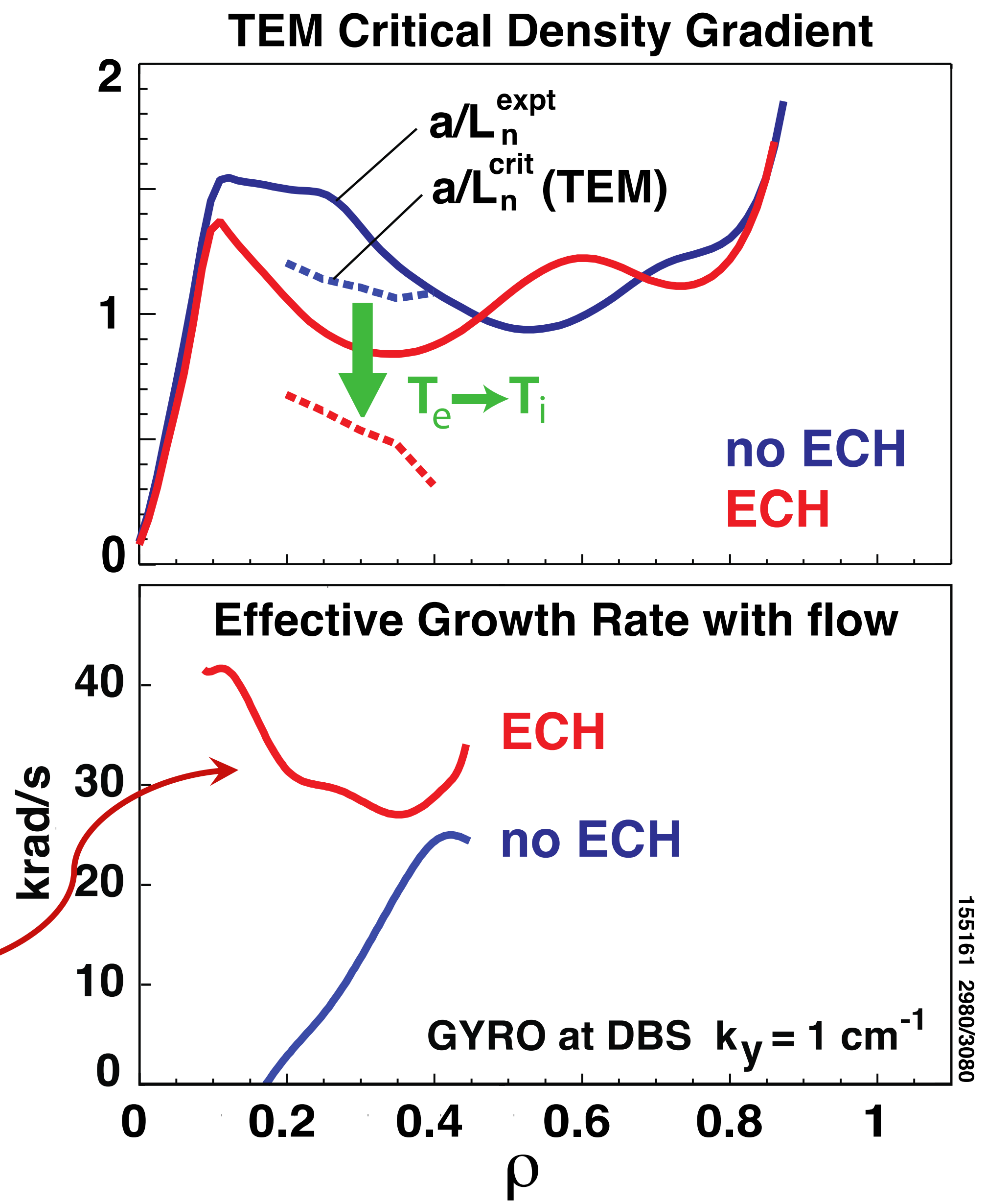


- GS2 matches TRANSP heat flux when density gradient matches nonlinear TEM critical density gradient

