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

E. M. Davis[1], M. Porkolab[1], J.W. Hughes[1], and X. Q. Xu[2]

[1]Plasma Science and Fusion Center, MIT, Cambridge, MA 02139, [2]Lawrence Livermore National Laboratory, Livermore, CA 94550

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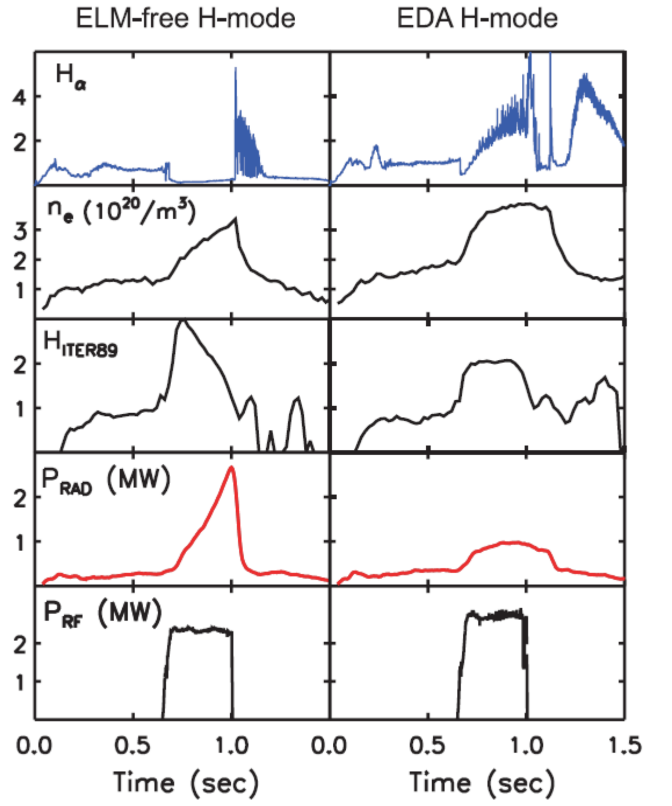
(1) Abstract

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. Incorporation of experimentally measured flow profiles has allowed the self-consistent calculation of the edge radial electric field. Nonlinear simulations have reached turbulent steady state, allowing for future comparison with fluctuation diagnostics.

