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

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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; local flattening in the plasma pressure profile alters plasma bootstrap current profile (and thus confinement) near resonant magnetic surfaces in helical, self-reinforcing perturbations.

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

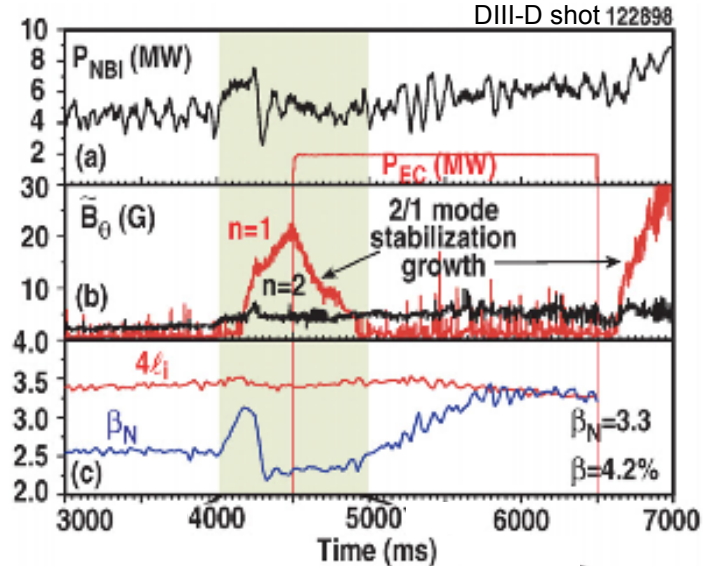
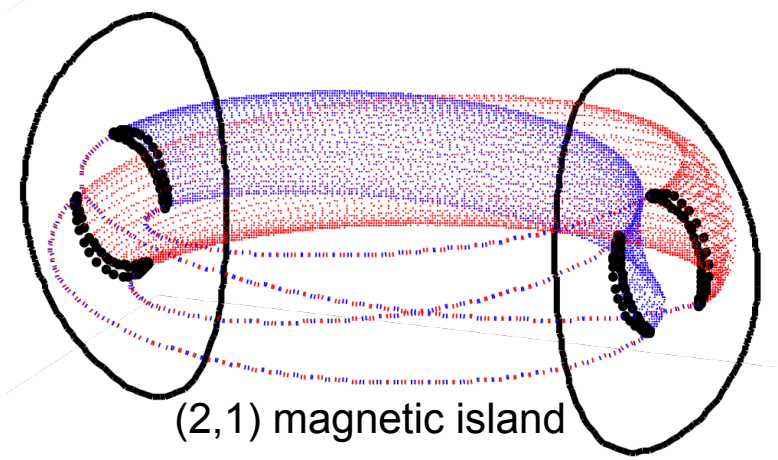


Figure from Prater *et al*., Nucl. Fusion **47**, 371 (2007).

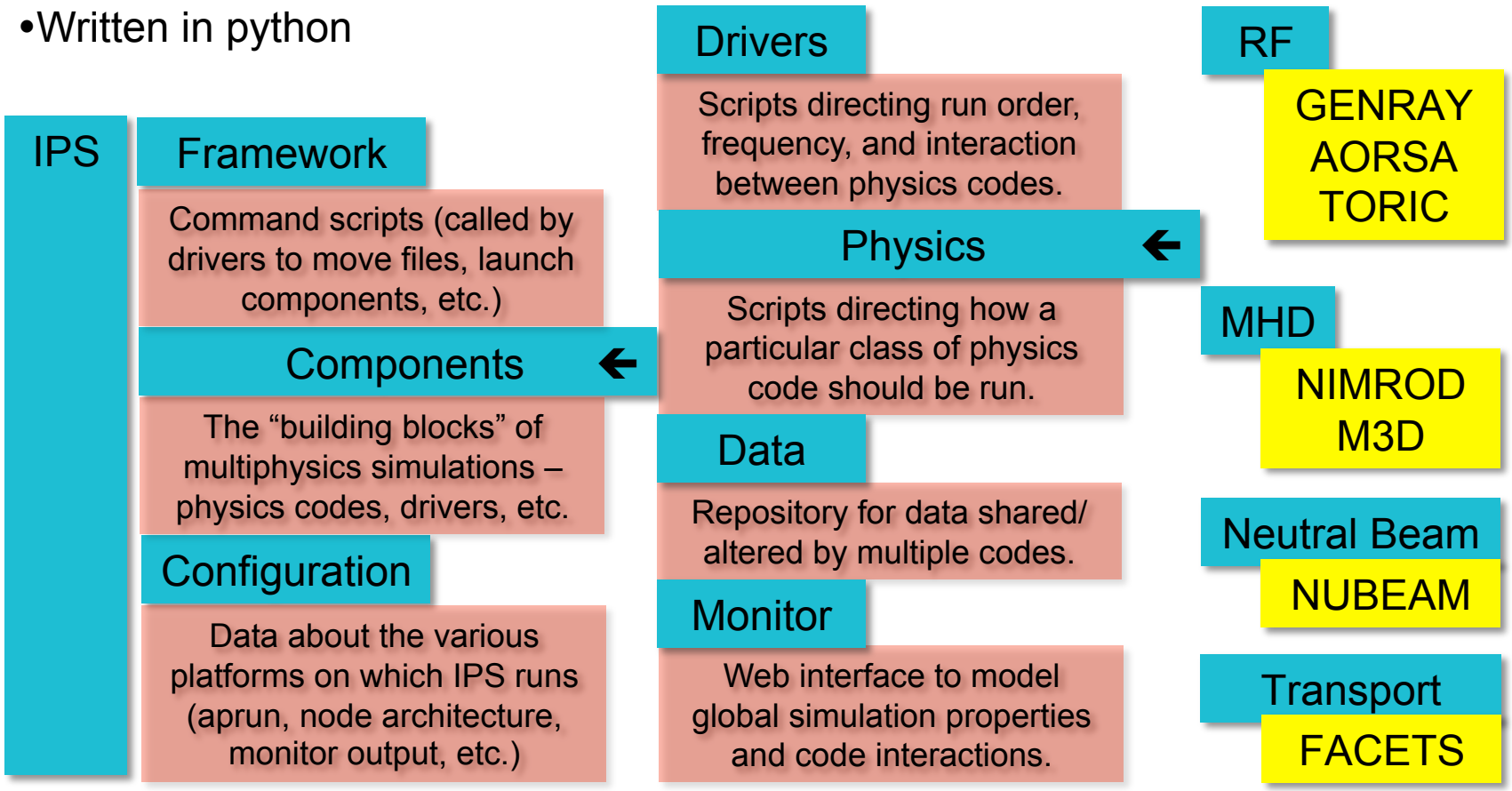


•Experimentally, RF waves resonant with electron cyclotron motion can drive currents that alter or suppress the island structures.

