Simulations of EHO equilibria in the pedestal region of NSTX utilizing BOUT++

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Introduction

Edge localized modes (ELMs) are MHD instabilities found in the edge region of tokamak plasmas, characterized by nearly periodic relaxations of the pedestal and the eruption of high energy plasma towards the reactor wall [1]. ELM behaviors are typically observed while operating at a high confinement (H-mode) state and the physics of their onset is currently studied through developing peeling-ballooning (P-B) models. However, observations from the DIII-D tokamak have shown ELM free operation in the dubbed quiescent H-mode, where edge harmonic oscillations (EHOs) are present [2]. EHOs provide a mechanism for better particle transport within the edge region that mitigates ELM events. In this way, operation in the quiescent H-mode would negate the need for ELM suppression via external resonant magnetic fields. Ultimately, it is hoped that this would allow for a near steady-state edge plasma in fusion reactors and prevent damage to the first wall and diverter surfaces.

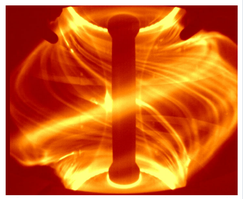


Figure 1. A negative image of ELM filamentary structures in the MAST tokamak [3].

Motivations

- The mechanisms behind QH-mode operation and EHO presence are still not well resolved
- Using an existing framework from the 3D plasma code BOUT++ (designed for ELM simulations) in conjunction with EHO equilibria could lead to computational verification of the experimental observations of quiescent H-mode operation in NSTX

BOUT++ Reduced MHD Simulations

BOUT++ is a C++ code, which performs 3 dimensional plasma fluid simulations in a curvilinear coordinate system.

- It is designed to simulate the edge of tokamak plasmas
- The code utilizes the method of lines (MOL) for finite differencing
- It also uses the time integration solver CVODE to evolve the system through advancing time steps using the Newton-Krylov BDF method
- BOUT++ solves the following high-β reduced ideal MHD equations [4]:

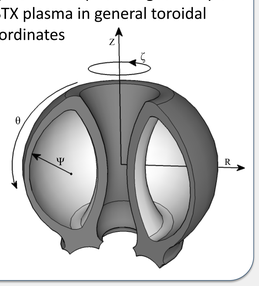
$$\rho_0 \frac{d\omega}{dt} = B_0^2 \mathbf{b}\cdot\nabla\left(\frac{J_\parallel}{B_0}\right) + 2\mathbf{b}_0 \times \kappa_0 \cdot \nabla p$$

$$\frac{dp}{dt} = -\frac{1}{B_0}\mathbf{b}_0 \times \nabla\phi \cdot \nabla p_0$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{1}{B_0}\mathbf{b}_0 \times \nabla\phi \cdot \nabla \qquad \frac{\partial A_\parallel}{\partial t} = -\nabla_\parallel \phi$$

$$J_\parallel = J_{\parallel 0} - \frac{1}{\mu_0}\nabla_\perp^2 A_\parallel \qquad \omega = \frac{1}{B_0}\nabla_\perp^2 \phi$$

Figure 2. The spherical geometry of NSTX plasma in general toroidal coordinates



BOUT++ Geometry

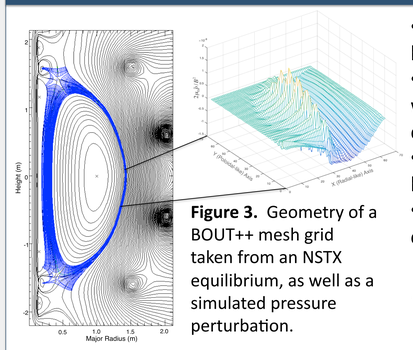


Figure 3. Geometry of a BOUT++ mesh grid taken from an NSTX equilibrium, as well as a simulated pressure perturbation.

- The grid files for the simulations were create using BOUT++ built-in routines
- The NSTX equilibria were obtained from the EFIT02 code, which utilizes Thomson scattering data for temperature and density measurements
- The grid size of 68 X-coordinates and 64 Y-coordinates was held constant for all runs
- The BOUT++ coordinate transform from general toroidal coordinates to Cartesian coordinates is as follows [4]:

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

Results

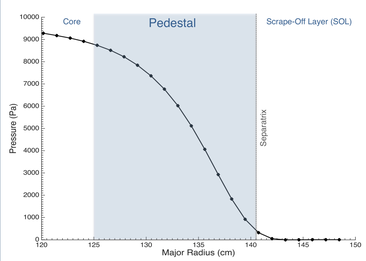


Figure 4. Plot of the edge pressure of NSTX with the pedestal region highlighted in blue. The separatrix location is indicated as the boundary of the plasma pedestal. Note the steep pressure gradient in this region.