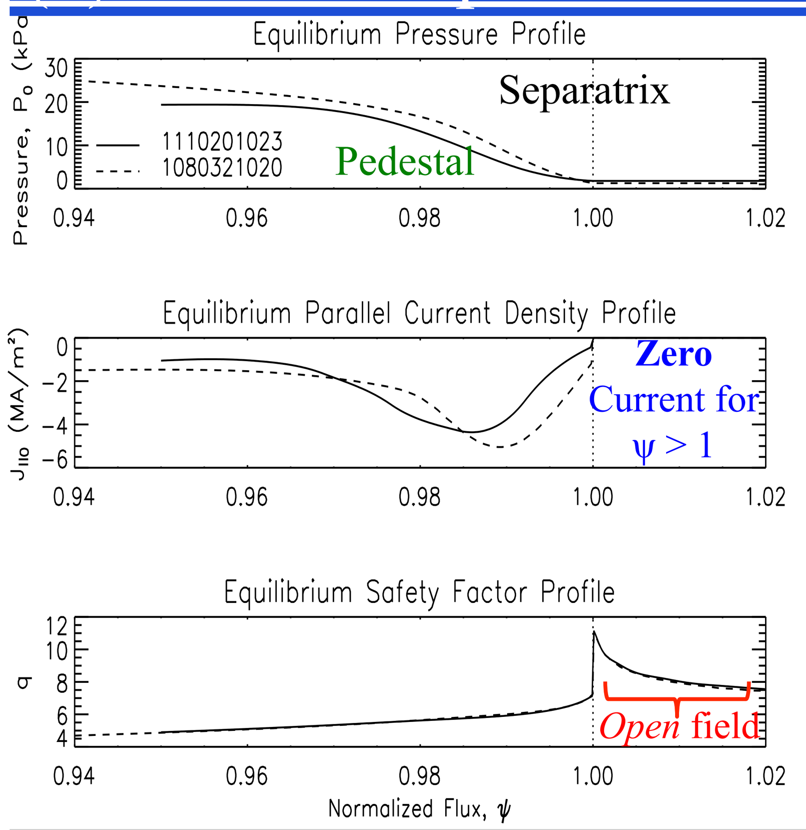
(2) Motivation

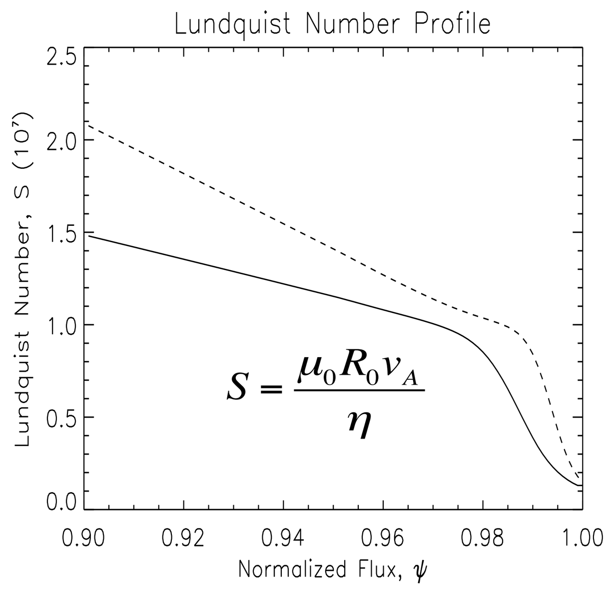


- The Quasi-Coherent Mode (QCM) reduces impurity confinement during C-Mod's Enhanced D_α (EDA) H-Mode[1], allowing for steady-state operation
- Unlike Edge Localized Modes (ELMs), the QCM is **not** a dangerous mode
- The high collisionality ($\nu^* > 1$) of the EDA H-Mode suggests the use of a **fluid** code to investigate the QCM

[1] M. Greenwald et al. Fusion Sci. Tech. **51** 266 (2007).

(3) C-Mod Experimental Input





S ~10^7 in C-Mod EDA Pedestal, making it relatively resistive compared to ~10^8-10^9

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

Reduced MHD Equations

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

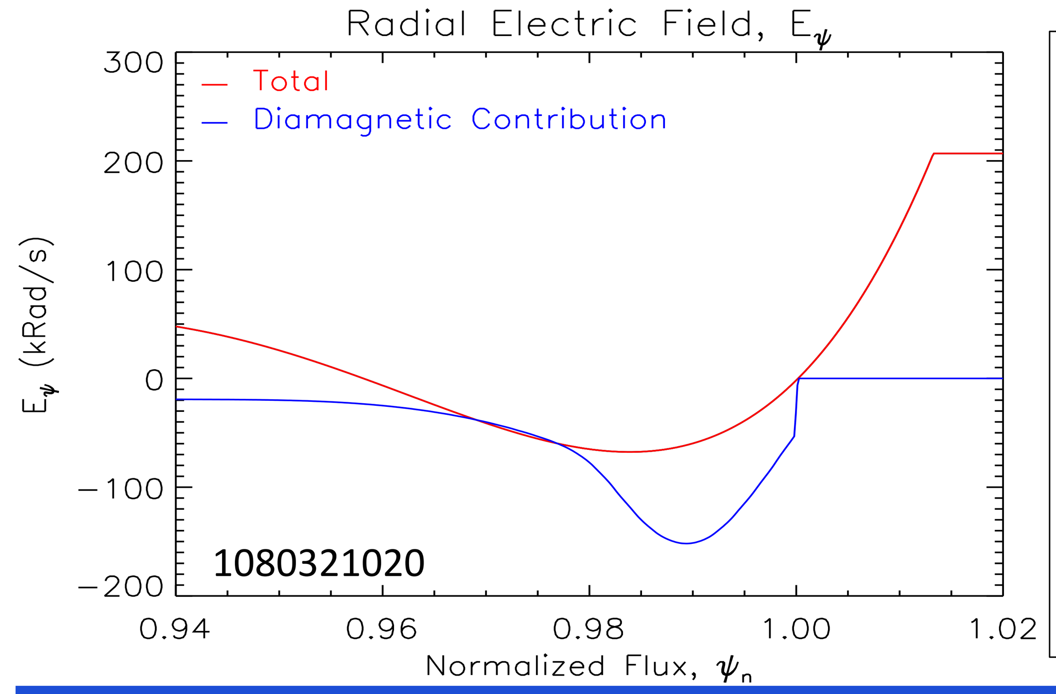
Pressure:
$$\frac{\partial P}{\partial t} + v_E \cdot \nabla P = 0,$$