•The self-consistent numerical modeling of NTM suppression via ECCD is one major goal of the SWIM project… also, need computational infrastructure.

The Integrated Plasma Simulator (IPS) – a framework developed by SWIM for multiscale code coupling

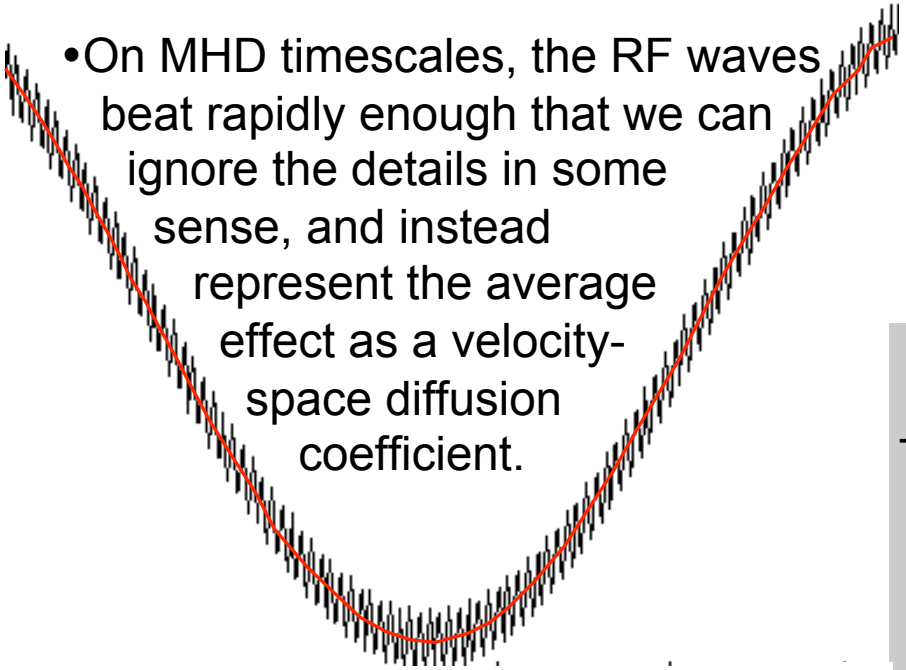
- ”Management” software – a flexible, extensible way to run multiple physics codes concurrently or sequentially, using consistent input parameters
- Physics codes can be adapted as IPS components and used in large-scale, multiphysics simulations on HPC platforms (e.g. NERSC, jaguar)
- Written in python



MHD and RF spatiotemporal scales are well-separated for the NTM suppression problem

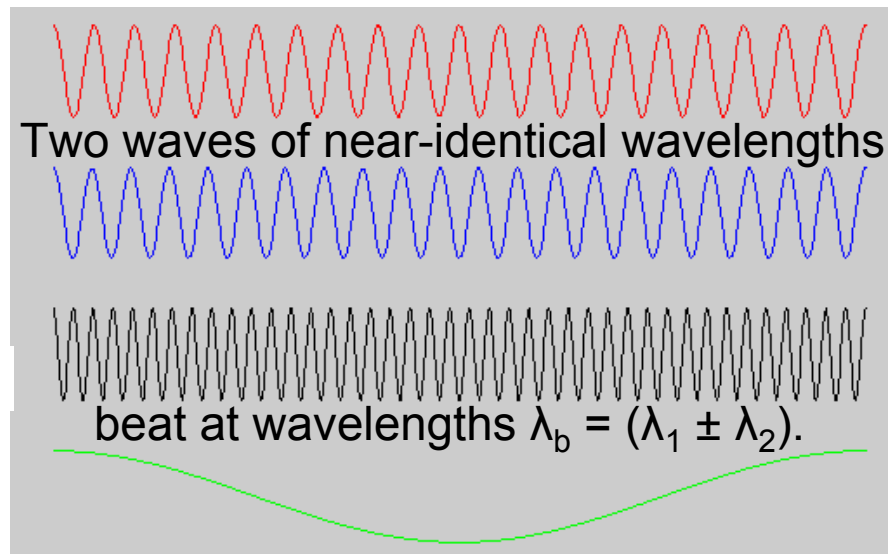
- MHD-type physics happens at *low frequencies* and *long wavelengths* compared to the RF frequencies and wavelengths.

- Effectively, the RF physics rides on top of the slowly evolving MHD profiles.



- On MHD timescales, the RF waves beat rapidly enough that we can ignore the details in some sense, and instead represent the average effect as a velocity-space diffusion coefficient.

- On RF timescales, MHD quantities are effectively constant in time and in space.



- However, fast, short-wavelength RF quantities may beat together and yield physical effects on MHD time and spatial scales.

Fields and distribution functions have components associated with RF and MHD spatiotemporal scales

•Let

$$f_\alpha = \langle f_\alpha \rangle_{MHD} + \epsilon f_{\alpha RF}$$
$$\mathbf{E} = \langle \mathbf{E} \rangle_{MHD} + \epsilon \mathbf{E}_{RF}$$
$$\mathbf{B} = \langle \mathbf{B} \rangle_{MHD} + \epsilon \mathbf{B}_{RF}$$

where ε labels quantities with RF spatiotemporal scales, and the average <…> is over these scales.