In DIII-D, ECH Raises T_e/T_i from 0.5 to 1.0, Destabilizing TEM; Provides Mechanism for Density Flattening with ECH

- **ECH increases TEM growth rate by doubling T_e/T_i, which halves a/L_n^{crit}**
- **Rotation slows in pedestal with ECH, hence in core, reducing E × B shear**
  - Prior to ECH, shear in parallel flow doubles growth rate
  - Not important during ECH

Density gradient driven TEM is sole instability in inner core during ECH



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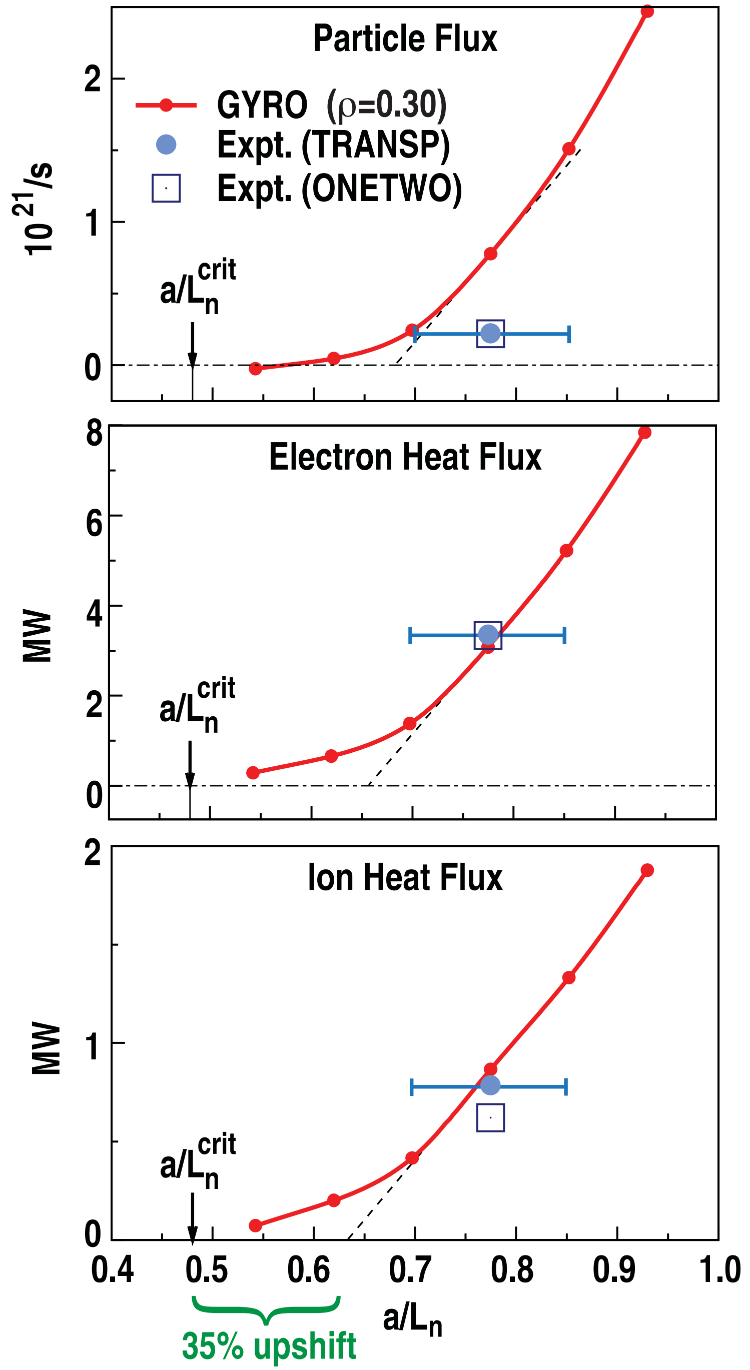
Nonlinear GYRO TEM Simulations Closely Match Fluxes Inferred from Transport Analysis at ρ=0.30 with ECH