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

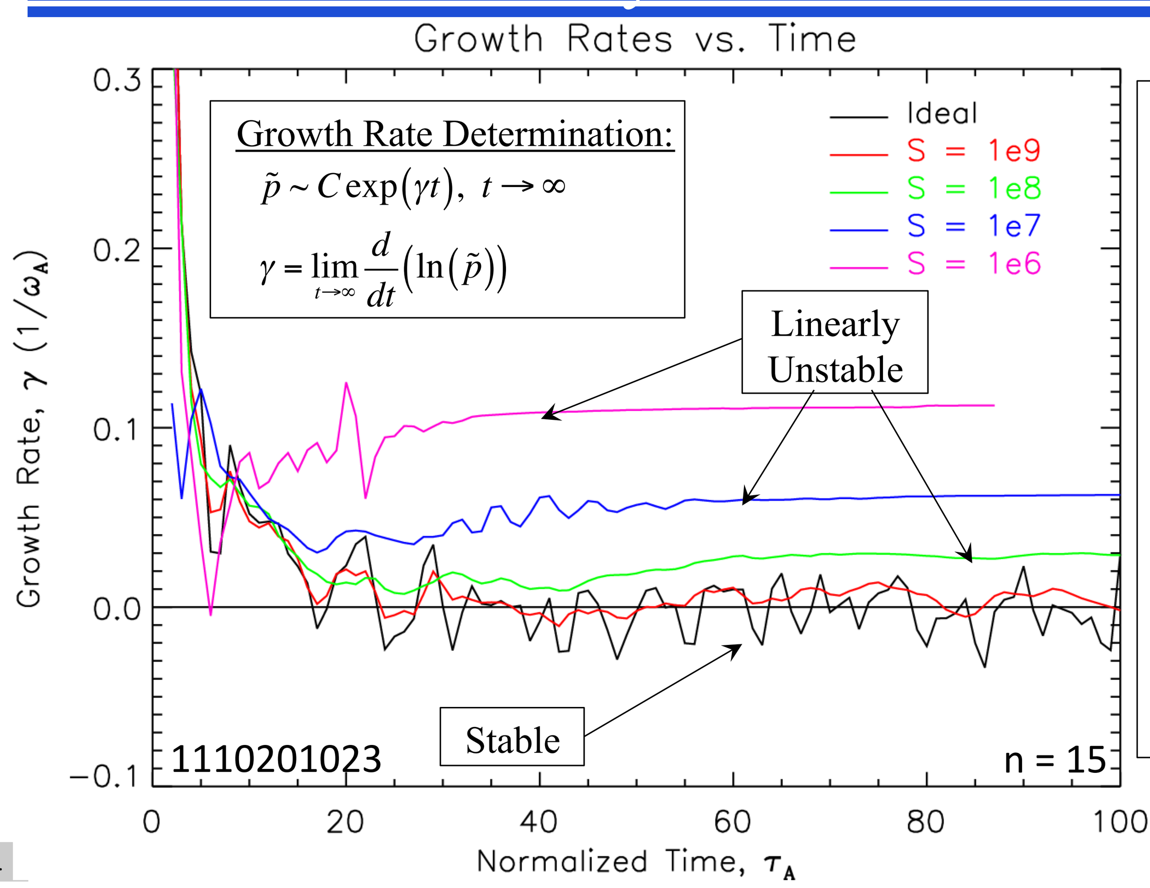
Non-ideal physics

- ✓Include resistive MHD
- ✓After gyroviscous cancellation, the diamagnetic drift modifies the vorticity
- ✓Radial electric field is (1) read in from experiment **or** (2) calculated using force balance assuming no net rotation, $E_{r0} = (1/2n_0 Z_i e)\nabla_\perp P_0$
- ✓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



