BOUT++ Simulations of Edge Turbulence in Alcator C-Mod's EDA H-Mode

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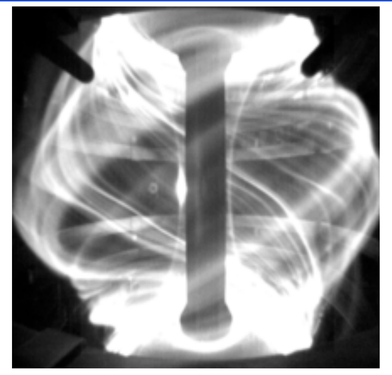
(1) Abstract

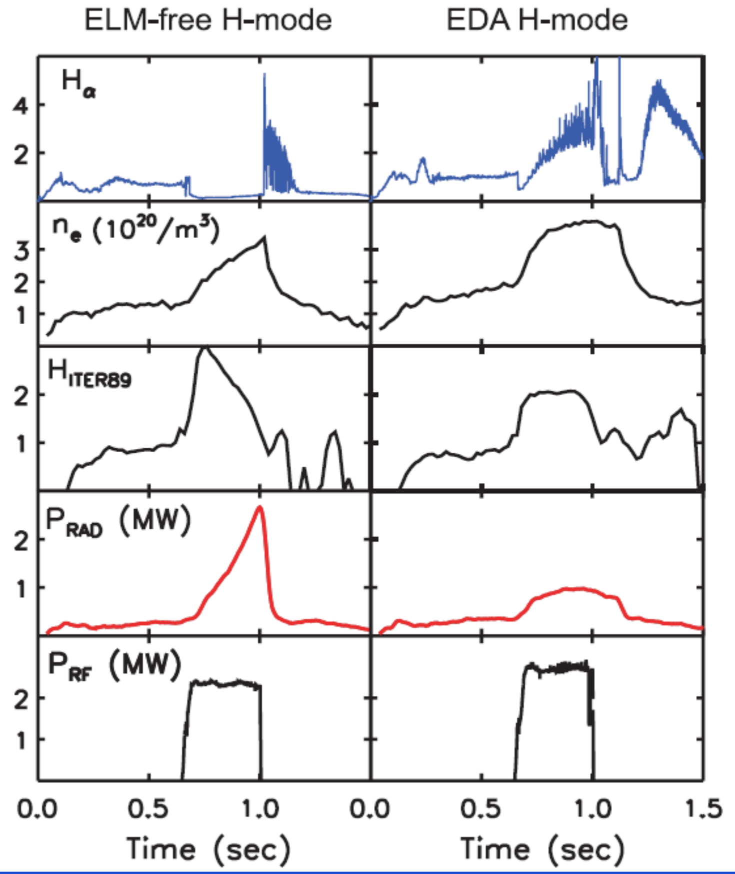
Energy confinement in tokamaks is believed to be strongly controlled by plasma transport in the edge region just inside the last closed magnetic flux surface, and a first principles understanding of these edge processes is an active field of theoretical and experimental research. The Boundary-plasma Turbulence (BOUT++) code is capable of nonlinear fluid boundary turbulence analysis in a general geometry. Using experimentally measured profiles as input, BOUT++ calculations show that typical C-Mod EDA H-modes are ideal MHD stable, but become linearly unstable when the pedestal resistivity is included ($\eta > 10^{-7}$ Ω-m). The computed resistive ballooning mode growth rate in such shots is shown to scale approximately as $\eta^{1/3}$ and $n^{2/3}$, consistent with theory. Inclusion of diamagnetic effects leads to a maximum growth rate at $n \sim 25$ and mode propagation in the lab frame electron diamagnetic direction, consistent with experimental observations. Nonlinear simulations have reached turbulent steady state, allowing for future comparison with fluctuation diagnostics.