- **Nonlinear simulations show strong increase of transport with density gradient, consistent with TEM**

- **TEM nonlinear upshift apparent**
  - Reduced at lower collisionality and higher q in DIII-D
  - GYRO shows 35%

- **Zonal flows are dominant in the upshift regime, close to the linear threshold**



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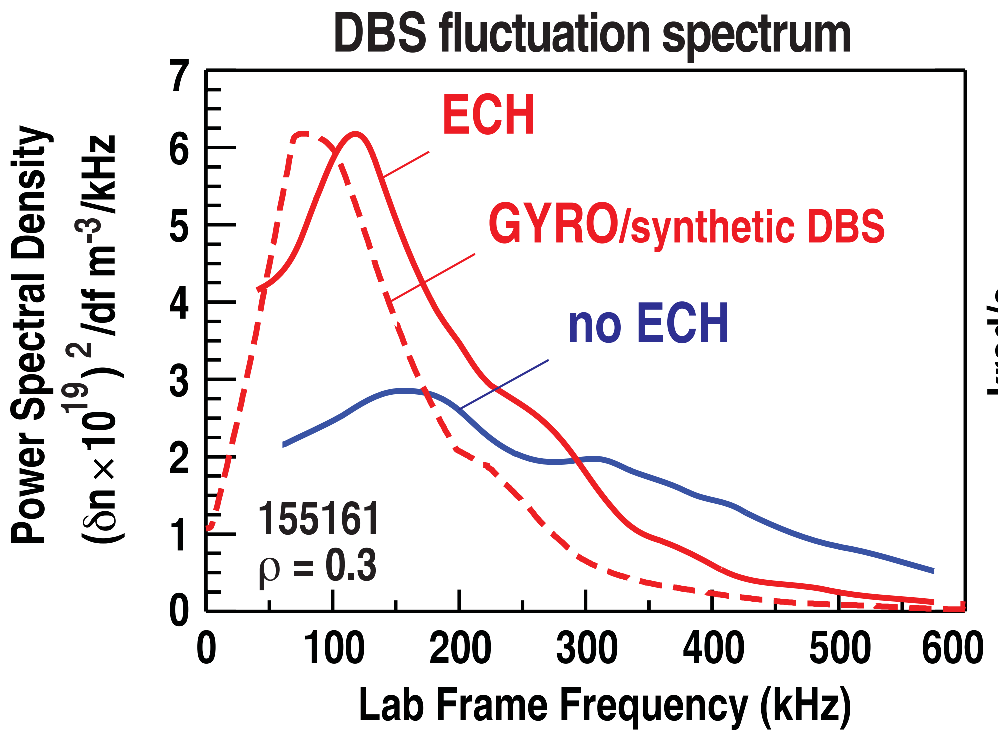
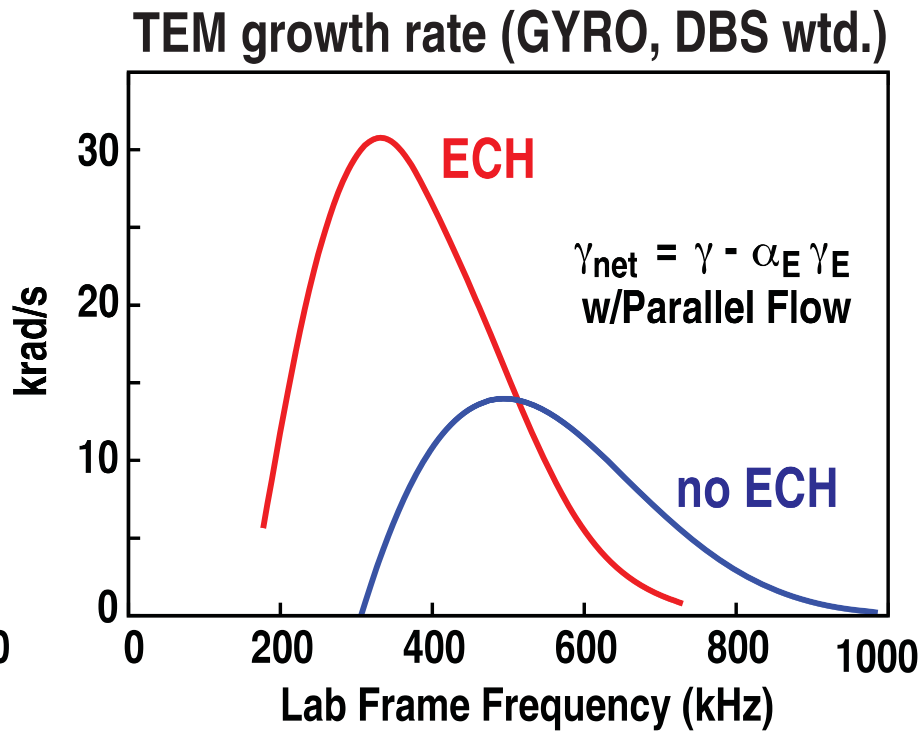
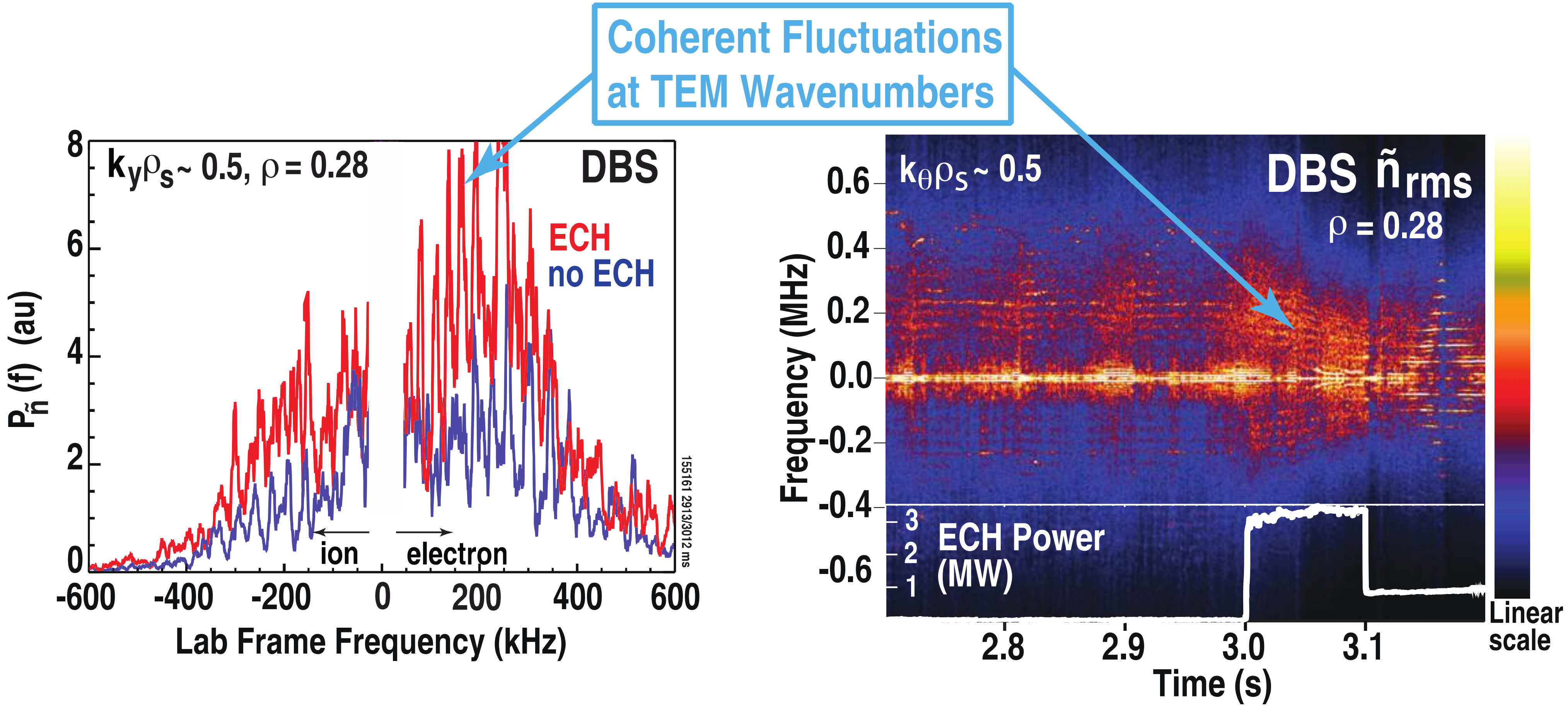
Shape of DBS Frequency Spectrum During ECH Reproduced by GYRO TEM Simulation with New DBS Synthetic Diagnostic





