Opportunities for synergy between experiments and BOUT++ modeling on Alcator C-Mod and DIII-D

E. M. Davis ¹, M. Porkolab ¹, J. W. Hughes ¹, B. LaBombard ¹, J. C. Rost ¹, P. B. Snyder ², and X. Q. Xu ³

¹MIT PSFC, ²GA, and ³LLNL

BOUT++ Workshop, Livermore, CA, Sept. 5, 2013

Work supported by USDoE awards DE-FC02-99-ER54512, DE-FG02-94-ER54235, DE-AC52-07NA27344, and NNSA SSGF

LLNL-PRES-639635
The plasma edge sets boundary conditions on the core plasma and needs to be understood.

BOUT++ is a maturing code, able to simulate an increasingly broad range of physical regimes.

\( \nu^* > 1 \): Alcator C-Mod’s EDA H-mode
  - Linear: stability analysis
  - Nonlinear: comparison to experimental measurements

\( \nu^* < 1 \): DIII-D’s ELM-free H-mode
  - BOUT++ gyro-Landau fluid code is desired to aid the interpretation of experimental measurements

Conclusions and future work
The “Standard Model”: Peeling-Ballooning (PB) modes constrain the pedestal in ELMy H-mode

- Peeling and ballooning modes *couple* at intermediate $5 \leq n \leq 25$ to drive ELMs
  - Ideal MHD instability

- Experimentally, ELMs are routinely observed when crossing the PB threshold

- Ideal MHD codes such as ELITE* can assess stability to PB modes

C-Mod’s EDA H-mode is a steady-state, high-performance regime regulated continuously by a QCM edge fluctuation. The Enhanced $D_\alpha$ (EDA) H-mode* exhibits:

- Excellent energy confinement
- Reduced impurity confinement
- EDA is C-mod’s “workhorse” H-mode
- EDA pedestal regulated by a quasi-coherent mode (QCM) oscillation $\sim 100$ kHz
- $\nu^* > 1 \Rightarrow$ amenable to fluid analysis

ELITE shows that ideal PB modes are *stable* in EDA H-mode; other physics needed to explain the QCM.
BOUT++ can solve a set of nonideal reduced MHD equations, including $\eta$ effects important for $\nu^* > 1$

Reduced MHD Equations* 

\[
\frac{\partial \omega}{\partial t} + \mathbf{V}_E \cdot \nabla \omega = B_0^2 \nabla || \left( \frac{J||}{B_0} \right) + 2\hat{\mathbf{b}}_0 \times \kappa \cdot \nabla p \\
\frac{\partial P}{\partial t} + \mathbf{V}_E \cdot \nabla P = 0 \\
\frac{\partial A||}{\partial t} = -\nabla || (\phi + \Phi_0) + \frac{\eta}{\mu_0} \nabla^2 A||
\]

Non-ideal Physics

- Include resistivity
- After gyroviscous cancellation, the diamagnetic drift modifies the vorticity
- Using force balance and assuming no net rotation, $E_{r0} = (1/n_i Z_i e) \nabla \perp P_{i0}$

Definitions

\[
\omega = \frac{n_0 m_i}{B_0} \left( \nabla^2 \phi + \frac{1}{n_0 Z_i e} \nabla^2 p_i \right), \quad \mathbf{V}_E = \frac{1}{B_0} \hat{\mathbf{b}}_0 \times \nabla (\phi + \Phi_0)
\]

\[
J|| = J||_0 - \frac{1}{\mu_0} \nabla^2 A||, \quad P = P_0 + p
\]

\n\n∇P was self-consistently varied to assess EDA’s linear stability with BOUT++

E. Davis
Opportunities for experimental and modeling synergy
BOUT++ indicates PB modes are stable at experimental values of $\nabla P$. 

![Graph showing FLR stability threshold for ideal MHD modes.](image)
BOUT++ marginal stability thresholds and growth rate trends for PB modes agree with ELITE.

E. Davis
Opportunities for experimental and modeling synergy
C-Mod’s resistivity drives unstable modes at experimental values of $\nabla P$ that may be responsible for the QCM.

![Graph showing FLR stability threshold for ideal MHD modes and model $\nabla P$ vs. experimental $\nabla P$.]
Nonlinear simulations show a quasi-coherent oscillation qualitatively similar to EDA’s QCM.
Nonlinear simulations show a quasi-coherent oscillation qualitatively similar to EDA’s QCM
The nonlinear quasi-coherent oscillation is peaked about $n \sim 16$, similar to C-Mod's EDA QCM.

**BOUT++ predicted toroidal mode spectrum**

Nonlinear saturation occurs at $t \sim 40 \mu s$, requiring $\sim 400 \tau_A$.
The nonlinearly computed mode spans the separatrix and sits in the edge $E_r$ well, similar to previous modeling results.

