ELM modelling with BOUT++

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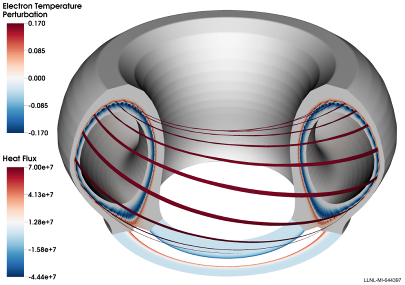


Publications and presentations

- B.Dudson *et al.* Comp. Phys. Comm. 180 (2009) p1467-1480
  $\rightarrow$ Linear benchmarking against ELITE
- X.Q.Xu *et al.* Phys. Rev. Lett. 105 (2010) 175005
  $\rightarrow$ Nonlinear multi-mode simulations
- B.Dudson *et al.* PPCF 53 (2011) 054005
- B.Dudson *et al.* ITPA Pedestal Group meeting 2011
  $\rightarrow$ More detailed linear benchmarking
  $\rightarrow$ Resistivity scans, and transition from peeling to tearing
- X.Q.Xu *et al.* Nucl. Fusion 51 (2011) 103040
- T.Y.Xia *et al.* Contrib. Plasma Phys. 52 (2012) 353-359
  $\rightarrow$ Added parallel compressibility terms
- P.W.Xi *et al.* Phys. Plasmas 19 (2012) 092503
  $\rightarrow$ Shear flow and K-H destabilisation
- B.Dudson *et al.* arXiv plasma-phys/1209.2054
  $\rightarrow$ Physics-based preconditioning

Publications and presentations

- J.T.Omotani, B.Dudson PPCF 55 (2013) 055009
  → Non-local heat flux model
- X.Q.Xu *et al.* Phys. Plasmas 20 (2013) 056113
  → Gyro-fluid models, non-Fourier Landau damping operator
- S.A.Myers *et al.* PPCF 55 (2013) 125016
  → Ballooning modes close to marginal stability
- T.Y.Xia *et al.* Nucl. Fusion 53 (2013) 073009
  → 6-field simulations of ELMs
- J.F.Ma *et al.* Nucl. Fusion 54 (2014) 033011
  → Linear simulations of snowflake configurations
- P.W.Xi *et al.* Phys. Rev. Lett. 112 (2014) 085001

ELM-pb model (publicly released)

- Compressional effects

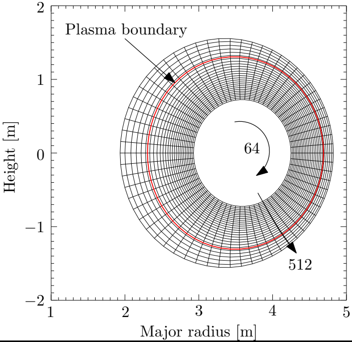
$$
\begin{aligned}
\frac{dP}{dt} &= P\left[-\frac{2}{B_0}\mathbf{b}_0 \times \kappa_0 \cdot \nabla\phi - B_0\nabla_{||}\left(\frac{V_{||}}{B_0}\right)\right] \\
\rho\frac{dV_{||}}{dt} &= -\nabla_{||}P \\
\rho\frac{dU}{dt} &= B^2\mathbf{b}\cdot\nabla\left(\frac{J_{||}}{B}\right) + 2\mathbf{b}_0 \times \kappa_0 \cdot \nabla P \\
\frac{\partial A_{||}}{\partial t} &= -\nabla_{||}\phi + \frac{\eta}{\mu_0}\nabla_\perp^2 A_{||} + \frac{\eta_H}{\mu_0}\nabla_\perp^4 A_{||} \\
U &= \frac{1}{B_0}\nabla_\perp^2\phi + \frac{1}{B_0}\nabla_\perp^2\frac{P}{en} \qquad J_{||} = J_{||0} - \frac{1}{\mu_0}\nabla_\perp^2 A_{||}
\end{aligned}
$$

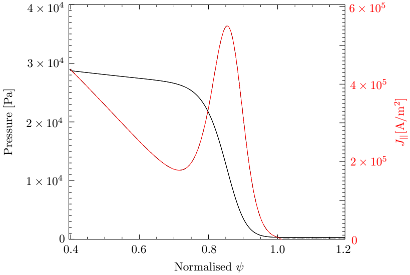
- Lowest-order diamagnetic drift
- All simulations multi-mode, so need to stabilise high n
- Resistivity η and hyper-resistivity (electron viscosity) η_H

Circular test case

Starting with a simplified benchmark case (cbm18_dens8), generated by TOQ equilibrium code

