ECCD-induced tearing mode stabilization in coupled IPS/NIMROD/GENRAY HPC simulations

Thomas G. Jenkins, Tech-X Corporation
in collaboration with
S.E. Kruger
Tech-X Corporation
E. D. Held
Utah State University
R. W. Harvey
CompX
D. D. Schnack
University of Wisconsin-Madison
W. R. Elwasif
ORNL
The SWIM Project Team
http://cswim.org

Center for Simulation of RF Wave Interactions with Magnetohydrodynamics

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Problem: modeling mitigation/control of tearing modes (magnetic islands) by electron cyclotron current drive (ECCD)

- Neoclassical tearing modes generate magnetic islands in tokamaks; pressure profile flattening $\Rightarrow$ altered plasma bootstrap current profile $\Rightarrow$ self-reinforcing altered confinement.

- Islands grow to macroscopic scales before nonlinearly saturating, causing degraded confinement and the possibility of disruption.

- Experimentally, RF waves resonant with electron cyclotron motion can drive currents that alter or suppress the island structures.

- Numerically, we want to detect the modes and suppress them in the same way that experimentalists do.

Figure from Prater et al., Nucl. Fusion 47, 371 (2007).
A basic numerical Plasma Control System for the RF/MHD problem

- time modulation of RF source (for rotating plasmas)
- instantaneously changing sources
Mode detection via synthetic Mirnov coils – taking advantage of NIMROD datastructures

• NIMROD’s toroidal Fourier representation is equivalent to an already-processed dataset from Mirnov coils (if we set ihist = mx, jhist = 1 in nimrod.in)

• n=1 tearing mode
  \[ \sim A \exp(i\omega t + \gamma t + \varphi) \]

• Read nimhist.bin with python; fit data; extract amplitude, growth rate, and mode rotation frequency.
Rational surface positions and magnetic island O-points can be found via other NIMROD datastructures

• polflux.bin – gives $\psi(R,Z)$
• flsurf.bin – gives $q(\psi)$
• Interpolation gives approximate $(R,Z)$ coordinates where $q(\psi) = 2$ (or other desired helicity)

• Then launch a bunch of serial nimfl runs at these coordinates to figure out where the O-point is (IPS can launch many serial jobs, if enough resources are allocated).
GENRAY input parameters can be adjusted to direct RF power to island O-point

- **Potential issues:**
  - Rotation (how much did the island rotate in the time it took to calculate the O-point location? Will we even be aiming at the right spot?)

  - Location – 2010 PoP paper showed that rational surfaces and islands will move in response to deposited RF, with different characteristic behavior at short and long times.

  - Relative size of RF deposition region and island width – RF is generally bigger if mode is not nearing saturation

  - Rampup – how do we gently get the data into NIMROD? Who “owns” the time variable?
Electron temperature contours prior to RF deposition

Using VisIt to help sort out what’s going on – good visualization becoming increasingly important

Electron temperature contours as RF deposition ramps up suddenly
Initial control system tests seem promising

- When mode amplitude exceeds threshold, PCS injects ECCD at island O-point; island shrinks.
- Mode growth resumes when PCS is shut off. (Show VisIt movie here.)
Further work on the PCS algorithms is needed to optimize the mode stabilization.

- RF deposition slightly outside the rational surface gives a more rapid initial stabilizing effect (consistent with observations from 2010 PoP paper). However, the initial reduction doesn’t continue; instead, mode energy plateaus.

- Initial efforts to reduce plateau height have not been successful, though linear growth has ceased.

Ramp time problem allocated to NIMROD – NIMROD reads ON or OFF status of PCS, and ramps up RF power on a timescale set in nimrod.in (compare to physical gyrotron ramp times?)
(A bad idea? This means that GENRAY thinks the mode is at full power all the time.)
When we change the steering angle of the RF, things get a bit choppy.
Other thoughts: How ray propagation physics relates to MHD/QL physics

- Increased ray density $\Rightarrow$ lower power content and smaller area-perpendicular-to-flow for each ray.

- $PC/A_\perp$ ratio appears in the quasilinear terms ($\Rightarrow$ convergence with more rays); area must be calculated to evaluate these terms along ray paths.