(2) Motivation

- The Quasi-Coherent Mode (QCM) reduces impurity confinement during C-Mod's Enhanced D_α (EDA) H-Mode[1], allowing for steady-state operation



An ELM in MAST

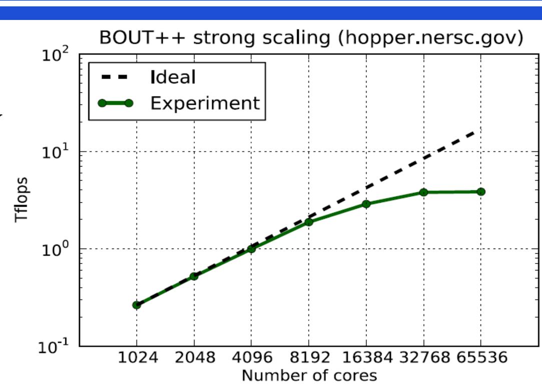


- Unlike Edge Localized Modes (ELMs), the QCM is **not** a dangerous mode
- The high collisionality ($\nu^* > 1$) of the EDA H-Mode suggests the use of a **fluid** code to investigate the physical origins and characteristics of the QCM
- I-Mode [2] is presently under investigation at C-Mod and elsewhere

[1] M. Greenwald et al. Fusion Sci. Tech. **51** 266 (2007).
[2] D.G. Whyte et al. Nucl. Fusion **50** 105005 (2010)

(3) Boundary-plasma Turbulence (BOUT++) Code

- 3D nonlinear fluid boundary plasma turbulence code in a general geometry
  - Realistic magnetic X-point geometry
- BOUT++ provides an object-oriented framework in C++
- MPI parallelization allows ideal strong scaling up to ***10,000*** cores!
- Multi-developer version control system allows efficient development
  - Jointly developed by LLNL and University of York
  - International BOUT++ workshop was held at LLNL in September 2011
  - **https://bout2011.llnl.gov**



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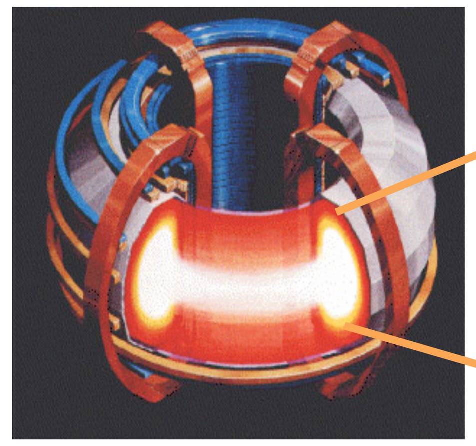
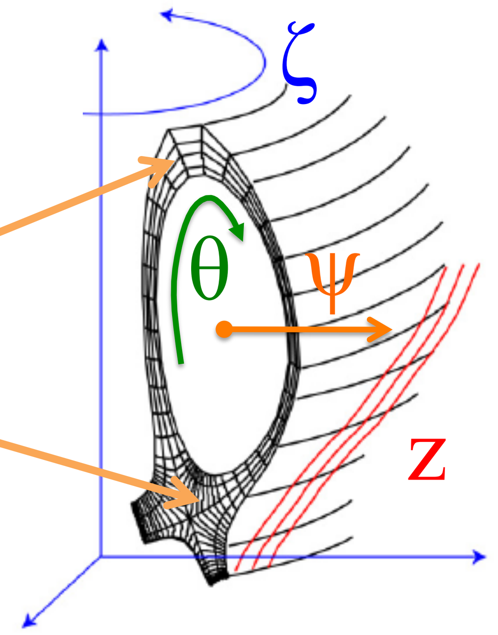
(4) BOUT++ Magnetic Geometry