•Vlasov-Maxwell system – order ε^2 pieces enter averaged kinetic equation at the same order as ε^0 pieces because of beating:

$$\frac{\partial \langle f_\alpha \rangle_{MHD}}{\partial t} + \mathbf{v} \cdot \frac{\partial \langle f_\alpha \rangle_{MHD}}{\partial \mathbf{x}} + \frac{q_\alpha}{m_\alpha}[\langle \mathbf{E} \rangle_{MHD} + \mathbf{v} \times \langle \mathbf{B} \rangle_{MHD}] \cdot \frac{\partial \langle f_\alpha \rangle_{MHD}}{\partial \mathbf{v}}$$
$$+ \left\langle \epsilon^2 \frac{q_\alpha}{m_\alpha}[\mathbf{E}_{RF} + \mathbf{v} \times \mathbf{B}_{RF}] \cdot \frac{\partial f_{\alpha RF}}{\partial \mathbf{v}} \right\rangle = C[\langle f_\alpha \rangle_{MHD}]$$

(quasilinear diffusion)

RF coupling enters only through the kinetic equation; Maxwell equations are unaffected

so the kinetic equation effectively has an extra term from the RF;

$$\frac{\partial f_\alpha}{\partial t} + \mathbf{v} \cdot \nabla f_\alpha + \frac{q_\alpha}{m_\alpha}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f_\alpha}{\partial \mathbf{v}} = C(f_\alpha) + Q(f_\alpha)$$

from which MHD equations with RF-induced corrections are derived.

MHD equations include RF correction terms; closures will also be affected by the RF

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

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

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J} + \frac{\mathbf{F}^{rf}_{e0}}{n|q_e|}$$ 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):

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

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

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

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

- For full self-consistency (Fisch-Boozer/Ohkawa effects), must get closures correct.

Equations can be solved hierarchically, and correspond to different codes and code interactions

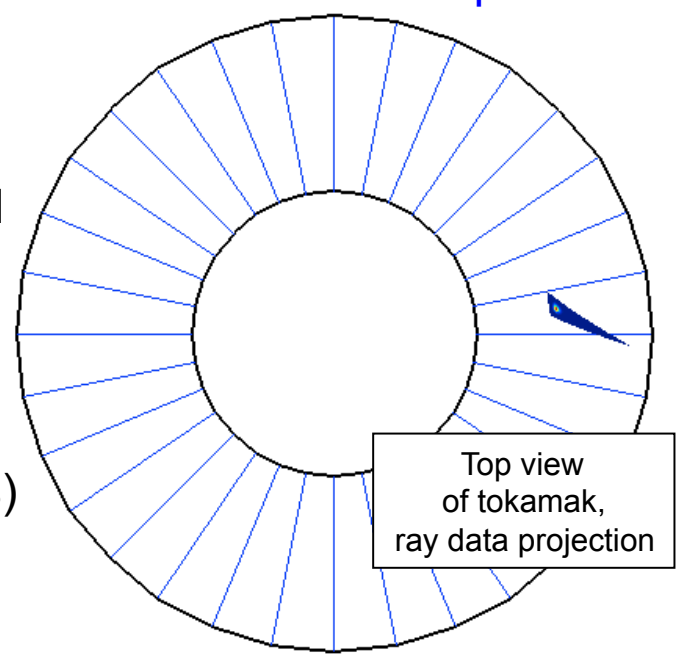
•Initial (ε^0) equations are regular MHD – n(**x**,t), T(**x**,t), **u**(**x**,t) + lowest-order closures.
MHD component under IPS (NIMROD).

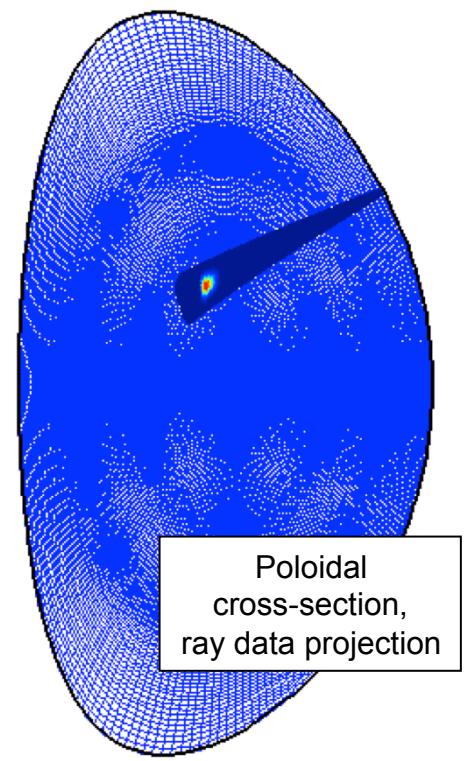
•Linear RF equations (ε^1) describe wave propagation (effectively instantaneous) through the plasma with the given n(**x**,t), T(**x**,t), **u**(**x**,t) profiles at a given time.
RF component under IPS (GENRAY), needs raw data from MHD component.

•Quasilinear terms (ε^2) describe effects of RF on MHD dynamics and add correction terms to MHD closures.
MHD component needs processed data from RF component.

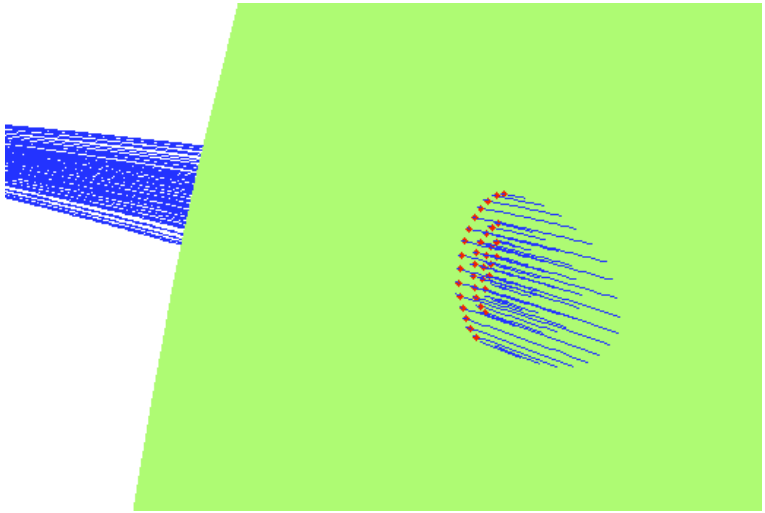
•NIMROD data – structured poloidal mesh, spectral toroidal representation