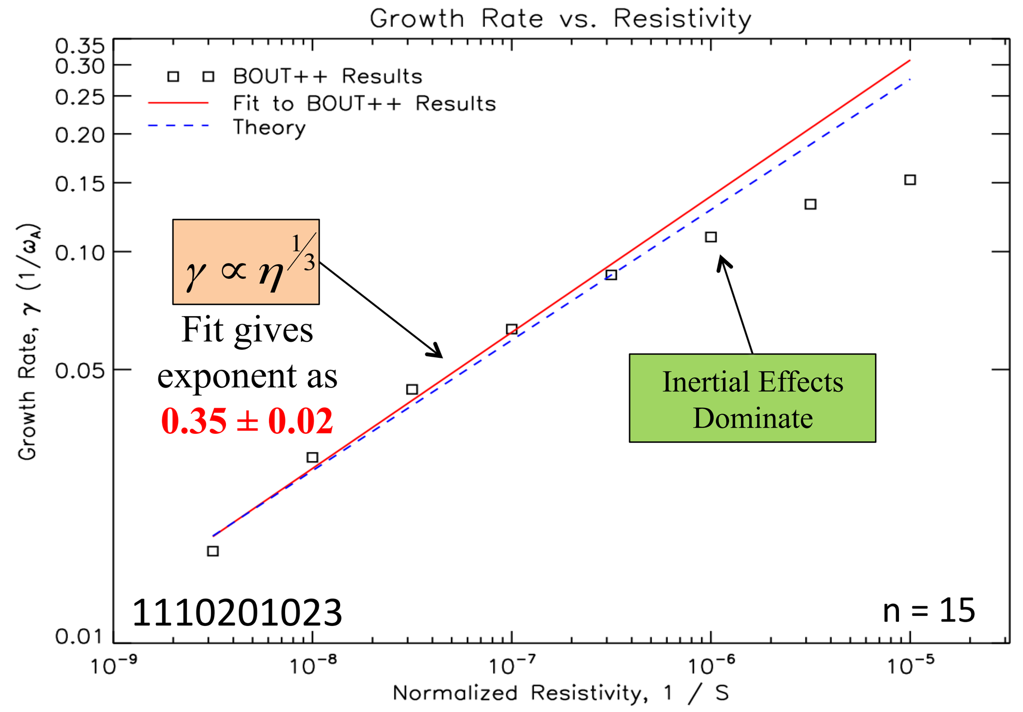
- BOUT++ can now read in experimentally measured E_{r0} to self-consistently evolve E_r
- The diamagnetic contribution to E_{r0} is qualitatively similar to the total, justifying approach (2, above) for calculating E_{r0} if an experimental profile is not available

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



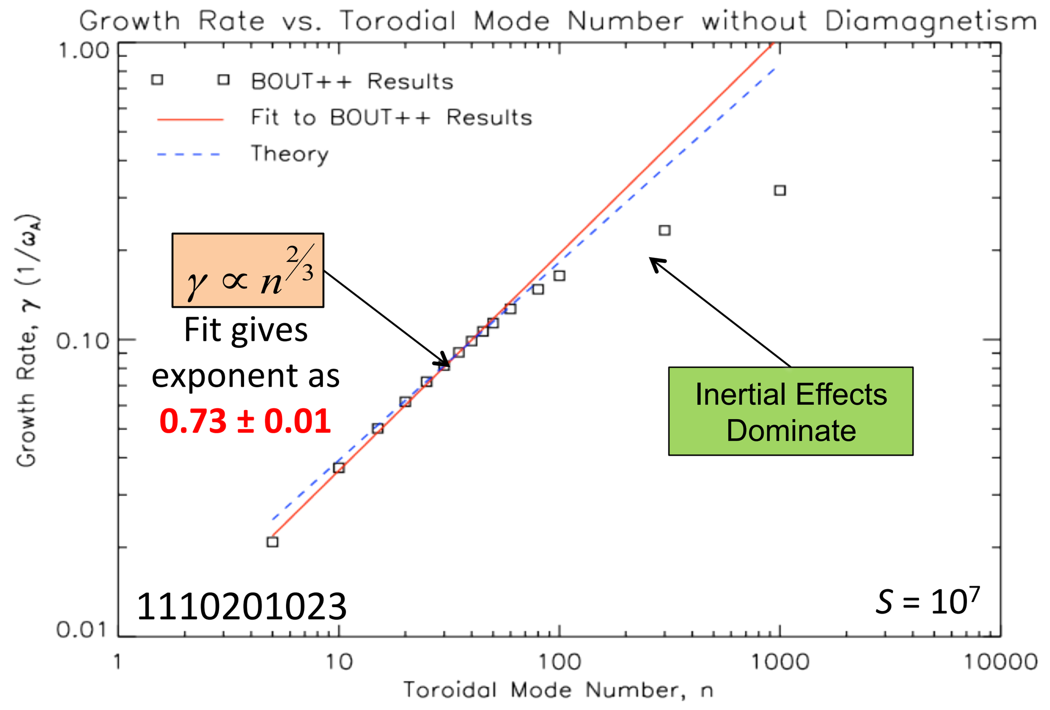
- No instabilities (i.e. ELMs) were observed in **ideal** simulations
- ELMs are **not** experimentally observed during EDA operation
- Inclusion of physical pedestal resistivity excites a linearly **unstable** mode