Field-aligned coordinates

$$x = \psi - \psi_0,$$
$$y = \theta,$$
$$z = \zeta - \int_{\theta_0}^{\theta} \nu(\psi,\theta)\, d\theta$$

where ν is the local safety factor given by:

$$\nu(\psi,\theta) = \frac{\vec{B}\cdot\nabla\zeta}{\vec{B}\cdot\nabla\theta}$$

(5) Non-Ideal MHD Peeling-Ballooning Mode Equations Solved in BOUT++

Reduced MHD Equations

Vorticity:
$$\frac{\partial\varpi}{\partial t} + v_E\cdot\nabla\varpi = B_0^2\nabla_\parallel\left(\frac{j_\parallel}{B_0}\right) + 2b_0\times\kappa\cdot\nabla p,$$

Pressure:
$$\frac{\partial P}{\partial t} + v_E\cdot\nabla P = 0,$$

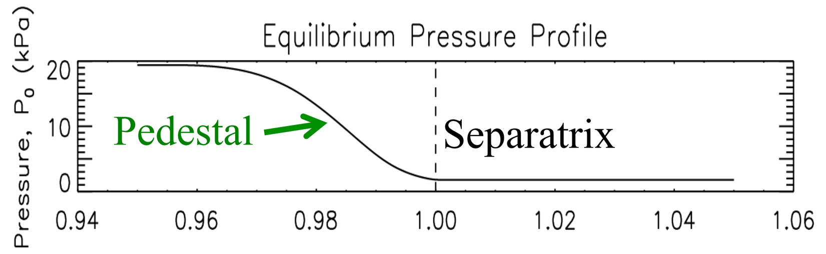
Ohm's:
$$\frac{\partial A_\parallel}{\partial t} = -\nabla_\parallel(\varphi+\Phi_0) + \frac{\eta}{\mu_0}\nabla_\perp^2 A_\parallel - \frac{\eta_H}{\mu_0}\nabla_\perp^4 A_\parallel,$$

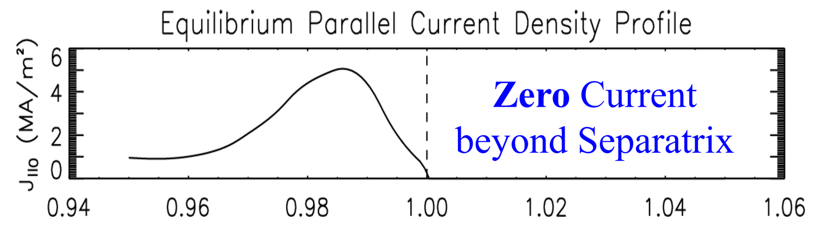
Definitions:
$$\varpi = \frac{n_0 M_i}{B_0}\left(\nabla_\perp^2\varphi + \frac{1}{n_0 Z_i e}\nabla_\perp^2 p_i\right), \quad P = P_0 + p$$
$$j_\parallel = J_{\parallel 0} - \frac{1}{\mu_0}\nabla_\perp^2 A_\parallel, \quad v_E = \frac{1}{B_0} b_0\times\nabla(\varphi+\Phi_0)$$