- New synthetic DBS diagnostic reproduces DBS frequency spectrum for first time in DIII-D
- Uses Gaussian spread in DBS wavenumbers based on 2D full wave simulations [J. Hillesheim et al., RSI (2010)]
- Accurate calculation of $k_y^{DBS} = n\,q(\rho,\theta) / r_{cyl}(\rho,\theta)$ in shaped geometry

Local DBS Measurement Reveals Coherent Fluctuations at TEM Wavelengths, which Intensify During ECH



- Separated in frequency by constant interval, corresponding to adjacent toroidal mode numbers n:

$$2\pi f_{lab} = k_y^{DBS} v_E = n\Omega_{tor} \qquad n = \ldots, 18, 19, 20, \ldots$$

- DBS PSD response for this case: $R(n) = \exp[-(n-19)^2/18^2]$

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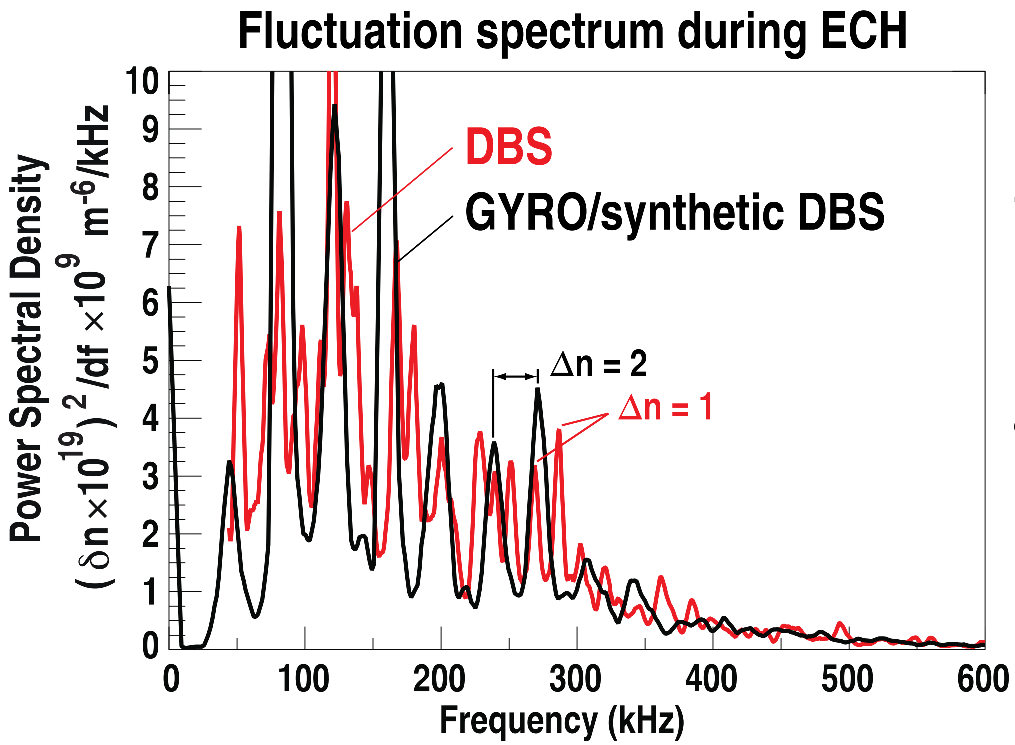
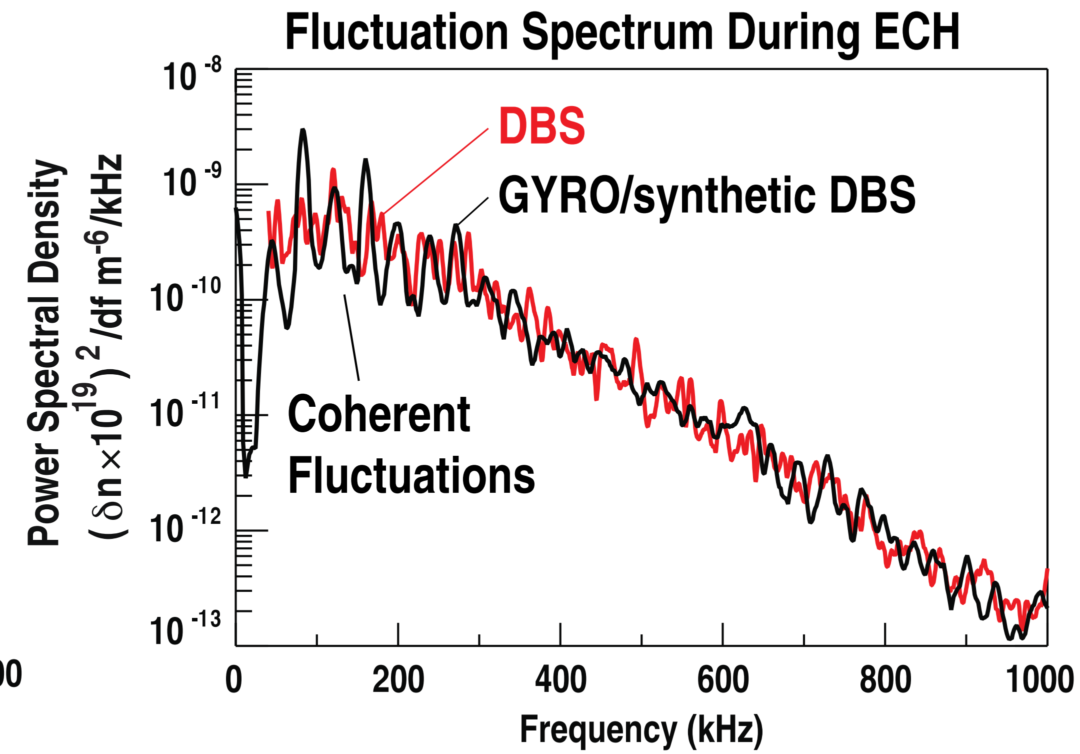
Nonlinear GYRO Simulations Reproduce Coherent TEM Fluctuations Seen on DBS, as Well as Spectral Decay





- **Coherent modes in GYRO correspond to resolution used, Δn = 2**
  - Match every second coherent mode seen on DBS (for which Δn = 1)
- **High resolution GYRO simulations in progress with Δn = 1**
- **Doppler shift in GYRO increased by 20% over CER measurement, based on interval between coherent modes (within uncertainties)**

Density Gradient Driven TEM Turbulence Shown to Regulate Particle and Thermal Transport in H-Mode Inner Core

- **Strong sensitivity to electron temperature allows central electron heating to locally control density peaking.**
- **New core localized, coherent fluctuations observed in DIII-D at TEM wavelengths, when TEM is found to be sole instability**
  - Intensify during ECH, while the density profile is locally flattened
  - Reproduced in GYRO nonlinear TEM simulations
- **Collisionality dependence of TEM nonlinear upshift experimentally confirmed**
- **TEM relevant when density moderately peaked, $T_i \sim T_e$, low collisionality**
  - α-heating would flatten density profile, reducing fusion power (self-regulating)