- Where the ray equations come from – paper in progress, describing numerical methodology for finding quasilinear diffusion coefficients from the collection of rays, and why we have individual ray equations in the first place.
Additional other thoughts... how closures will affect things as we move toward self-consistent NTMs

\[ E + u \times B = \eta J + \frac{F_{rf}^{e0}}{n|q_e|} \]

Ohm’s Law

\[ \rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla)u = -\nabla p + J \times B - \nabla \cdot \Pi + \sum_{\alpha} F_{\alpha 0}^{rf} + \sum_{\alpha} S_{\alpha 0}^{rf} \]

Momentum

\[ \frac{3}{2} n \left( \frac{\partial T}{\partial t} + (u \cdot \nabla)T \right) + p \nabla \cdot u = -\nabla \cdot q - \Pi : \nabla u + q + \sum_{\alpha} S_{\alpha 0}^{rf} \]

Energy

- Standard MHD closure – assume distribution function is local Maxwellian + kinetic distortion; kinetic distortion moments yield stress tensor \( \Pi \) and heat flux \( q \).

- Kinetic distortion equation will include RF terms on the same footing as other thermodynamic drives (temperature/flow gradients):

\[ \frac{\partial F_\alpha}{\partial t} + v \cdot \nabla F_\alpha + \frac{q_\alpha}{m_\alpha} [E + v \times B] \cdot \frac{\partial F_\alpha}{\partial v} - \sum_\beta C(f_{M\alpha} + F_\alpha, f_{M\beta} + F_\beta) = \]

\[ \frac{m_\alpha}{T_\alpha} \left[ (v - V_\alpha) (v - V_\alpha) - \frac{(v - V_\alpha) \cdot (v - V_\alpha)}{3} \right] : \nabla V_\alpha f_{M\alpha} \]

\[ + (v - V_\alpha) \cdot (\nabla \Pi - R_\alpha - \frac{F_{rf}^{\alpha}}{n_\alpha T_\alpha}) f_{M\alpha} - \frac{m_\alpha}{2T_\alpha} (v - V_\alpha) \cdot (v - V_\alpha) - \frac{5}{2} (v - V_\alpha) \cdot \nabla T_\alpha f_{M\alpha} \]

\[ + \left( \frac{m_\alpha}{3T_\alpha} (v - V_\alpha) \cdot (v - V_\alpha) - 1 \right) (\Pi_\alpha : \nabla V_\alpha + \nabla \cdot q_\alpha - Q_\alpha - S_{\alpha 0}^{rf}) \frac{f_{M\alpha}}{n_\alpha T_\alpha} \]

- Fisch-Boozer and Ohkawa effects
Some basic Fokker-Planck physics

$$m_\alpha n_\alpha \left[ \frac{\partial \vec{V}_\alpha}{\partial t} + (\vec{V}_\alpha \cdot \vec{\nabla})\vec{V}_\alpha \right] = n_\alpha q_\alpha (\vec{E} + \vec{V}_\alpha \times \vec{B}) - \vec{V}_\alpha p_\alpha - \vec{V}_\alpha \cdot \vec{\pi}_\alpha + \eta \left[ \vec{J} + \frac{3e\vec{q}}{5T_e} \right] + \vec{F}_\alpha$$

- RF interaction increases electron $v_\perp$
- Lower collisionality ($\sim 1/v^3$)
- Net momentum transfer between ions and electrons; current

- RF interaction moves particles across trapped-passing boundary
- Symmetric detrapping, asymmetric trapping; current (opposite direction)

Figure from R. Prater, *Phys. Plasmas* 11, 2349 (2004).
Present status and plans

• Developments to the control system are ongoing and will require additional careful thought.

• IPS capabilities in managing coupled RF/MHD simulations (and other complex workflows) vastly simplify things for the user.

• VisIt capabilities are very useful as we try to figure out what’s going on in the simulations.

• Dylan has provided higher-\(\beta\) equilibria near the NTM stability boundary – still trying to get that line of research going.

• Writing a paper on computational methods, and how to translate between the various physics objects in this problem (MHD fluids, individual RF rays, and the RF ray bundle).

• Plan to work with DIII-D experimentalists in coming months, to develop control system logic and synthetic diagnostics consistent with experiments.