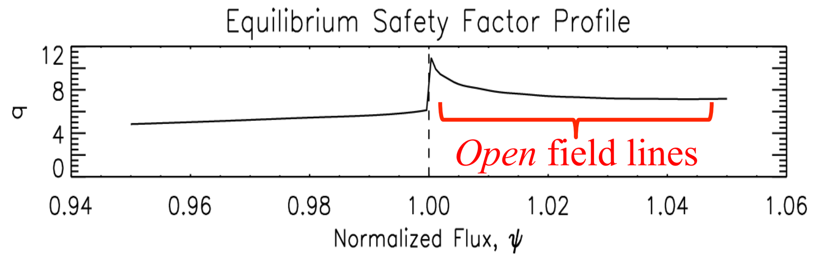
Non-ideal physics

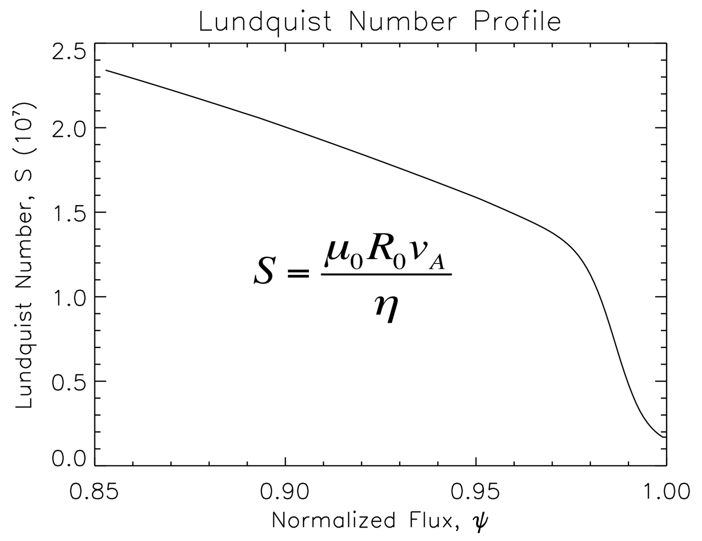
- ✓Include resistive MHD; resistivity can be renormalized as **Lundquist** Number $S = \mu_0 R v_A/\eta$
- ✓After gyroviscous cancellation, the diamagnetic drift modifies the vorticity
- ✓Using force balance and assuming no net rotation, $E_{r0} = (1/N_i Z_i e)\nabla_\perp p_{i0}$
- ✓Hyper-resistivity η_H, $S_H = \mu_0 R^3 v_A/\eta_H = S/\alpha_H$ is included in the physics module, but was **not** used in this work

