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

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

- Islands cause degraded confinement and the possibility of disruption.
- Experiment: Control systems use ECRF to drive currents that suppress the islands.
- Numerically: How can we optimize the control system and minimize RF power required to stabilize islands?

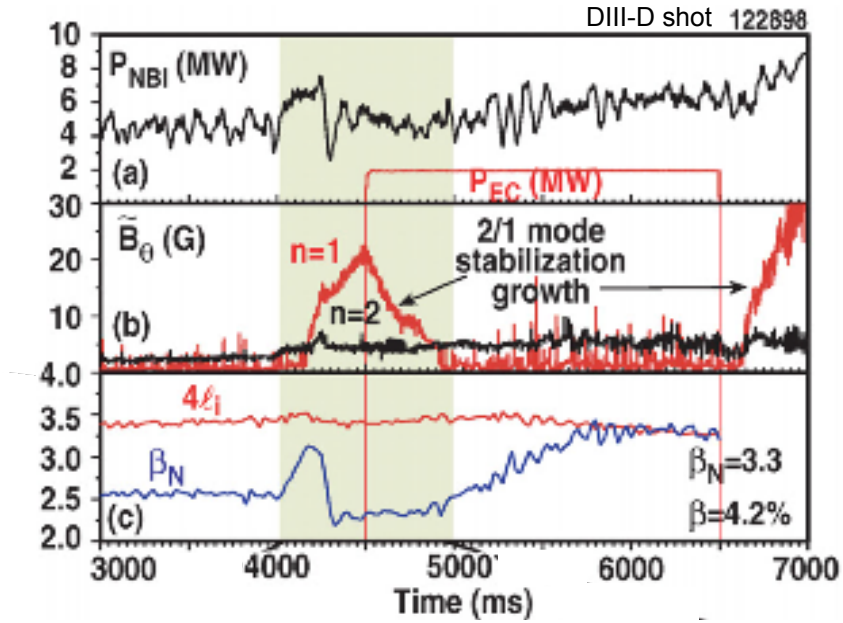
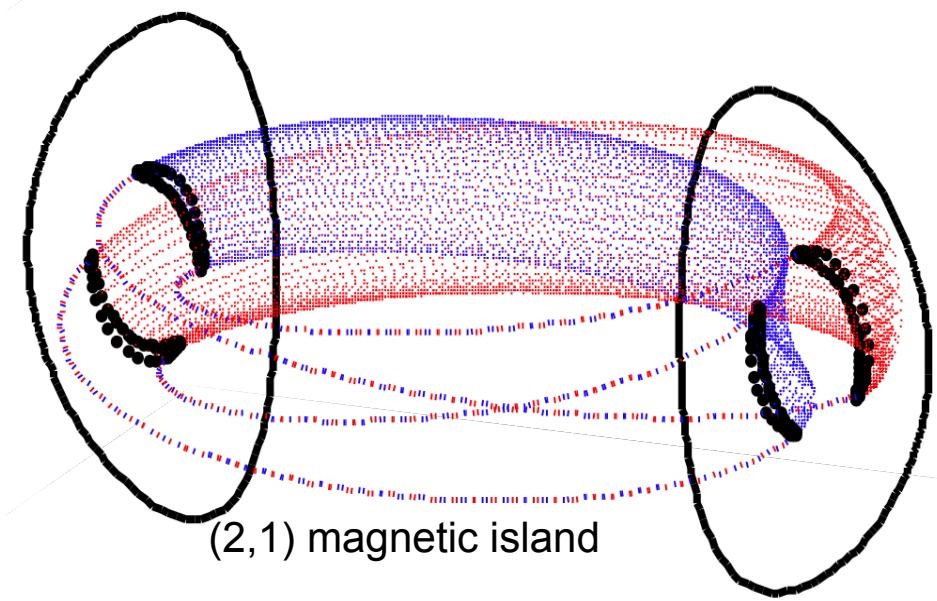


Figure from Prater *et al.*, Nucl. Fusion **47**, 371 (2007).



(2,1) magnetic island

Problem formulation: How to include RF physics in MHD simulations

$$S^{rf}_{\alpha 0} \equiv \int \frac{1}{2} m_\alpha v^2 Q(f_\alpha) d\mathbf{v}$$

$$\mathbf{F}^{rf}_{\alpha 0} \equiv \int m_\alpha \mathbf{v} Q(f_\alpha) d\mathbf{v}$$

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J} + \frac{\mathbf{F}^{rf}_{e0}}{n|q_e|}$$ Ohm's Law

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mathbf{J} \times \mathbf{B} - \nabla \cdot \mathbf{\Pi} + \sum_\alpha \mathbf{F}^{rf}_{\alpha 0}$$ Momentum

$$\frac{3}{2} n \left(\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T \right) + p \nabla \cdot \mathbf{u} = -\nabla \cdot \mathbf{q} - \mathbf{\Pi} : \nabla \mathbf{u} + Q + \sum_\alpha S^{rf}_{\alpha 0}$$ Energy

- Standard MHD closure – assume distribution function is local Maxwellian + kinetic distortion; kinetic distortion moments yield stress tensor **π** and heat flux **q**.
- Kinetic distortion equation will include RF terms on the same footing as other thermodynamic drives (temperature/flow gradients):

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

$$\frac{m_\alpha}{T_\alpha} \left[(\mathbf{v} - \mathbf{V}_\alpha)(\mathbf{v} - \mathbf{V}_\alpha) - \frac{(\mathbf{v} - \mathbf{V}_\alpha) \cdot (\mathbf{v} - \mathbf{V}_\alpha) \mathbf{I}}{3} \right] : \nabla \mathbf{V}_\alpha f_{M\alpha}$$

$$+ (\mathbf{v} - \mathbf{V}_\alpha) \cdot (\nabla \cdot \mathbf{\Pi}_\alpha - \mathbf{R}_\alpha - \mathbf{F}^{rf}_\alpha) \frac{f_{M\alpha}}{n_\alpha T_\alpha} - \left(\frac{m_\alpha}{2T_\alpha} (\mathbf{v} - \mathbf{V}_\alpha) \cdot (\mathbf{v} - \mathbf{V}_\alpha) - \frac{5}{2} \right) (\mathbf{v} - \mathbf{V}_\alpha) \cdot \nabla T_\alpha \frac{f_{M\alpha}}{T_\alpha}$$

$$+ \left(\frac{m_\alpha}{3T_\alpha} (\mathbf{v} - \mathbf{V}_\alpha) \cdot (\mathbf{v} - \mathbf{V}_\alpha) - 1 \right) (\mathbf{\Pi}_\alpha : \nabla \mathbf{V}_\alpha + \nabla \cdot \mathbf{q}_\alpha - Q_\alpha - S^{rf}_\alpha) \frac{f_{M\alpha}}{n_\alpha T_\alpha}$$

- Fisch-Boozer and Ohkawa effects

References:

- C. C. Hegna and J. D. Callen, *Phys. Plasmas* **16**, 112501 (2009).
- J. J. Ramos, *Phys. Plasmas* **15**, 082106 (2008).
- J. J. Ramos, *Phys. Plasmas* **17**, 105106 (2010).
- J. J. Ramos, *Phys. Plasmas* **18**, 102506 (2011).