(7) BOUT++ Calculations Consistent with Resistive-Ballooning Mode Theory[2]



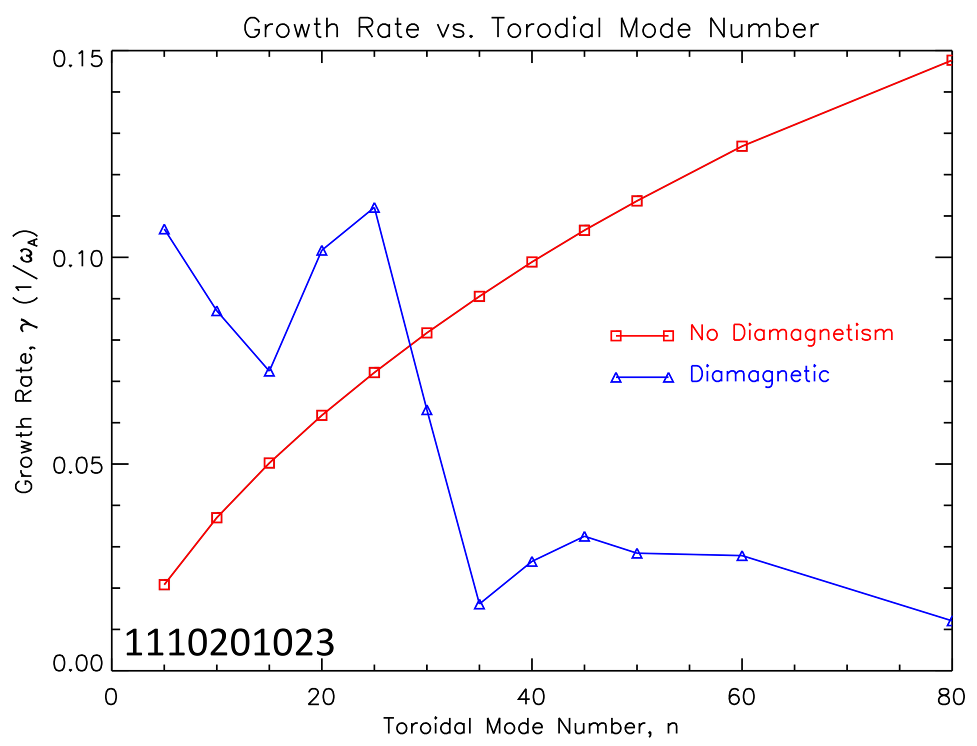
[2]B.A. Carreras, et. al., *Phys. Fluids* **30**, 1388, (1987)