(6) C-Mod Experimental Input



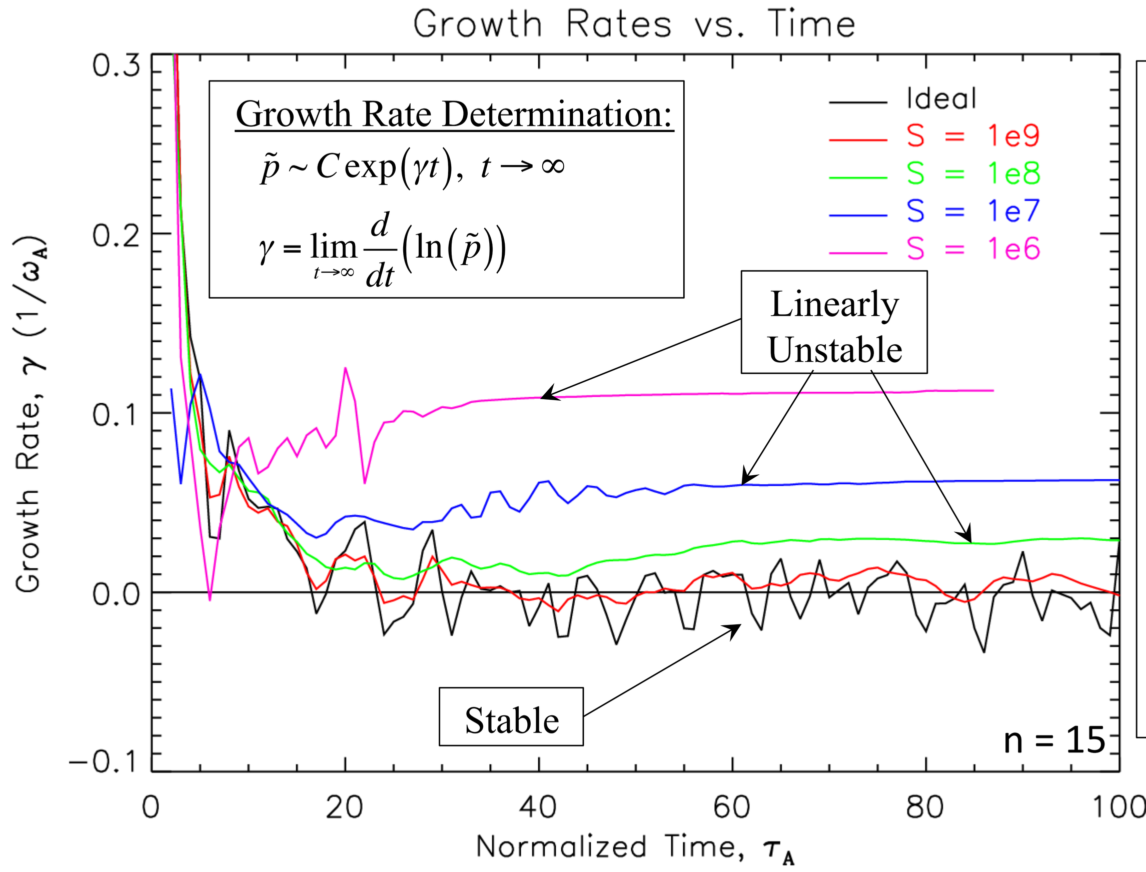






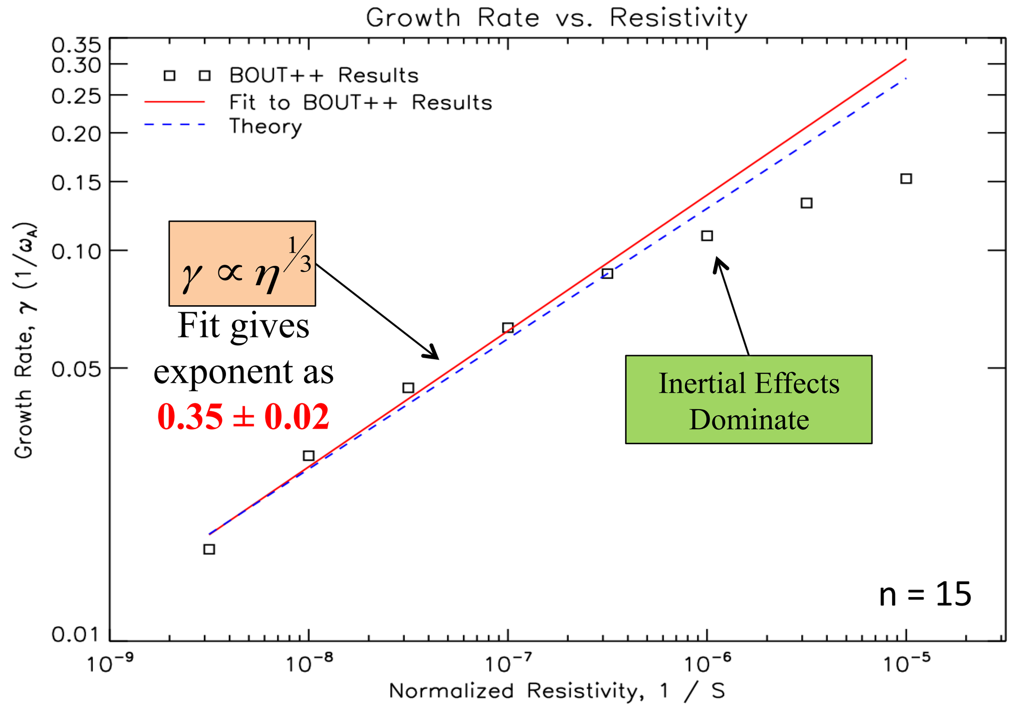
S ~10⁷ in C-Mod EDA Pedestal, making it relatively resistive compared to ~10^8-10^9

(7) BOUT++ Calculations show C-Mod EDA H-Mode Resistively Unstable



- No instabilities (i.e. ELMs) were observed in ideal simulations
- ELMs are **not** experimentally observed during EDA operation
- Inclusion of physical pedestal resistivity excites a linearly **unstable** mode