Where did the RF physics go?

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

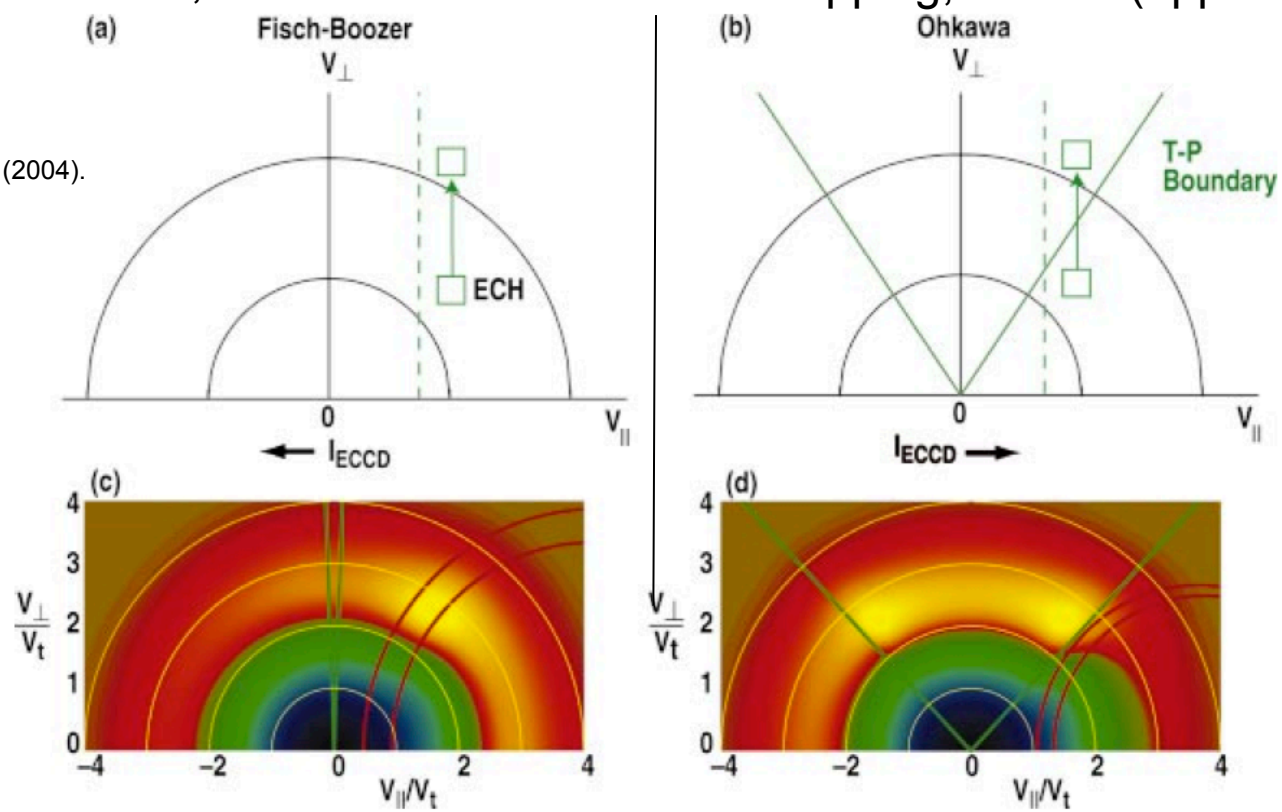
Fisch-Boozer Currents

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

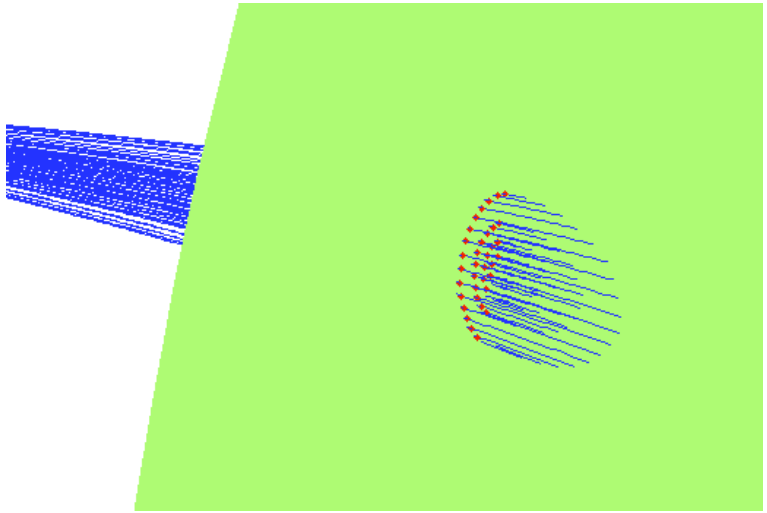
Ohkawa Currents

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

Figure from R. Prater, *Phys. Plasmas* **11**, 2349 (2004).



Coupling scheme requires local calculation of quasilinear operator: New numerical schemes developed



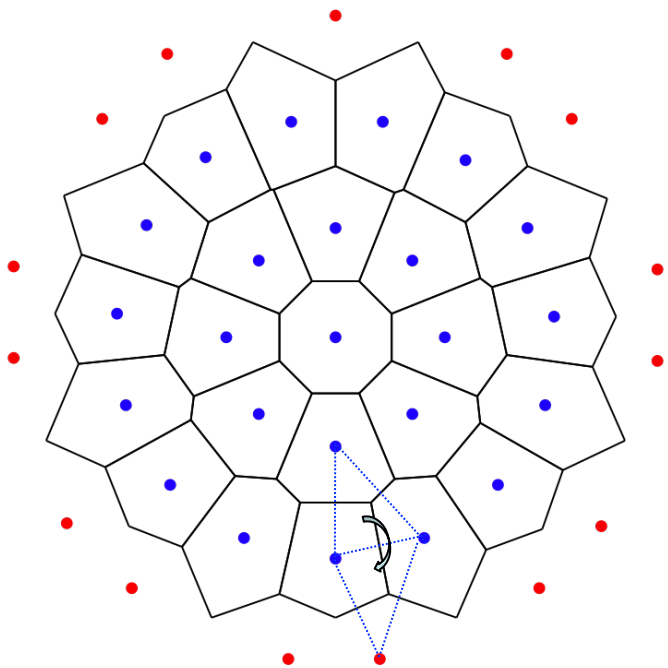
Need to relate:

- Fluid equations
- Individual ray equations
- Collective (quasilinear) effects of ray bundle

- Increased ray density ➔ lower power content, smaller ray volume.