- JET-like aspect ratio, circular cross-section
- Highly unstable to ballooning modes ($\gamma \sim 0.2\omega_A$)

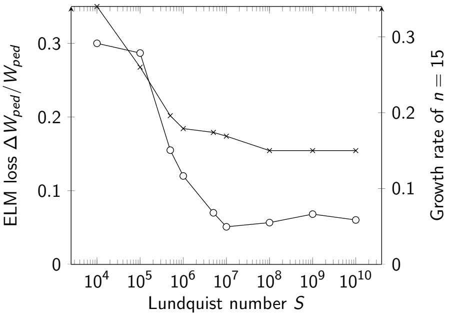




- Provides a standard base-case for ELM simulations
- Used by NIMROD, M3D, M3D-c1

Effect of resistivity on ELM size

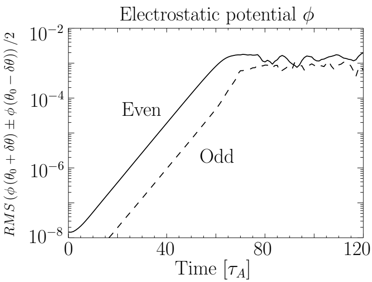
- Fixed $S_H = 10^{12}$, varying the resistivity
- Drop in ELM size ΔW_{ped} in range $S = 10^5 - 10^7$
- Approximately follows change in linear growth-rate
- At $S \simeq 2 \times 10^6$, $\Delta_R \simeq \Delta_H$ so for $S > 2 \times 10^6$ hyper-resistivity becomes the dominant dissipative effect

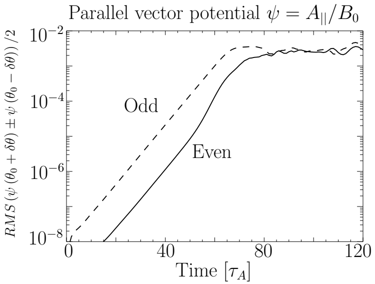


$$\frac{\partial A_{||}}{\partial t} = \begin{cases} \frac{\eta}{\mu_0}\nabla_\perp^2 A_{||} & \rightarrow \gamma \sim \frac{\eta}{\mu_0}\frac{1}{\Delta_R^2} \\ \frac{\eta_H}{\mu_0}\nabla_\perp^4 A_{||} & \rightarrow \gamma \sim \frac{\eta_H}{\mu_0}\frac{1}{\Delta_H^4} \end{cases}$$

ϕ and ψ parities

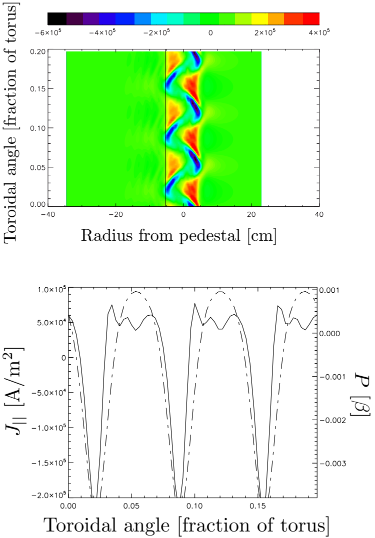
- Magnetic field perturbations $\delta B_r / B \sim 2 - 4\%$
- Linear evolution, ϕ and $\psi = A_{||}/B_0$ have ballooning parity
- In the nonlinear stage, tearing parity component appears



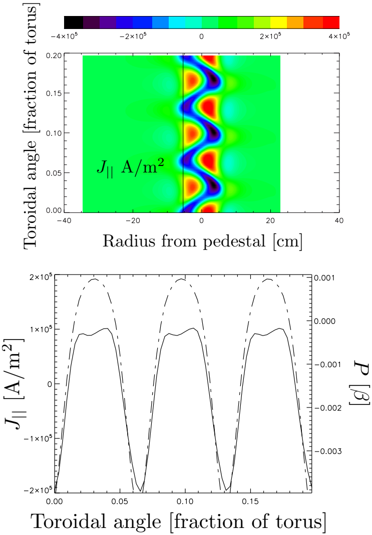


Coupling of harmonics: Parallel current

$S = 10^8$, $\delta r = -5.4\text{cm}$



$S = 10^6$



Websites:

- http://boutproject.github.io
  - http://boutproject.github.io/workshop2014
- http://bout.llnl.gov
  - http://bout2011.llnl.gov
  - http://bout2013.llnl.gov
- www-users.york.ac.uk/~bd512/