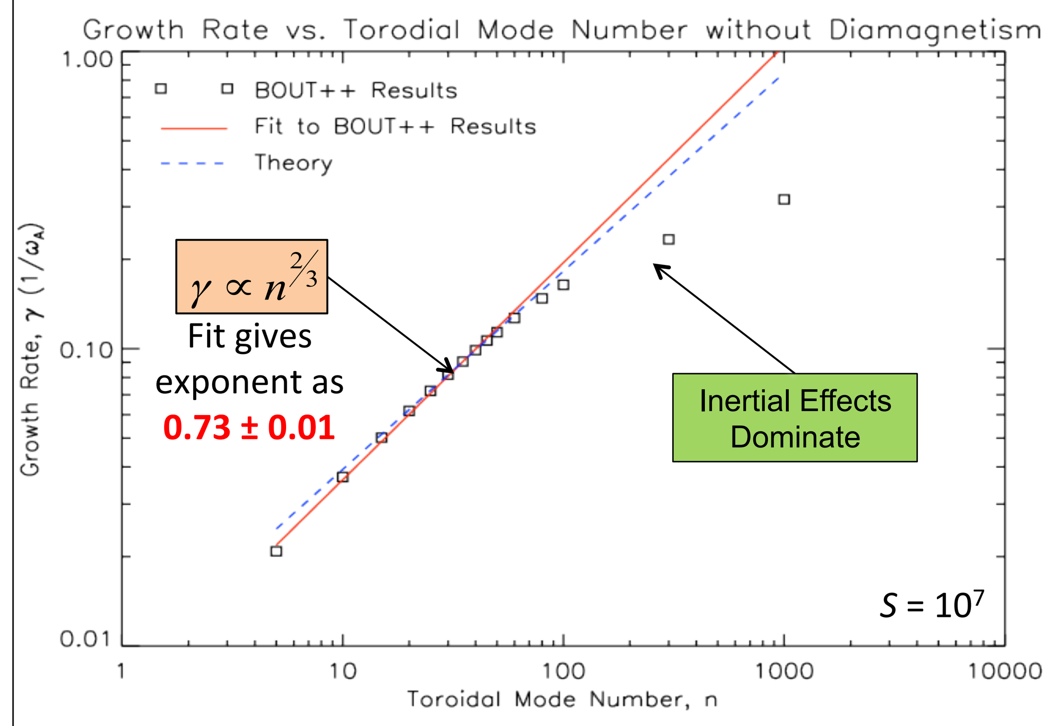
(8) BOUT++ Calculations Agree with Resistive-Ballooning Mode Theory