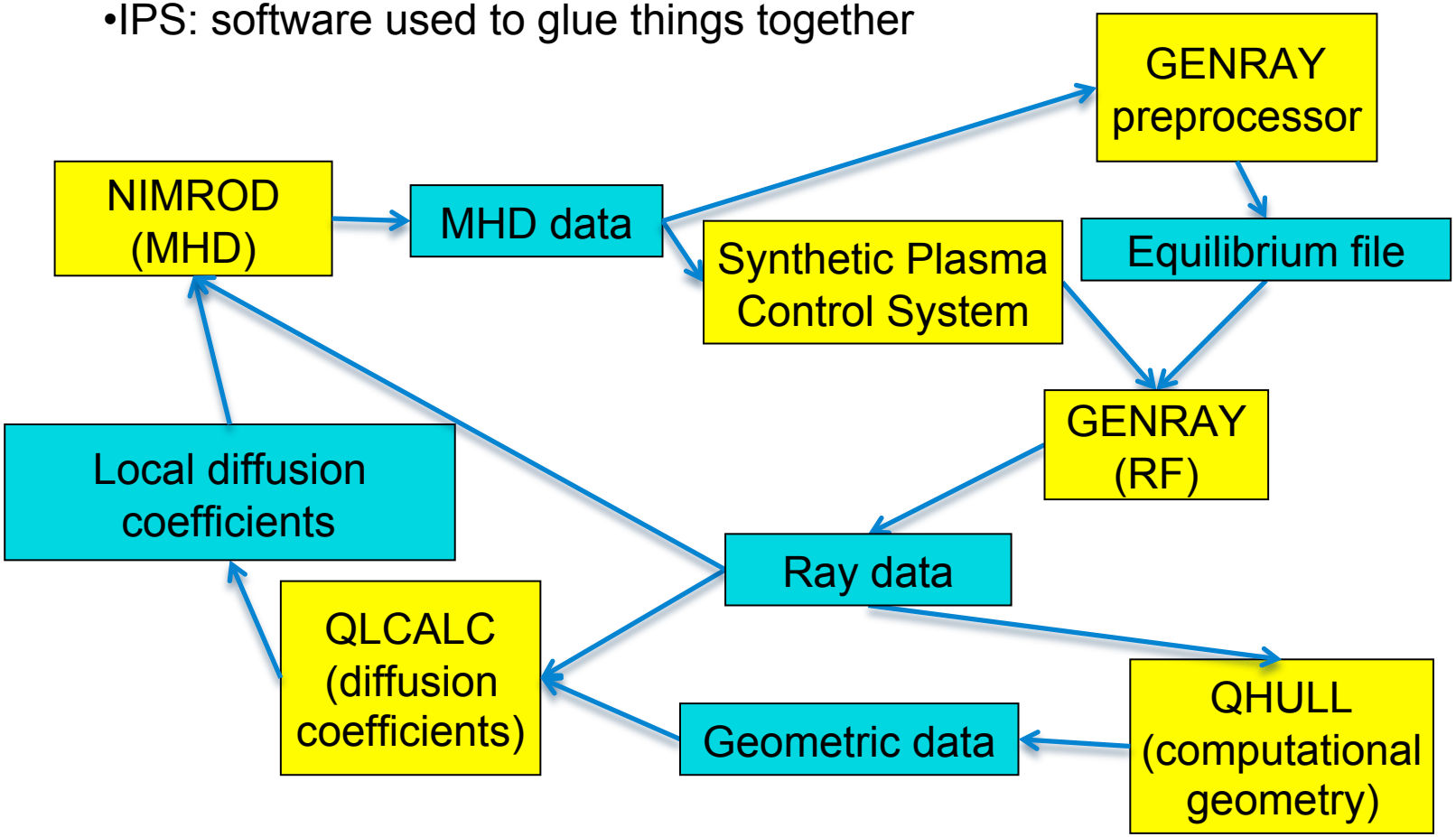
- Power/(area-perpendicular-to-flow) ratio appears in QL terms at each ray point

- QHULL computational geometry software

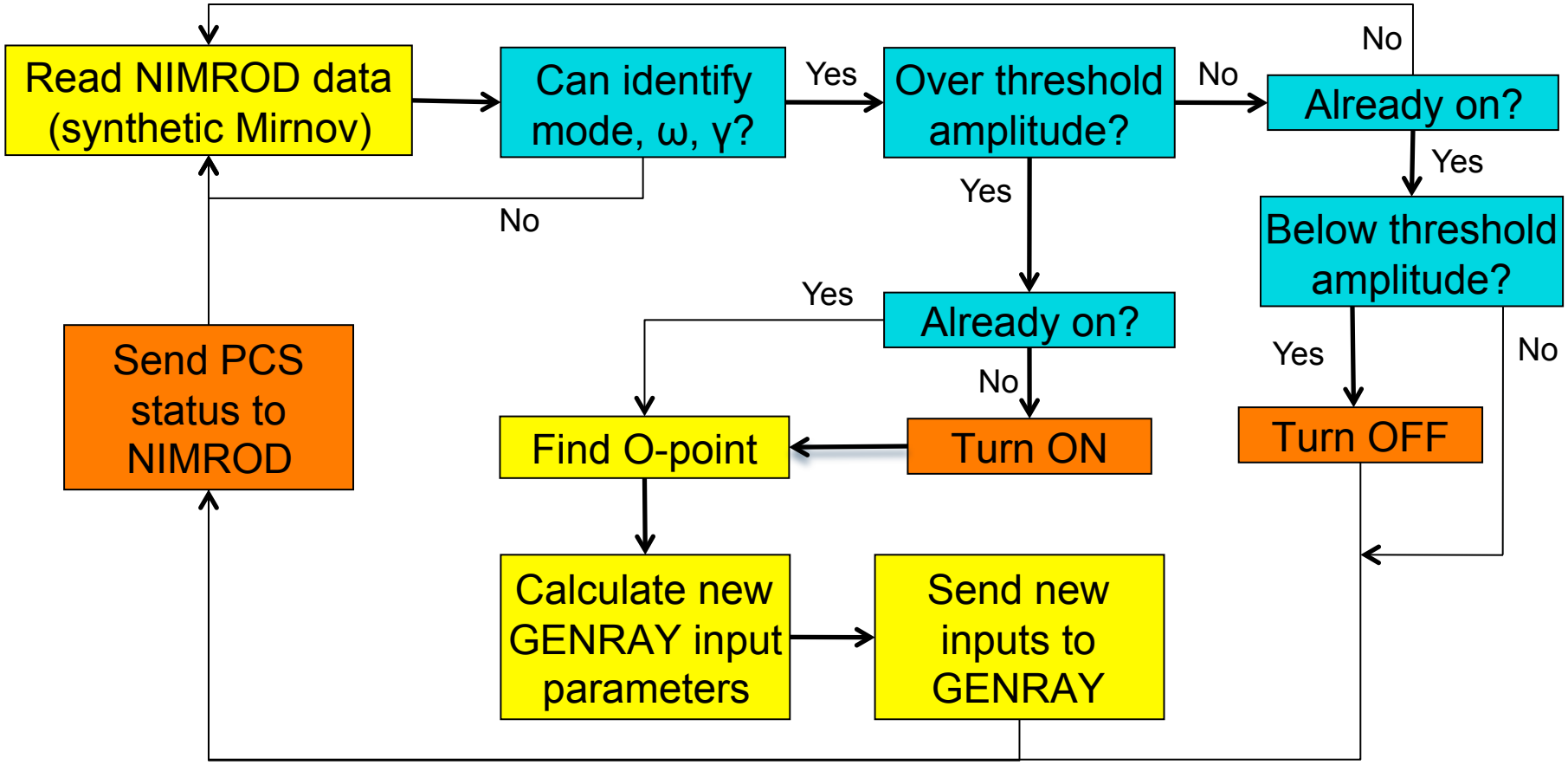


Coupling multiple codes to get at the physics we need

- Getting the quasilinear diffusion coefficients into NIMROD is a multistep process using several codes and moving several files.
- Control system is goal of this work
- IPS: software used to glue things together