•GENRAY data – unstructured mesh (data along bundled rays)





Computational geometry routines are needed to bridge the gap between data formats



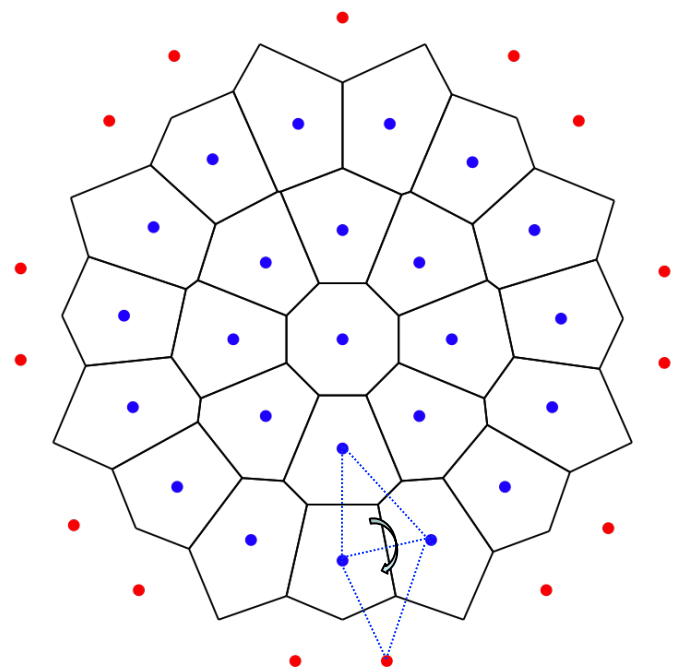
•Increased ray density ➔ lower power content and smaller area-perpendicular-to-flow for each ray.

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

•Interpolate ray data to planes along bundle path; use QHULL libraries to find areas:

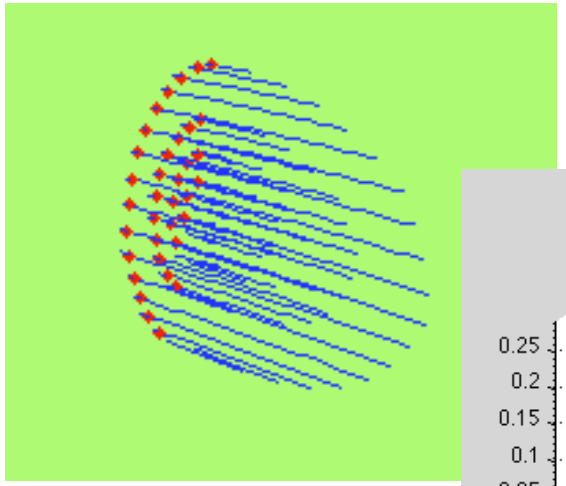
-Delaunay triangulation
-Ghost points via reflection over convex hull
-Construct dual (Voronoi) mesh
-Find area of resultant polygons.

•Then we have the data NIMROD needs, but it is still attached to the GENRAY datastructures.

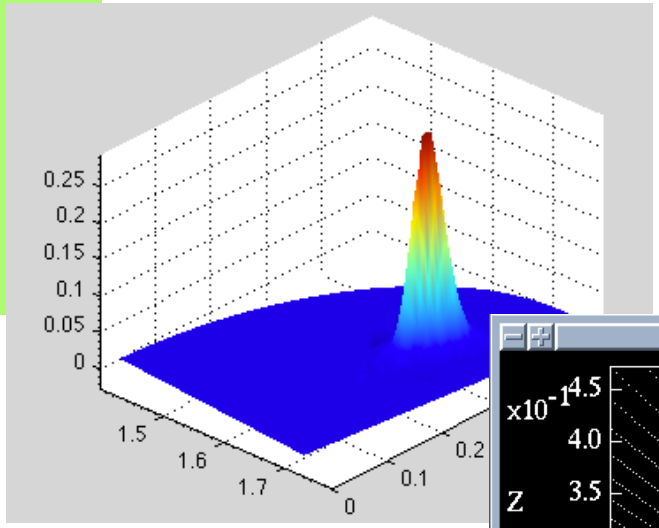


Additional spline interpolations are required to transfer the RF data to NIMROD's representation

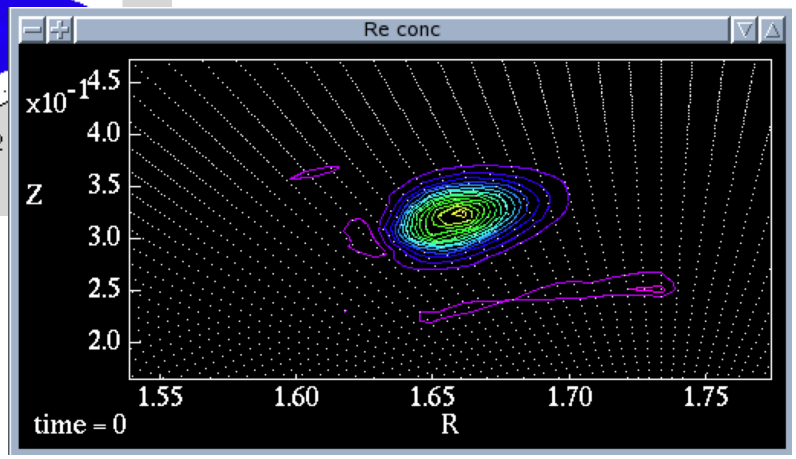
•Ray intersections with NIMROD poloidal planes are not necessarily gridpoints.