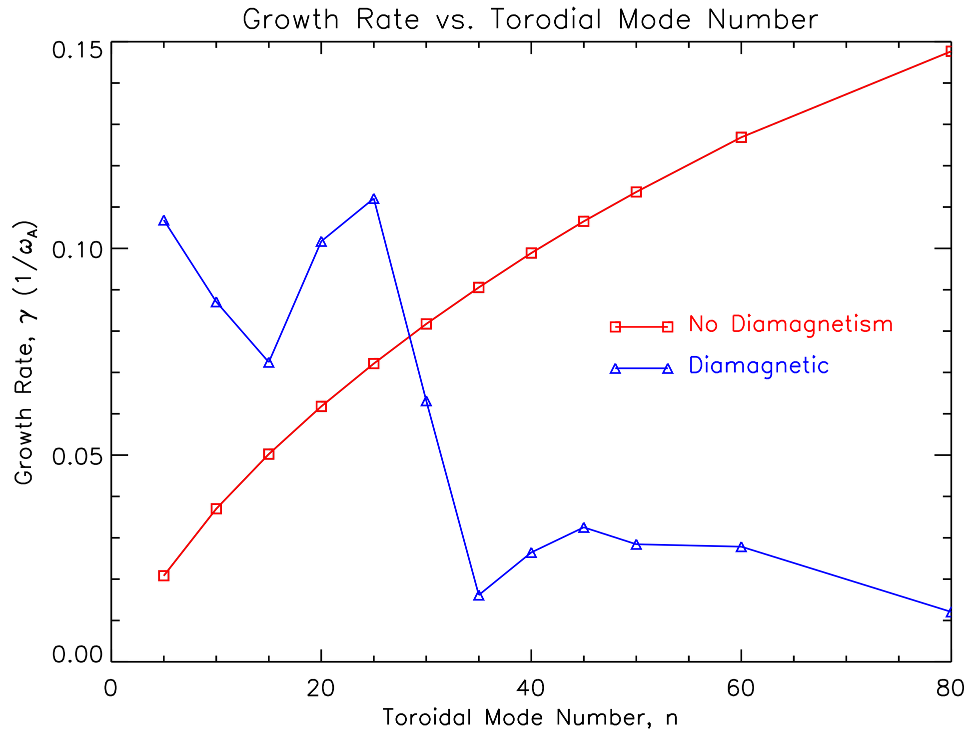
- In the linear regime, the growth rate scales as $\eta^{1/3}$ and $n^{2/3}$
- Growth rates "rollover" as inertial effects begin to limit the plasma response

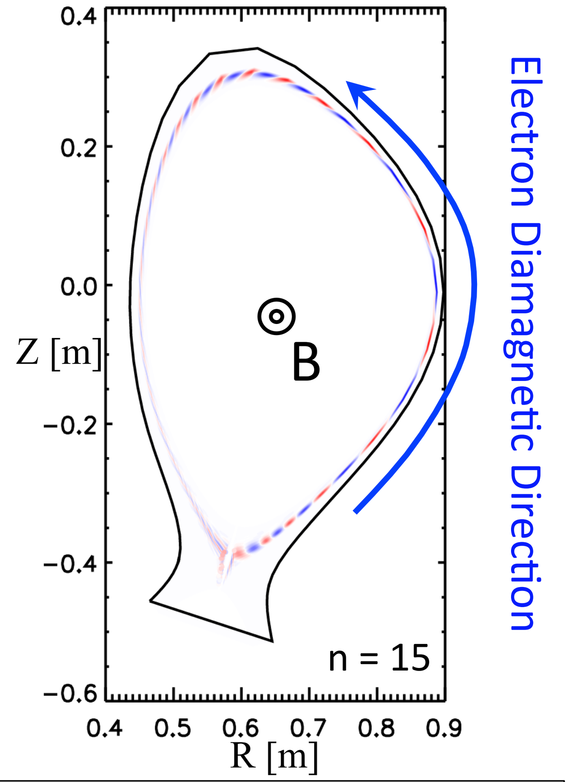
- Growth rate scalings are **consistent** with a theory of resistive ballooning modes developed by Carreras, et al[3]
- Small discrepancies between simulations and theory may be due to the *limitations* in the Carreras model, which employs a sheared slab geometry and is electrostatic

[3]B.A. Carreras, et. al., *Phys. Fluids* **30**, 1388, (1987)