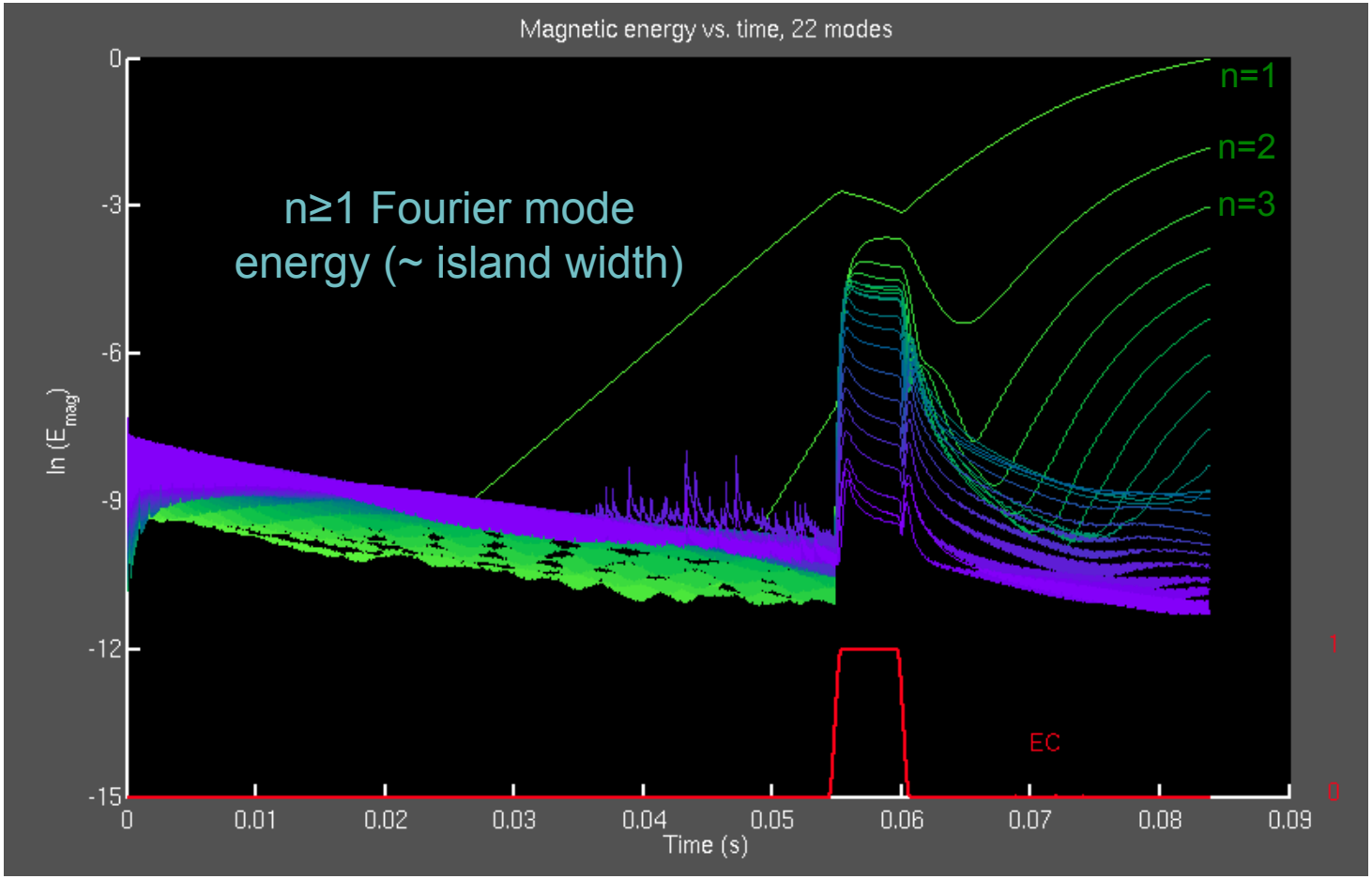
Rough outline of control system logic



Hierarchy of control systems desired:

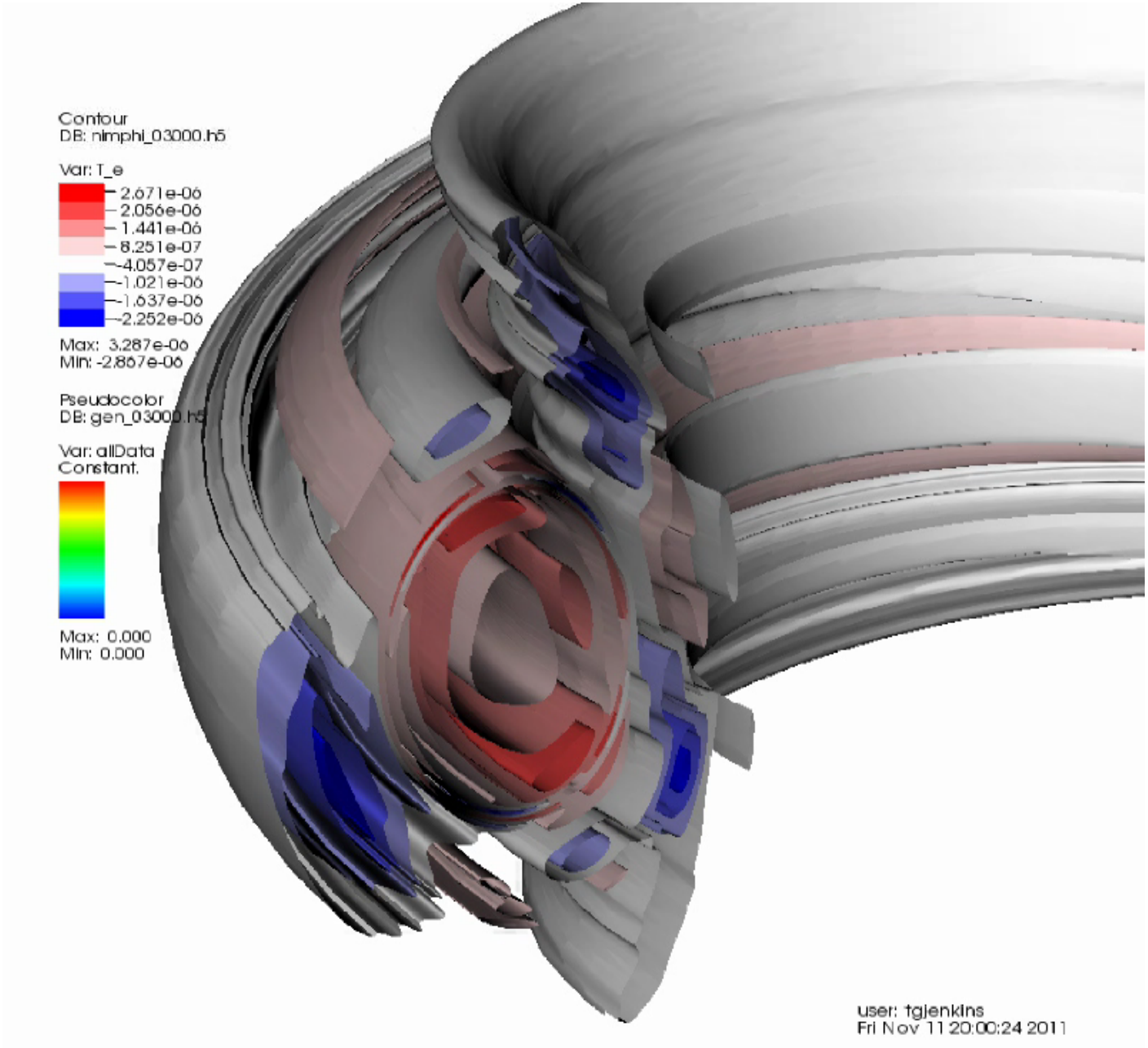
- "Dumb system": Mirnov coils only (for detection)
- Experimental mimicking system: Implement system similar to DIII-D
- Optimized control system: What we want to provide
- "Perfect system": Hit the O-point exactly (what we are doing in this talk)

Initial control system tests show moderate stabilization when RF is applied

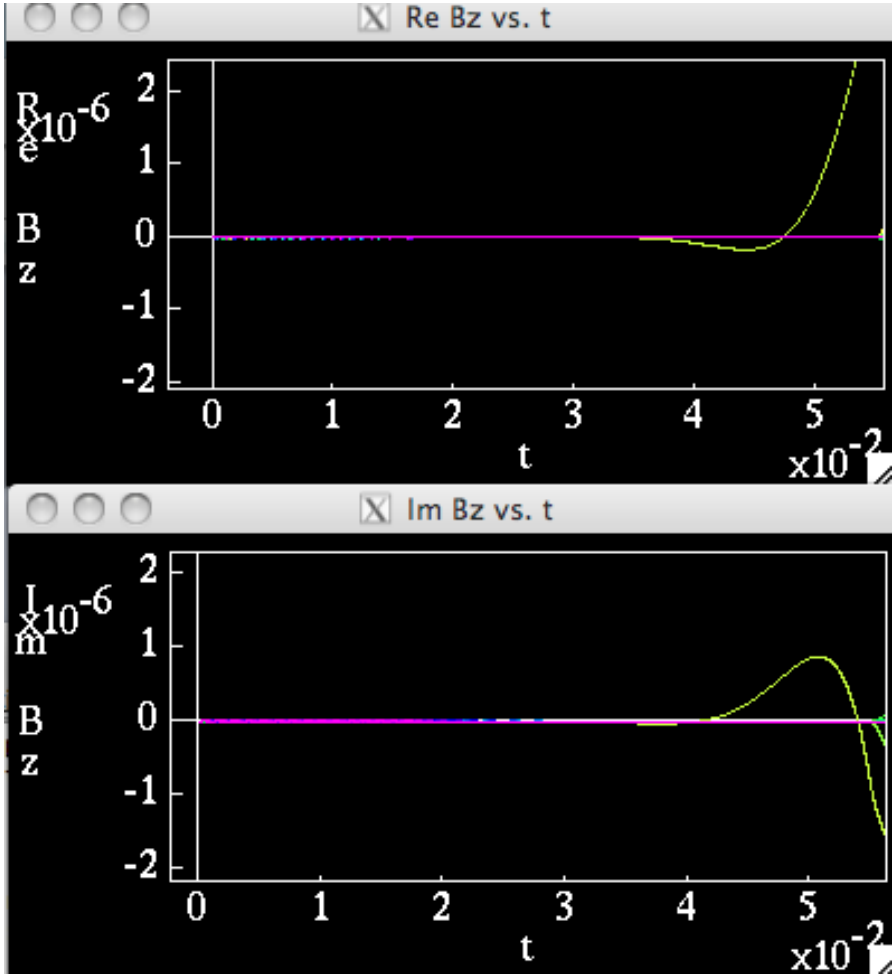


- When mode amplitude exceeds threshold, PCS injects ECCD at island O-point; island shrinks.
- Mode growth resumes when ECCD is shut off.

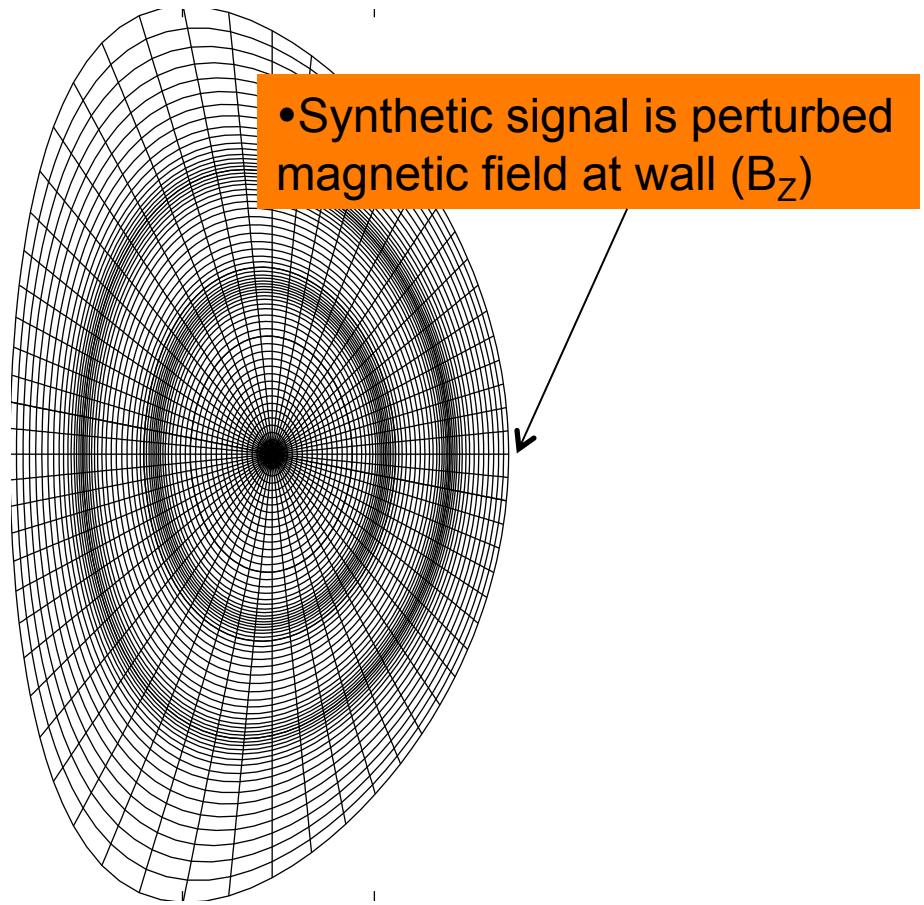
Perturbed electron temperature evolution with RF



