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

by
D.R. Ernst¹

with K.H. Burrell², W. Guttenfelder³, T.L. Rhodes⁴, L. Schmitz⁴, A.M. Dimits⁵, E.J. Doyle⁴, B.A. Grierson³, M. Greenwald¹, C. Holland⁶, G.R. McKee⁷, R. Perkins³, C.C. Petty², J.C. Rost¹, D. Truong⁷, G. Wang⁴, L. Zeng⁴ and the DIII-D and Alcator C-Mod Teams

¹MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA
²General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
³Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543-0451, USA
⁴University of California Los Angeles, PO Box 957099, Los Angeles, CA 90095-7099, USA
⁵Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551-0808, USA
⁶University of California San Diego, 9500 Gilman Dr., La Jolla, California 92037-0417, USA
⁷University of Wisconsin - Madison, 1500 Engineering Dr., Madison, WI 53706, USA

Presented at the
25th IAEA Fusion Energy Conference
Saint Petersburg, Russia

October 13–18, 2014

Email: dernst@psfc.mit.edu
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:
  - $\alpha$-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.
  

- 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 $\rho < 0.5$ in all cases shown
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
Density Profile Locally Flattened by Modulated ECH in DIII-D

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

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

- Density (QH-Mode)

  - no ECH
  - $T_e = 0.5 T_i$
  - $T_e = T_i$
  - ECH power density

- DBS Fluctuations

- ECH Power

- $a/L_n$ (averaged $\rho = 0.3 - 0.4$)

- $n_e (10^{19} \text{ m}^{-3})$

- Time (s)

- ECH power

- $\rho$

- TEM
Electron Heating Raises $T_e$ by $\sim 50\%$ in Both C-Mod and DIII-D Experiments

C-Mod EDA H-Mode

DIII-D QH-Mode

Electron Heating raises $T_e$ by $\sim 50\%$ 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 $E\times B$ 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
Nonlinear GYRO TEM Simulations Closely Match Fluxes Inferred from Transport Analysis at \( \rho=0.30 \) 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
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 $k_{DBS} = n q(\rho, \theta) / r_{cyl}(\rho, \theta)$ 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 $n$:
  \[ 2\pi f_{\text{lab}} = k_y^{\text{DBS}} v_e = n\Omega_{\text{tor}} \quad n = \ldots, 18, 19, 20, \ldots \]

- DBS PSD response for this case: $R(n) = \exp \left[ - (n-19)^2 / 18^2 \right]$
Nonlinear GYRO Simulations Reproduce Coherent TEM Fluctuations Seen on DBS, as Well as Spectral Decay

• Coherent modes in GYRO correspond to resolution used, $\Delta n = 2$
  - Match every second coherent mode seen on DBS (for which $\Delta n = 1$)
• High resolution GYRO simulations in progress with $\Delta n = 1$
• 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
  - $\alpha$-heating would flatten density profile, reducing fusion power (self-regulating)