![BOUT++ Graph](image)

- $P_0 / 10$ [kPa]
- $\delta P$ [kPa]
- $E_r / 100$ [kV/m]
The nonlinearly computed mode spans the separatrix and sits in the edge $E_r$ well, similar to previous modeling results.

\[ \begin{align*}
\text{Values from BOUT++} \\
\text{P}_0 / 10 \, [\text{kPa}] & \quad \delta P \, [\text{kPa}] \\
\text{E}_r / 100 \, [\text{kV/m}] & \\
\end{align*} \]

2002 BOUT Results

\[ \begin{align*}
\text{n}_e & \times 10^{19} / \text{m}^3 \\
\delta n_e & \times 2 \times 10^{18} / \text{m}^3 \\
\delta B_\theta \, (\text{G}) & \\
E_r \, (\text{kV/m}) & \\
\end{align*} \]

The pressure and potential fluctuations are *out* of phase, in contrast to recent QCM measurements.

**BOUT++ $\delta p$ and $\delta \phi$ predictions:**

![Graph showing $\delta p$ and $\delta \phi$ predictions](image)
The pressure and potential fluctuations are *out* of phase, in contrast to recent QCM measurements.

BOUT++ $\delta p$ and $\delta \phi$ predictions:

Mirror Langmuir Probe (MLP) Measurements*:

![Graph showing $\delta p$ and $\delta \phi$ predictions and MLP measurements.](image)
The pressure and potential fluctuations are out of phase, in contrast to recent QCM measurements.

BOUT++ $\delta p$ and $\delta \phi$ predictions:

Mirror Langmuir Probe (MLP) Measurements*:

$\Rightarrow$ Drift wave!

* B. LaBombard et al. TTF Workshop, Santa Rosa, CA (Apr. 9-12, 2013).
The pressure and potential fluctuations are *out* of phase, in contrast to recent QCM measurements.

**BOUT++** $\delta p$ and $\delta \phi$ predictions:

![Graph showing $\delta p$ and $\delta \phi$ fluctuations over time](image)

**Mirror Langmuir Probe (MLP) Measurements**:  
![Mirror Langmuir Probe](image)

Hall term in Ohm’s law for drift wave-like response may help:

$$\frac{\partial A_{||}}{\partial t} = -\nabla_{||} \Phi - \eta J_{||} + \frac{1}{en} \nabla_{||} p_e$$

or may need 2-fluid model

$\Rightarrow$ Drift wave!

*B. LaBombard et al. TTF Workshop, Santa Rosa, CA (Apr. 9-12, 2013).*

E. Davis 

Opportunities for experimental and modeling synergy
Gyro-Landau BOUT++ needed to interpret measurements in $\nu^* < 1$ regimes, e.g. DIII-D’s ELM-free H-mode

- Phase Contrast Imaging (PCI) measures $\int \tilde{n} dl$
- Detector: 16 channel linear array
- Large range in $(f, k)$ space
  - $10 \text{ kHz} < f < 10 \text{ MHz}$
  - $2 \text{ cm}^{-1} < k < 30 \text{ cm}^{-1}$
Gyro-Landau BOUT++ needed to interpret measurements in $\nu^* < 1$ regimes, e.g. DIII-D’s ELM-free H-mode

- Phase Contrast Imaging (PCI) measures $\int \tilde{n} dl$
- Detector: 16 channel linear array
- Large range in ($f, k$) space
  - $10 \text{ kHz} < f < 10 \text{ MHz}$
  - $2 \text{ cm}^{-1} < k < 30 \text{ cm}^{-1}$

![Phase Contrast Imaging Image](image-url)
The $S(f, k)$ measured by PCI in DIII-D’s ELM-free H-mode has highly asymmetric features with well-defined $v_{ph}$
The $S(f, k)$ measured by PCI in DIII-D’s ELM-free H-mode has highly asymmetric features with well-defined $\nu_{ph}$. 

E. Davis
Opportunities for experimental and modeling synergy
PCI’s $S(f, k)$ structures suggest regions of strong localized edge turbulence*, begging theoretical validation.

* J. C. Rost et al. in preparation (2013), and
J. C. Rost et al. TTF Workshop, Santa Rosa, CA (Apr. 9-12, 2013).
Conclusions and Future Work

- **BOUT++** ideal linear growth rates are in good agreement with those from ELITE.
- Both C-Mod and DIII-D are capable of accessing $\nu^* > 1$ and $\nu^* < 1$ regimes.
- $\nu^* > 1$ simulations in BOUT++:
  - EDA H-mode is a steady-state, high performance operational regime in C-Mod not explained by PB theory.
  - Inclusion of C-Mod’s resistivity drives RBMs that may explain the QCM and the resulting particle flux.
  - Disagreement with MLP measurements indicates the need to include drift wave physics.
- $\nu^* < 1$ simulations in BOUT++:
  - PCI measures asymmetric turbulent spectra in DIII-D’s ELM-free H-modes.
  - Modeling with the gyro-Landau extension to BOUT++ will complement empirical knowledge.

E. Davis
Opportunities for experimental and modeling synergy.
C-Mod’s mirror Langmuir probe measurements show QCM lives in region with *positive* radial electric field*

* B. LaBombard et al. TTF Workshop, Santa Rosa, CA (Apr. 9-12, 2013).