Using data values at the crossing points, construct a weighted spline fit (Shepard's algorithm);

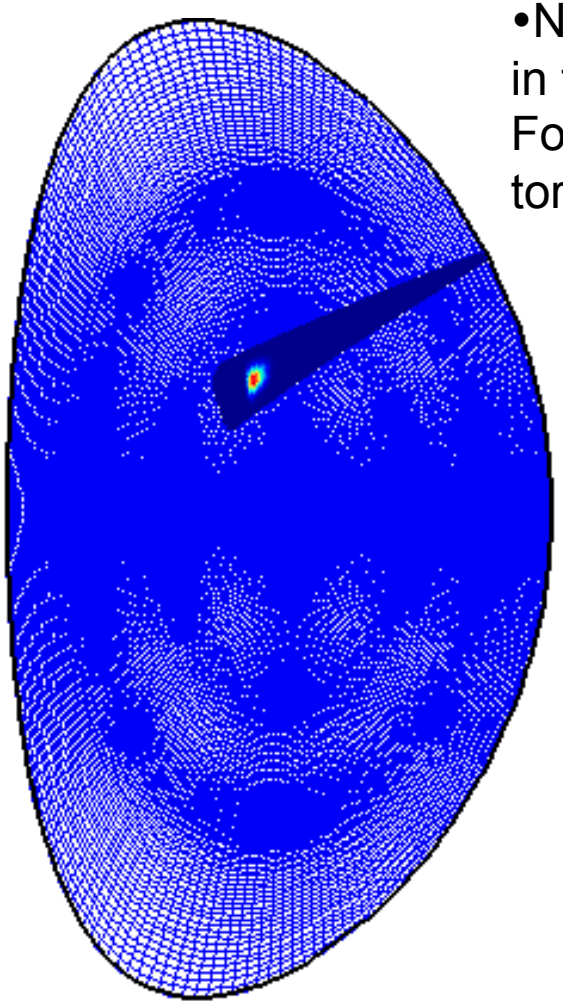


and evaluate this function on NIMROD's poloidal grid.



Cubic polynomial basis or cosine basis sets can be used in Shepard's algorithm; the latter yield smoother solutions at the ray bundle's edge.

Despite different characteristic scales, GENRAY data can be resolved on NIMROD's poloidal grid representation

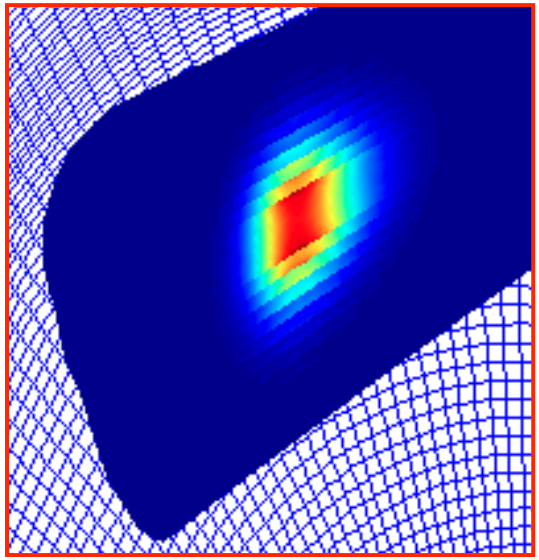


GENRAY ray bundle (421 rays) and NIMROD grid, R-Z projection

- NIMROD uses finite elements in the R-Z plane, and a discrete Fourier representation in the toroidal direction.

- Ray bundles are highly localized; quasilinear diffusion coefficients are only large near electron cyclotron resonance, so we get even more localization…

$$\mathbf{F}^{\mathrm{rf}}_{\alpha 0} \sim \exp\left[-\left(\frac{\omega - n\Omega_e}{2k_{\parallel}v_{te}}\right)^2\right]$$

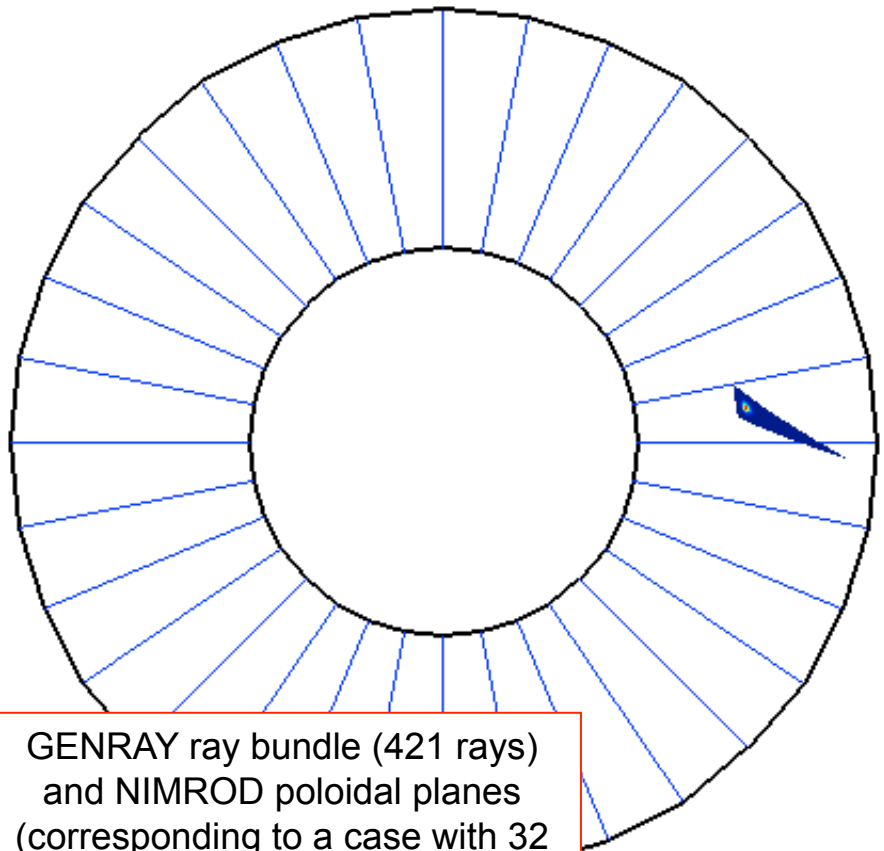


Quasilinear diffusion coefficient amplitude (R-Z projection) and NIMROD grid

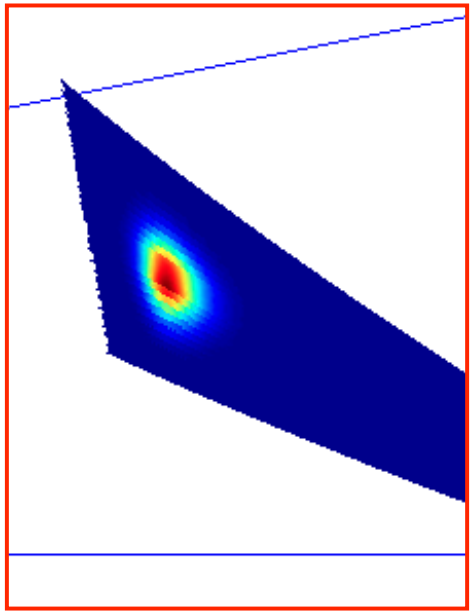
- Only a few points on the NIMROD R-Z grid are affected by the RF source, but the poloidal grid resolution is adequate.