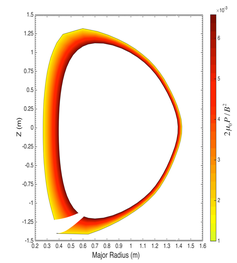


Figure 5. The initial pressure profile implemented in the simulations and obtained from an EHO equilibrium (NSTX shot: 141125).

- The grid files used in the simulation inputs had a domain bounded by the separatrix due to both a cutoff in the EFIT02 equilibrium files and an issue with the diverter geometry
- The profiles (e.g. pressure and parallel current) then terminated at a finite number, instead of a value of zero

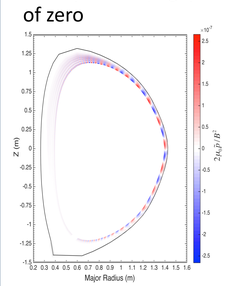


Figure 6. Poloidal plot showing the pressure perturbation for toroidal mode number n = 4. The filamentary structures appear more prominent on the outboard side during the linear growth phase, in agreement with previous studies.

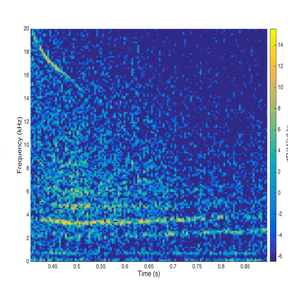


Figure 7. Spectrogram of beam emission spectroscopy (BES) data from NSTX shot 141125. The yellow band at 4 kHz corresponds to the toroidal mode number n = 4, as shown in poloidal cross section in the previous figure.

- The EHO equilibrium simulations were carried out with a time step of interval 10 ω_A^{-1} in order to reach the linear growth phase at approximately 1,000 ω_A^{-1}

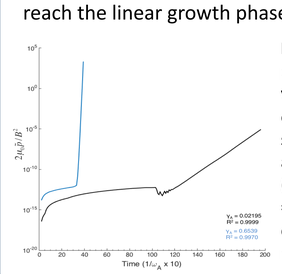


Figure 8. Plot of the pressure perturbation versus time for an EHO equilibrium (black) simulation with n = 3 and an ELM equilibrium (blue) simulation with n = 4. Notice the difference in growth rate size and onset time.

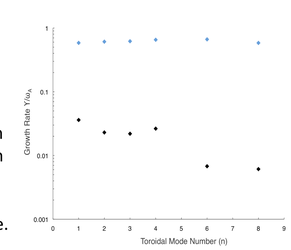


Figure 9. Plot of the measured growth rates against toroidal mode number for the ELM simulations shown in blue and the EHO simulations shown in black. Note the y-axis is on a logarithmic scale

Additional Findings

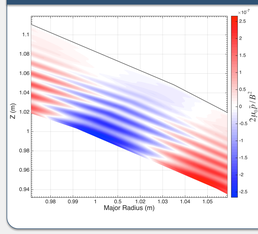


Figure 10. A closer view of the poloidal plot shown in Figure 6 with a toroidal mode number n=4. Notice that the filamentary structures show a clear propagation towards the core boundary of the simulation domain. This type of mode structure may be a result of the location of the domain (i.e. the outer boundary was set as the separatrix location and not a larger value of ψ).

Conclusions

- Linear growth rates were found for toroidal mode numbers n = 1-8 of the form characteristic of previous studies of ELMs by Dudson [4] and Xu [1] with the exception of n = 5 and n = 7.
- The lack of mode growth for n = 5 and 7 observed for NSTX shots 140989 and 141125 indicates that no single eigenmode grew out of the transient phase of the simulations
- Further research is required in order to explain the lack of ELM-like growth and to determine whether it is related to EHO observance in NSTX experimental data
- However, the data did indicate significantly lower growth rates for EHO equilibria simulations, in agreement with experiment

Future Work

- In order to accurately simulate the plasma edge, the diverter region should be incorporated into the input grid files with the appropriate equilibrium data
- Further investigation into the absence of a growth rate for toroidal mode numbers n=5 and 7, as well as the propagation of the pressure perturbation towards the core could also be conducted

References

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Acknowledgements

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