Mode detection is carried out using synthetic Mirnov coil diagnostics in NIMROD



•n=1 tearing mode
~ A exp(iωt+γt+φ)

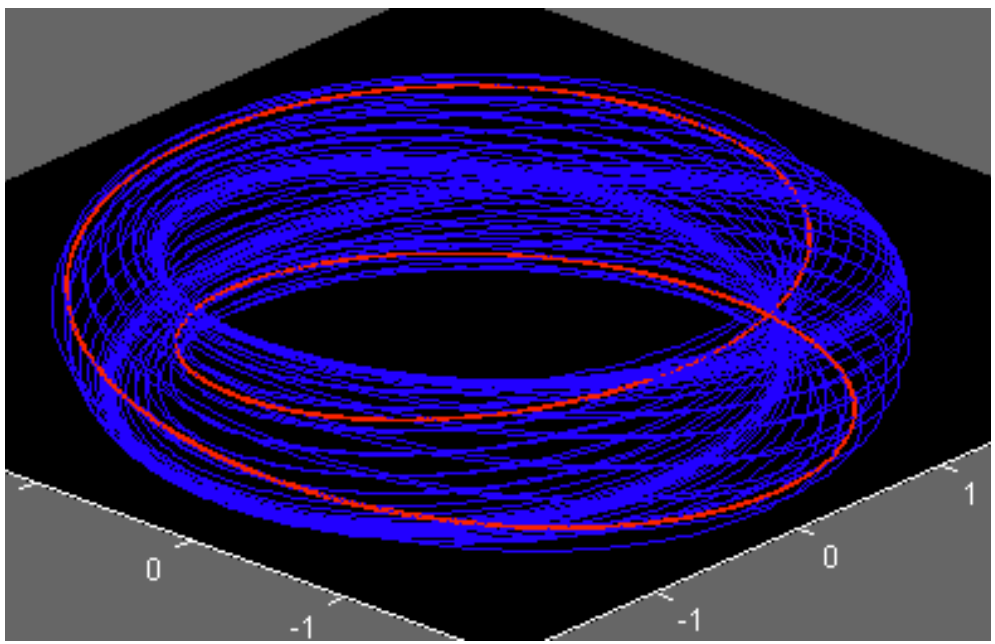


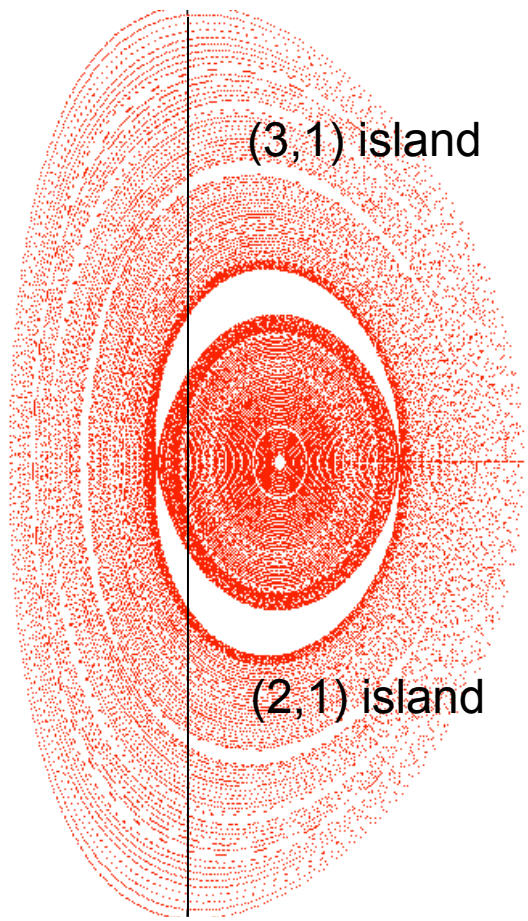
•Extract NIMROD data with python; fit data; extract amplitude, growth rate, and toroidal rotation frequency.

"Perfect" control system - rational surface positions and magnetic island O-points can be calculated exactly

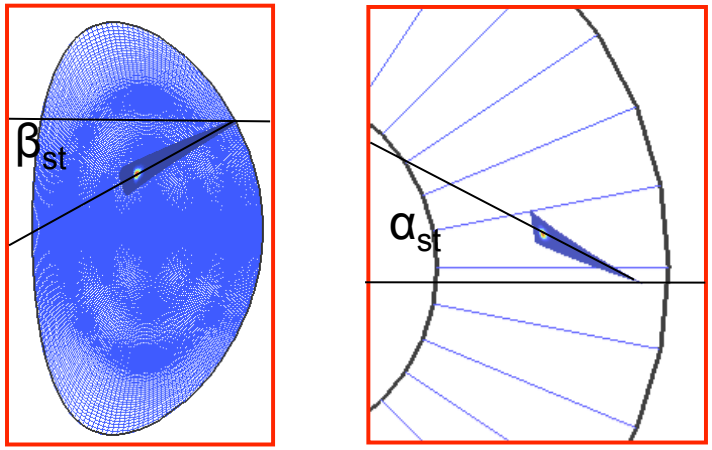
•From NIMROD, get ψ(R,Z) and q(ψ) – calculate (R,Z) coordinates where q(ψ) = 2 (or other desired value)