NIMROD's pseudospectral toroidal representation makes the toroidal resolution of GENRAY data a challenge

•A fixed number of toroidal modes corresponds to a fixed number of planes on which poloidal data can be sampled.



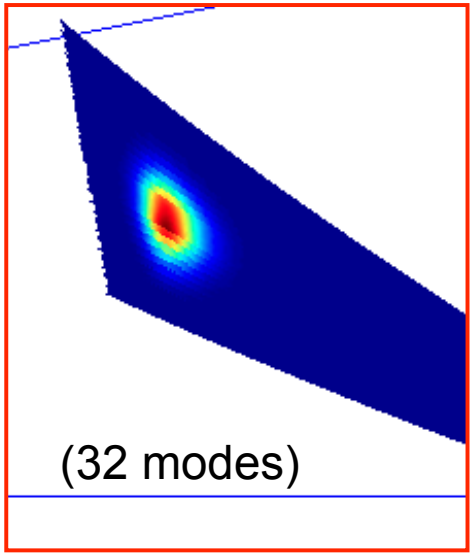
GENRAY ray bundle (421 rays) and NIMROD poloidal planes (corresponding to a case with 32 toroidal modes), viewing tokamak from above.

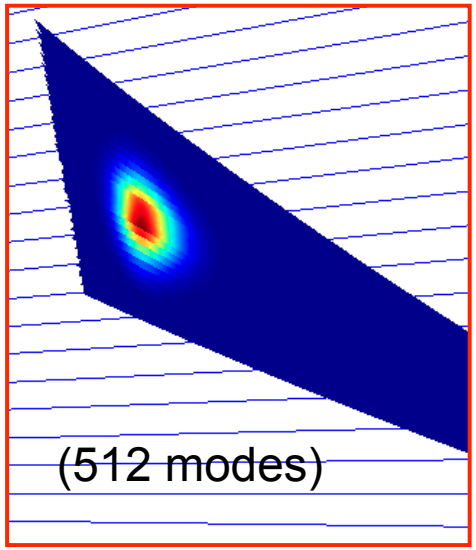


•For typical NIMROD toroidal resolution values, the quasilinear diffusion data from GENRAY may land between collocation points (planes) and will not be captured by NIMROD's toroidal representation.

•Two approaches– very large NIMROD runs, reformulation of toroidal dependence.

Though toroidally resolving the RF deposition is feasible, it is computationally expensive





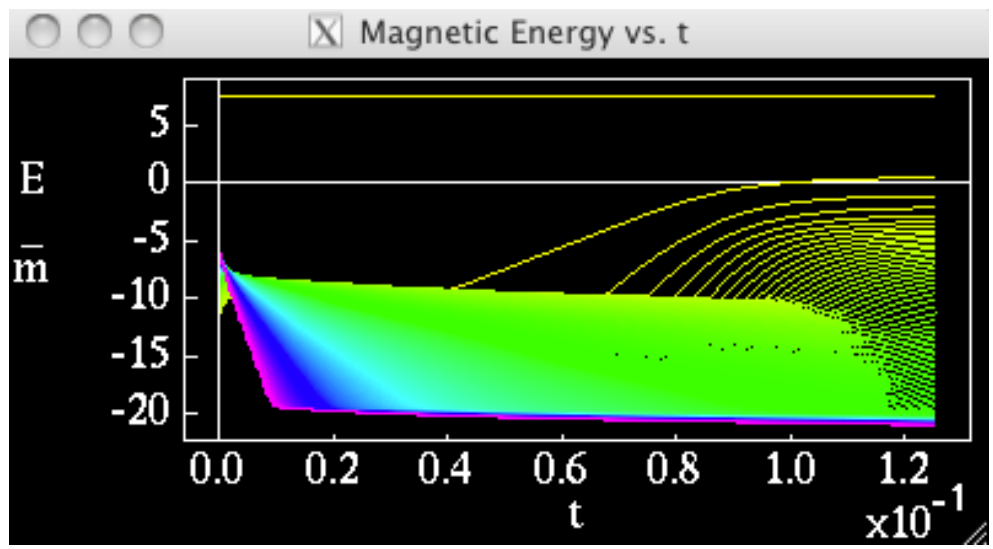
•One approach – sample entire toroidal domain at desired resolution. NIMROD uses 16-128 processors per poloidal plane – high processor count (12-28K), high data volume (several TB) for computationally efficient runs.

Somewhat wasteful, but can be done in principle…

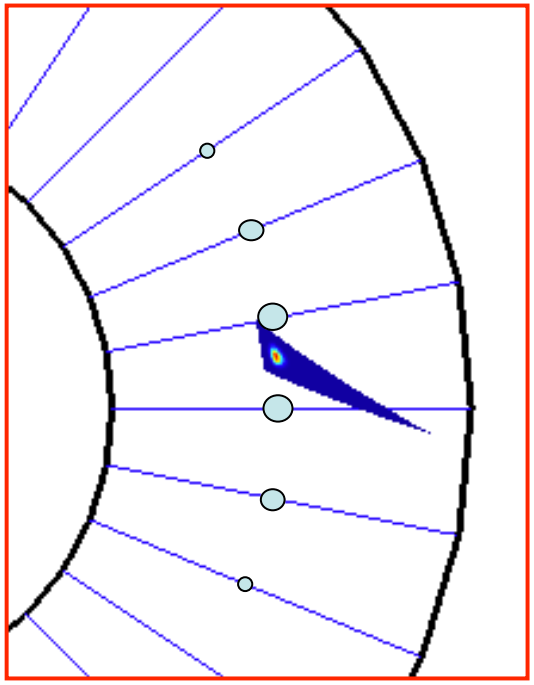
•Alternative approach - variation of island along toroidal coordinate is slow for low-helicity modes (which are of greatest concern). Toroidal approximation… spread the deposition toroidally;

$$\mathbf{F}^{\mathrm{rf}}_{\alpha 0}(R,Z,\phi) \approx \left[\int_0^{2\pi} \frac{\mathbf{F}^{\mathrm{rf}}_{\alpha 0}(R,Z,\phi')}{2\pi}\, d\phi'\right] g(\phi)$$

for some normalized *g(ϕ)*, after toroidally averaging.