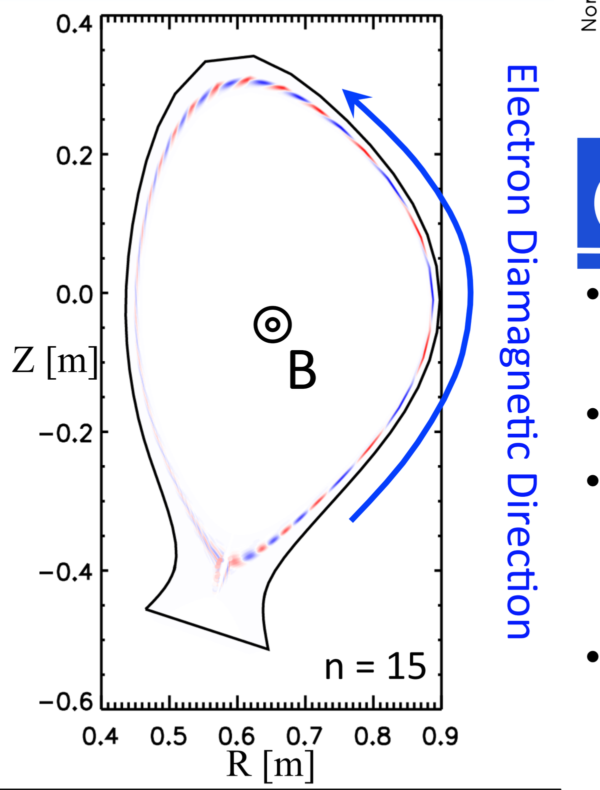
- In the linear regime, the growth rate scales as $\eta^{1/3}$ and $n^{2/3}$
- Growth rates "rollover" as inertial effects begin to limit the plasma response



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

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

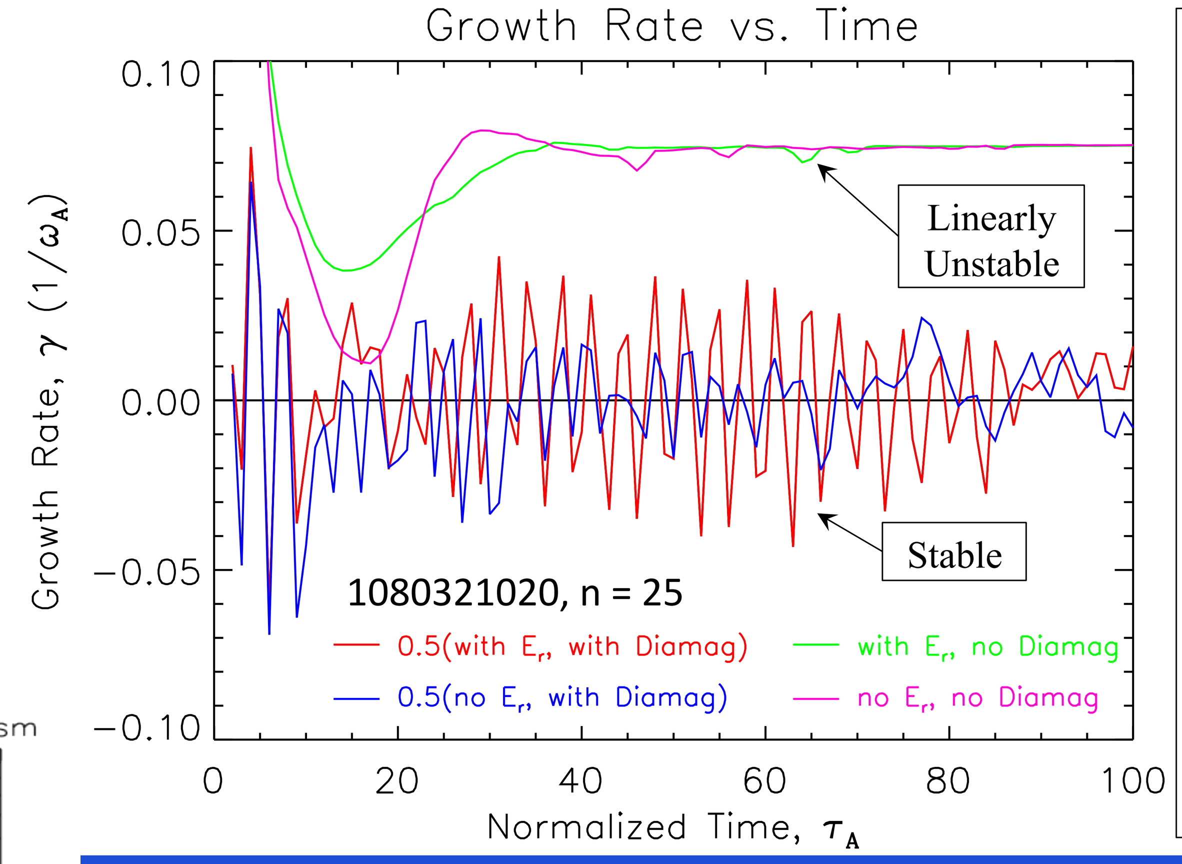




- BOUT++ results show significant growth rates for **n < 25**, with a maximum at **n ~ 25**
- *Experimentally*, the QCM occupies **n~10-25**
- High mode numbers (n > 30) are damped
- **Note:** Still attempting to replicate these results with latest version of BOUT++