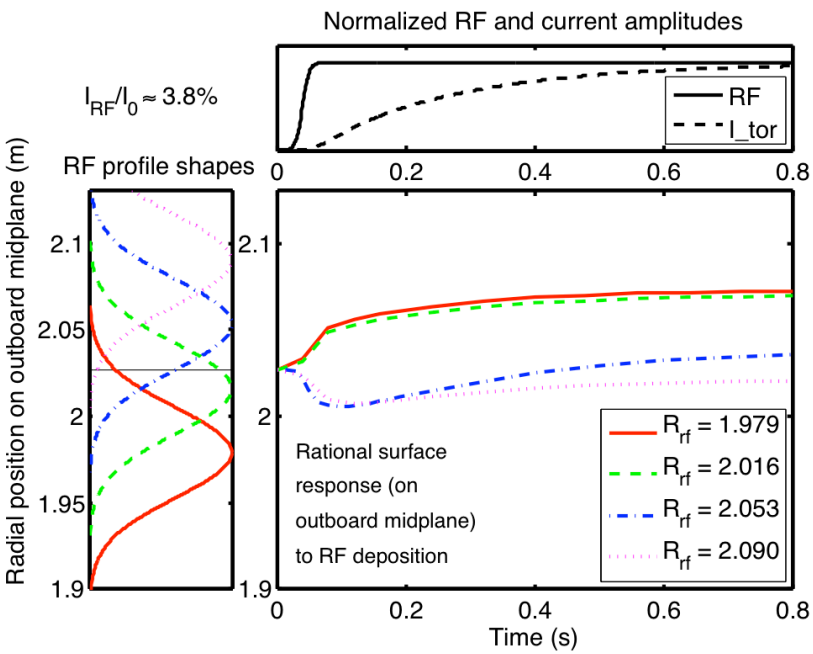
•Field line traces at these coordinates – O-points (many serial IPS jobs).





GENRAY input parameters can be adjusted to direct RF power to island O-point, in a "perfect" PCS





- Potential issues:

  Rotation:

  -How to hit island as it rotates.

  ECCD modifications:

  -Rational surfaces and islands move in presence of RF (2010 PoP paper).

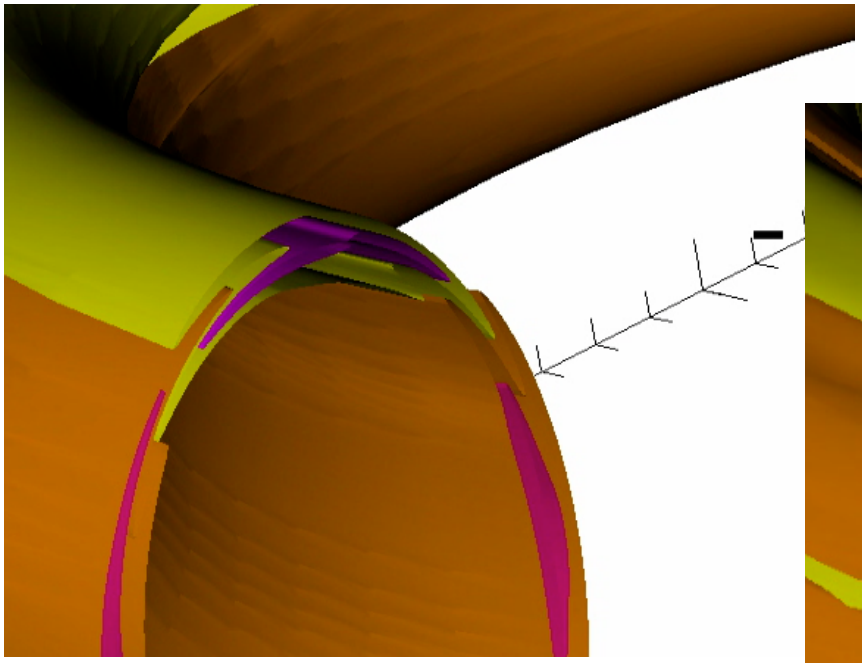
  Size of RF deposition region:

  -RF spot size > island width at times we want to stabilize (detection limit)

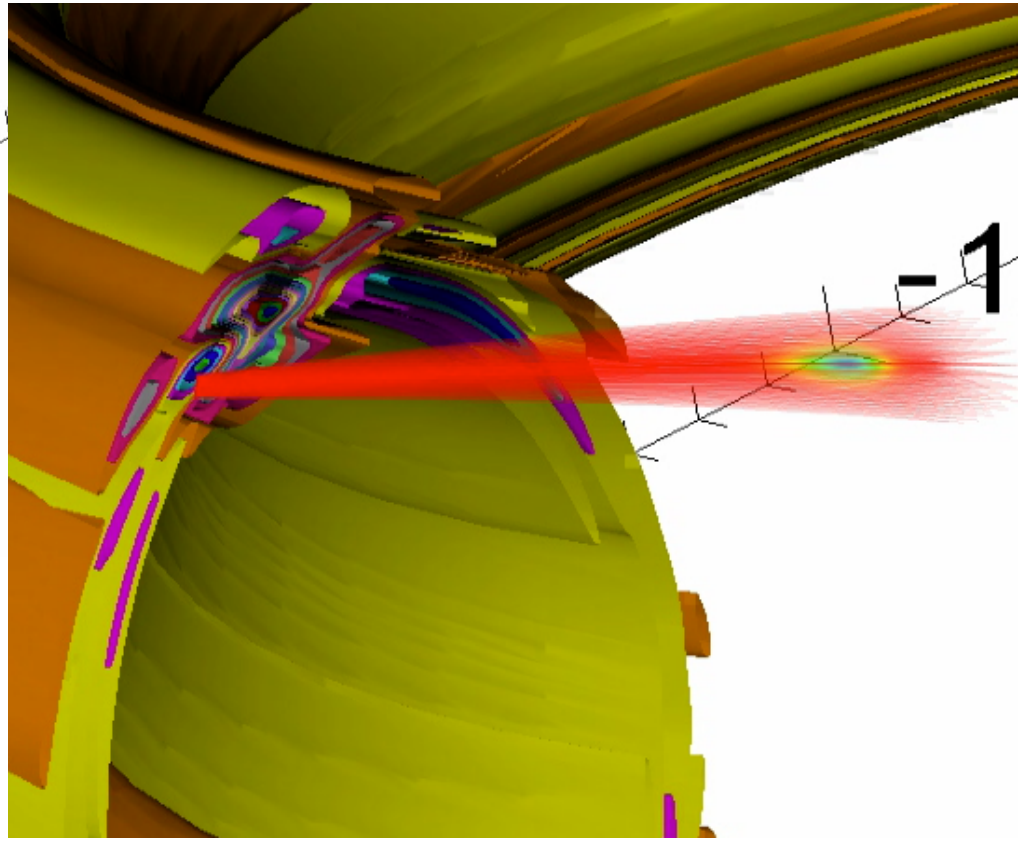
  Rampup:

  -Computational issues remain in coupling.