Toroidal spreading of the RF reduces computational cost while model developments proceed

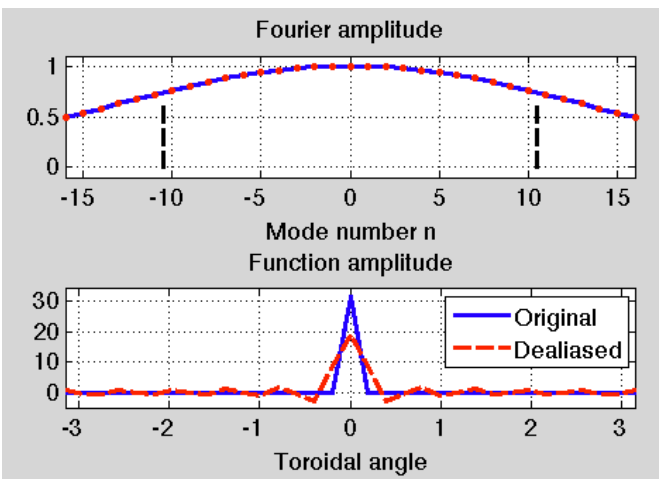


•NIMROD uses dealiasing in the toroidal direction; need to choose a function toroidally broad enough that information is not lost. 5-6 planes generally adequate.

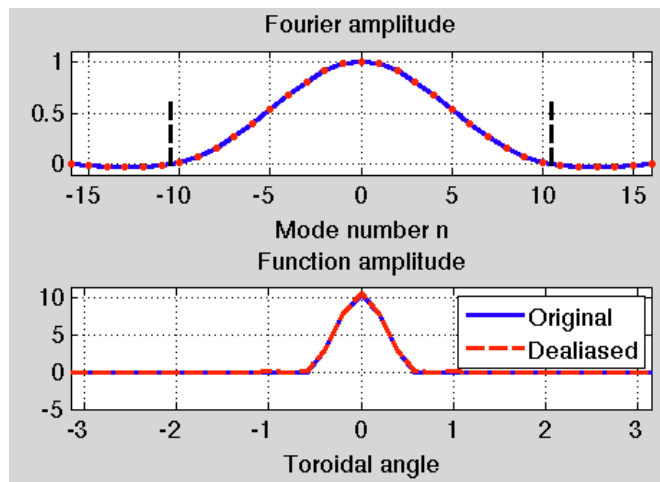
$$g(\phi) = \frac{2\pi}{\phi_c}\cos\left(\frac{\pi(\phi-\phi_0)}{2\phi_c}\right)^2 \; ; \; |\phi-\phi_0| \le \phi_c$$

(zero otherwise)

•Lowers typical processor count to 2-4K while retaining relevant physics (current interaction with island).

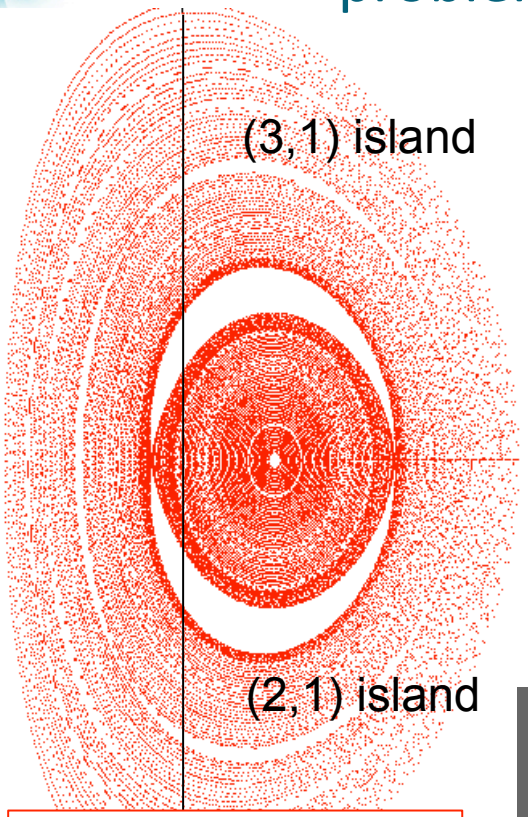


ϕ_c = 0.2; 32 modes



ϕ_c = 0.6; 32 modes

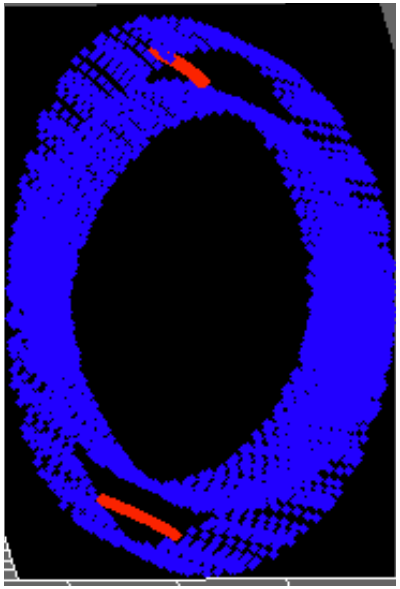
Depositing RF at the island O-point is a 3D targeting problem whose solution may evolve in time