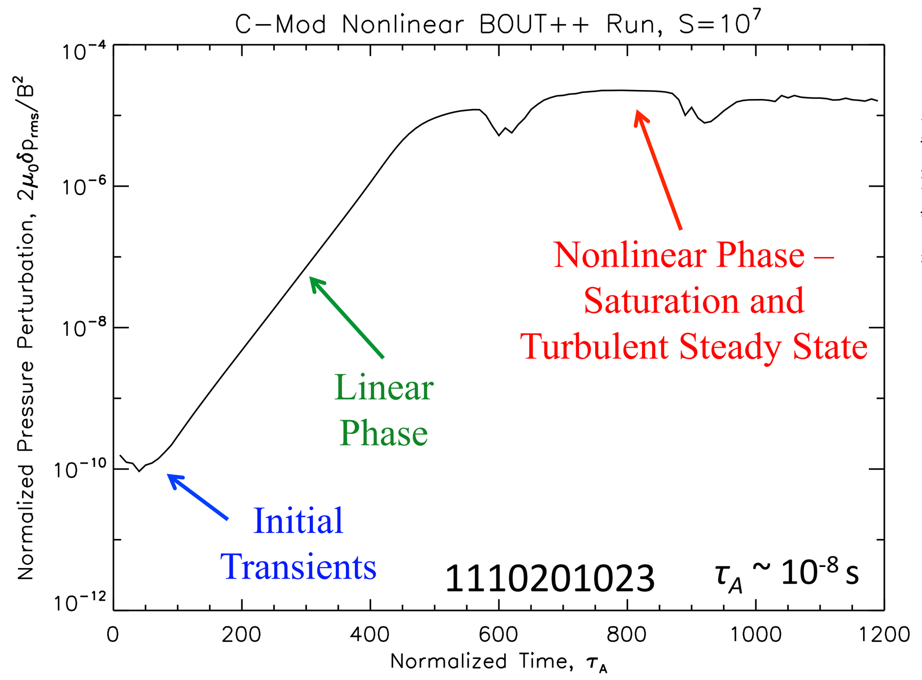
The mode propagates in the **electron** diamagnetic direction in the lab frame when diamagnetic effects are included, consistent with experiment

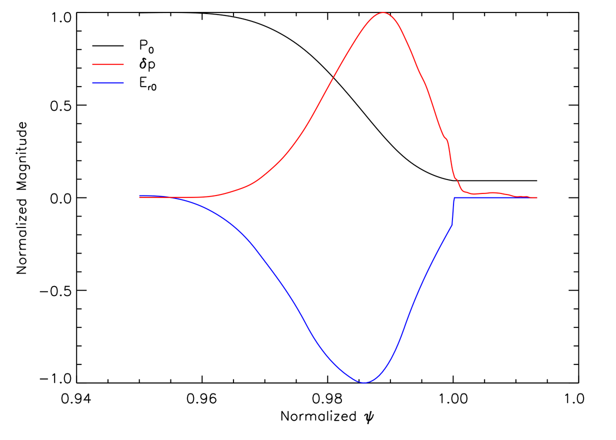
(10) BOUT++ Suggests that Radial Electric Field Minimally Affects EDA Linear Stability



- Inclusion of E_{r0} does **not** appear to qualitatively affect the *linear* behavior of n = 25 mode
- Diamagnetic effects appear to *stabilize* the mode, in **contrast** to the behavior in 1110201023
- Does E_{r0} substantially influence aspects of edge turbulence?

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





Turbulent steady state allows comparison with fluctuation diagnostics

(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 modes
- 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
- Plasma flow has been incorporated into BOUT++ simulations to self-consistently calculate the edge radial electric field. Preliminary analysis indicates that it may not critically influence EDA stability.
- 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
- Future gyrofluid modifications to BOUT++ may allow for more accurate simulation of lower collisionality plasmas (e.g. I-Mode)

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