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

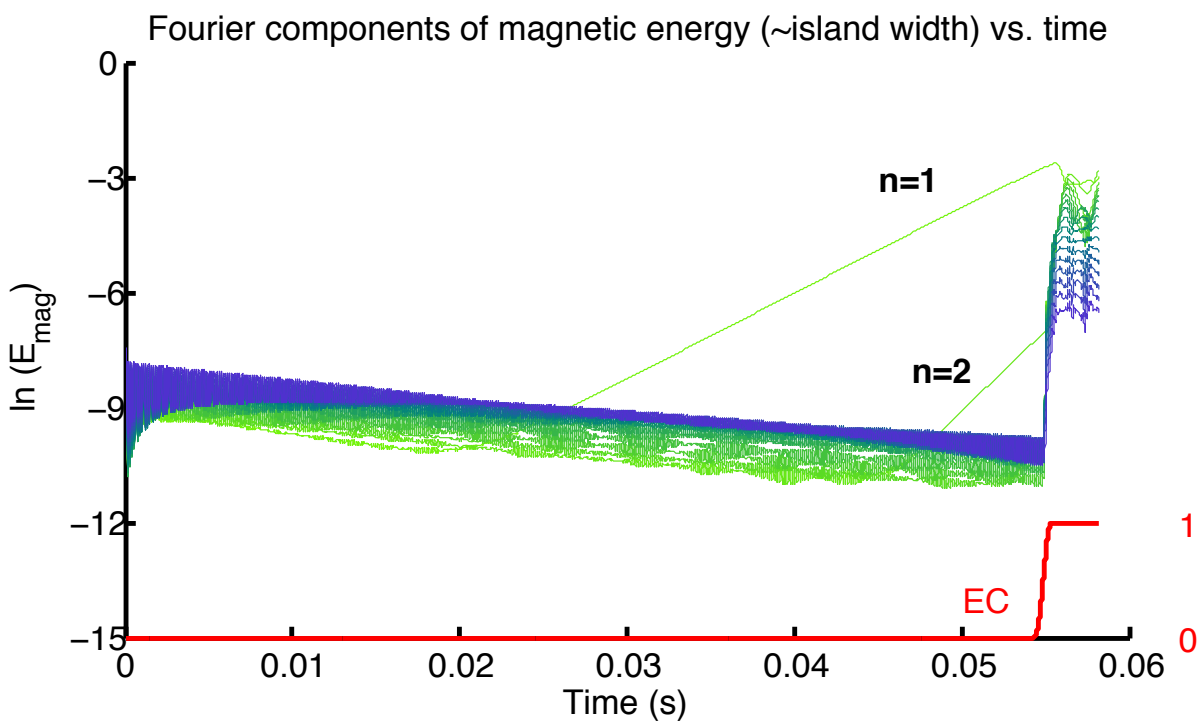


Electron temperature contours
prior to RF deposition



Electron temperature contours
as RF deposition ramps up suddenly

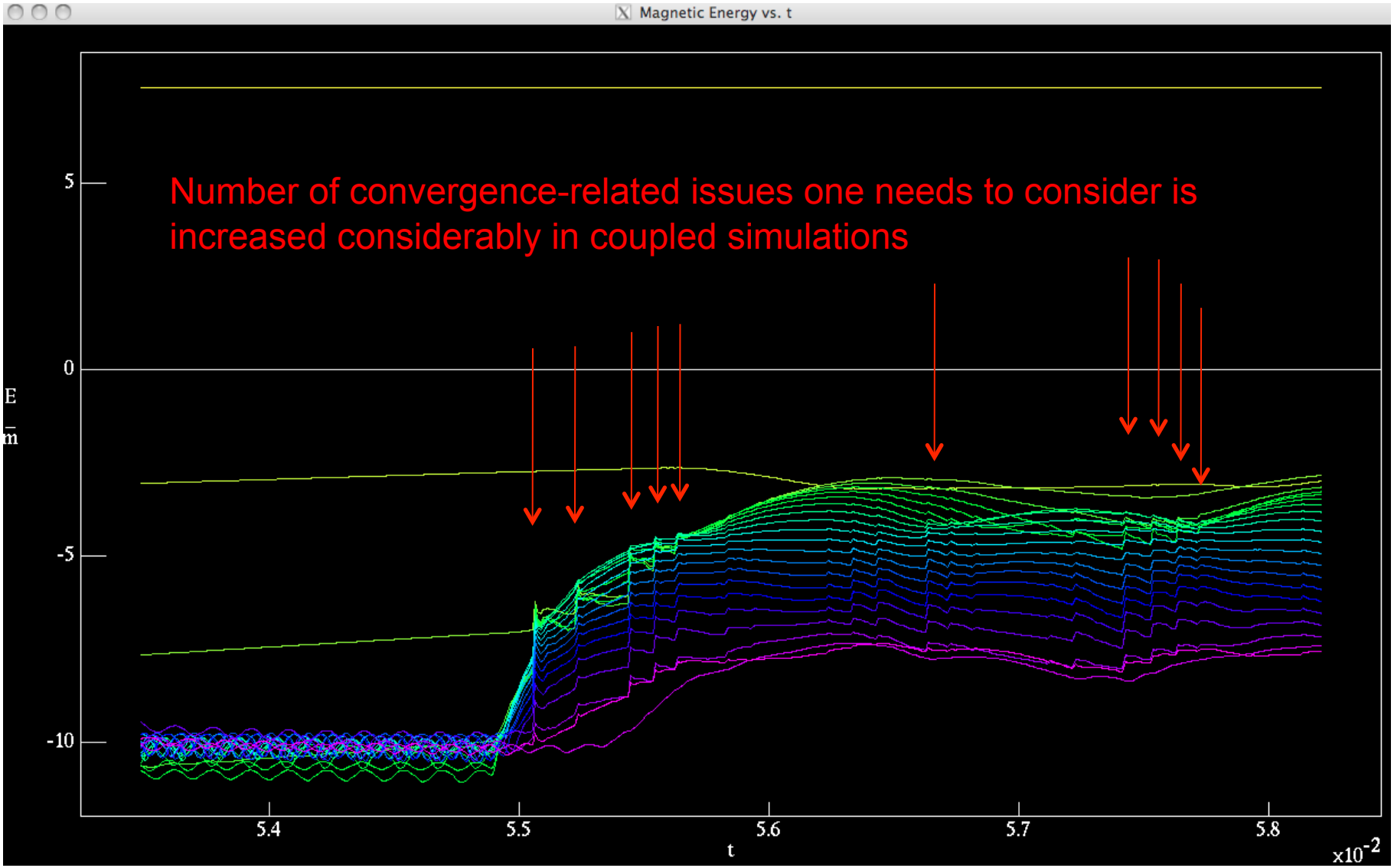
Further work on the PCS algorithms is needed to optimize the mode stabilization



- RF deposition slightly outside the rational surface gives rapid initial stabilizing effect
  - consistent with observations from 2010 PoP paper).
- Initial reduction doesn't continue; instead, mode energy plateaus.
- Initial efforts to reduce plateau height have not been successful, though linear growth has ceased.

- Moving towards more heuristic adjustments to current deposition

Temporal discretization of coupled system needs to be considered: Speed of injection angle needs to be resolved



Present status and plans

•Developments to the control system are ongoing; a pragmatic approach to mode suppression (like experimentalists use) is probably a better approach going forward

•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 Brennan (U. Tulsa) has provided higher-β equilibria near the NTM stability boundary so that we can move to more experimentally relevant regimes – a work in progress

•Paper in progress: computational methods, translating between the various physics objects in this problem (MHD fluids, individual RF rays, RF ray bundle).

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