(9) Inclusion of Diamagnetic Effects Reproduces Qualitative Aspects of the QCM

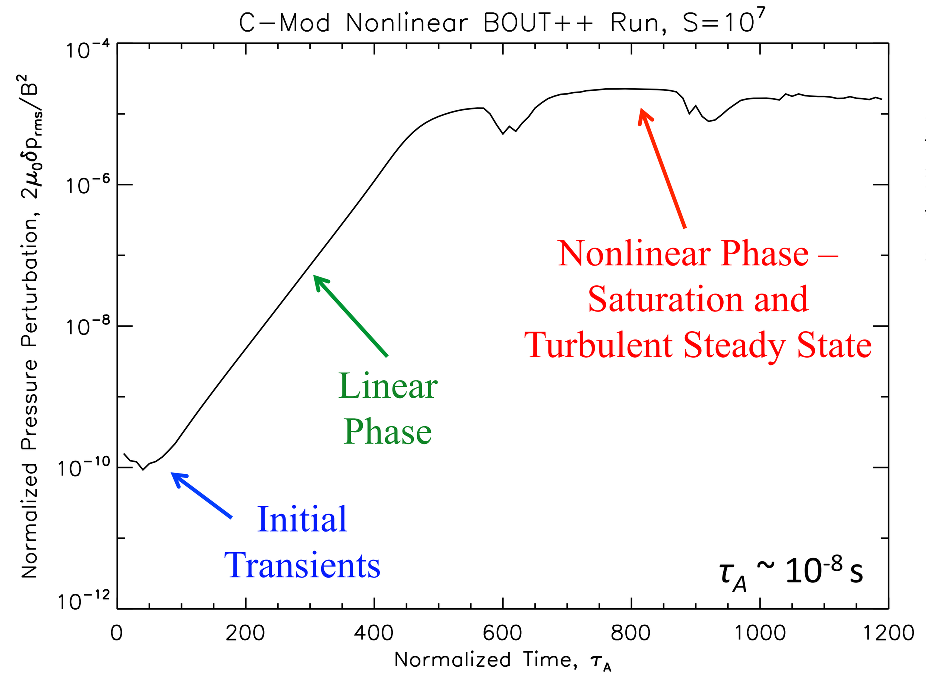


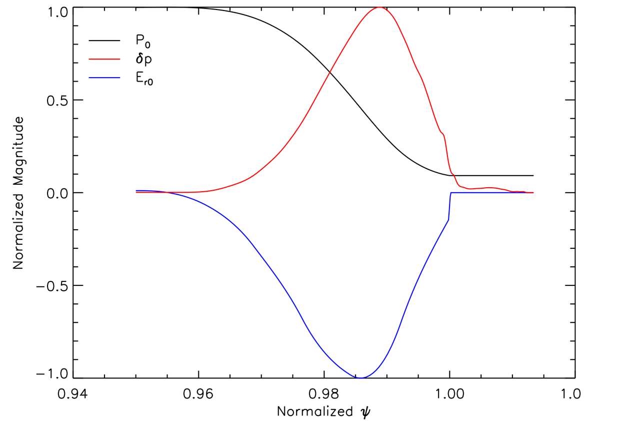


- BOUT++ results show significant growth rates for **n < 25**, with a maximum at **n ~ 25**
- *Experimentally*, the QCM typically occupies **n~10-25**
- High mode numbers (n > 30) are damped

The mode propagates in the **electron** diamagnetic direction in the lab frame when diamagnetic effects are included, consistent with experiment

(10) Turbulent Steady-State has been Achieved in Nonlinear Simulations





- Turbulent steady state allows comparison with fluctuation diagnostics
- Still need to compute fully nonlinear background E_r

(11) Conclusions and Future Work

- BOUT++ calculations show that typical C-Mod EDA H-modes are *stable* to ideal peeling-ballooning modes but are **unstable** to resistive edge instabilities
- BOUT++ results are **consistent** with resistive ballooning mode theory
- Diamagnetic effects *damp* high toroidal mode numbers (n > 30) and produce mode propagation in the *electron* diamagnetic direction, in **qualitative agreement** with experimental observations of the QCM
- Ongoing *nonlinear* BOUT++ simulations will be compared to fluctuation diagnostics (Phase Contrast Imaging, Reflectometry, etc.) in order to better understand the physical origins and effects of the QCM
- Plasma flow will be incorporated into future simulations in order to *self-consistently* calculate the edge radial electric field
- Future gyrofluid modifications to BOUT++ may allow for more accurate simulation of lower collisionality plasmas (e.g. I-Mode)