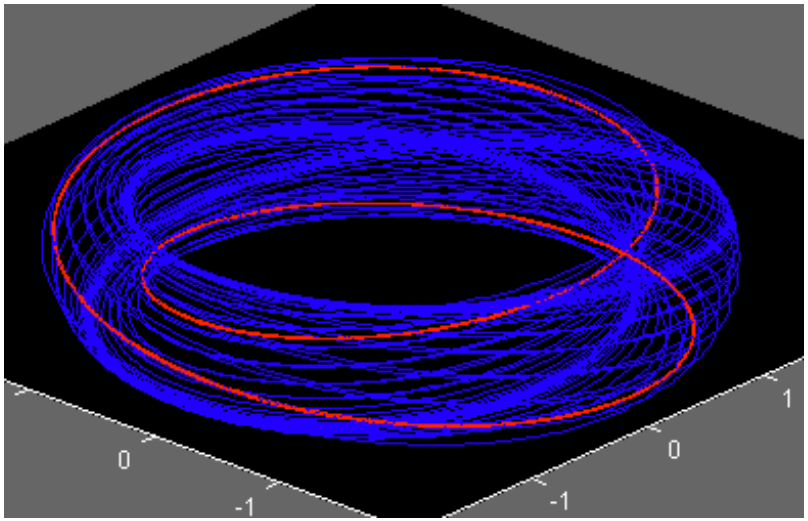


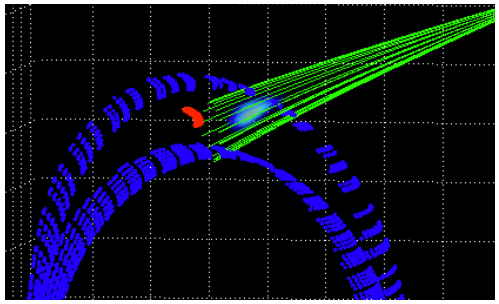
- Cyclotron resonance location determined by the strong toroidal field – RF frequency determines resonance location (cylindrical symmetry), toroidal launcher position constrained by machine geometry.

- Experiments: Alter toroidal field, alter plasma position, poloidally/toroidally steerable mirrors to alter deposition location (DIII-D, and our approach).

- Toroidal rotation shifts the O-point location in a fixed poloidal plane. RMPs?

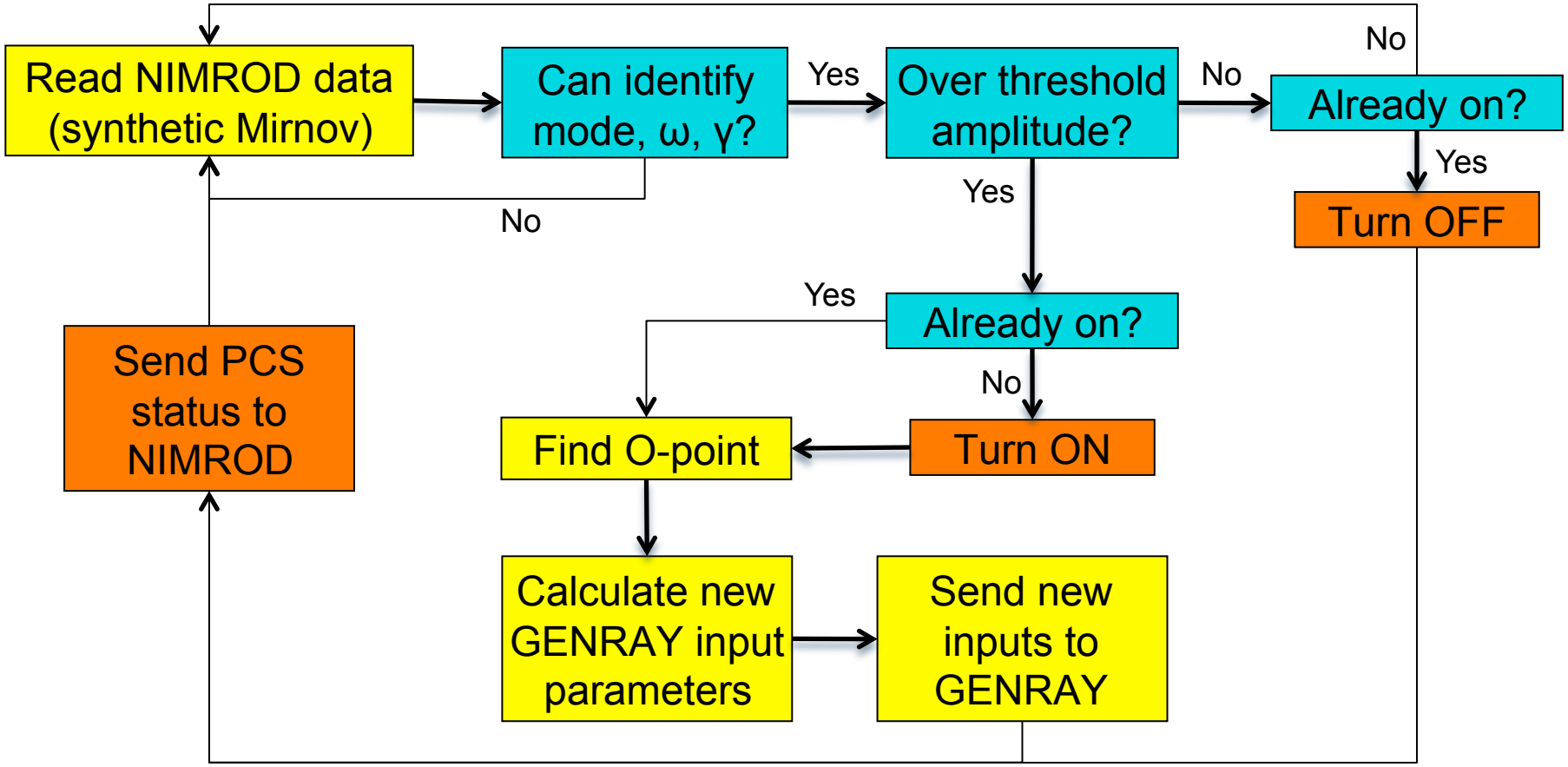






- Development of a numerical Plasma Control System is necessary to detect islands and to determine optimal RF power input.

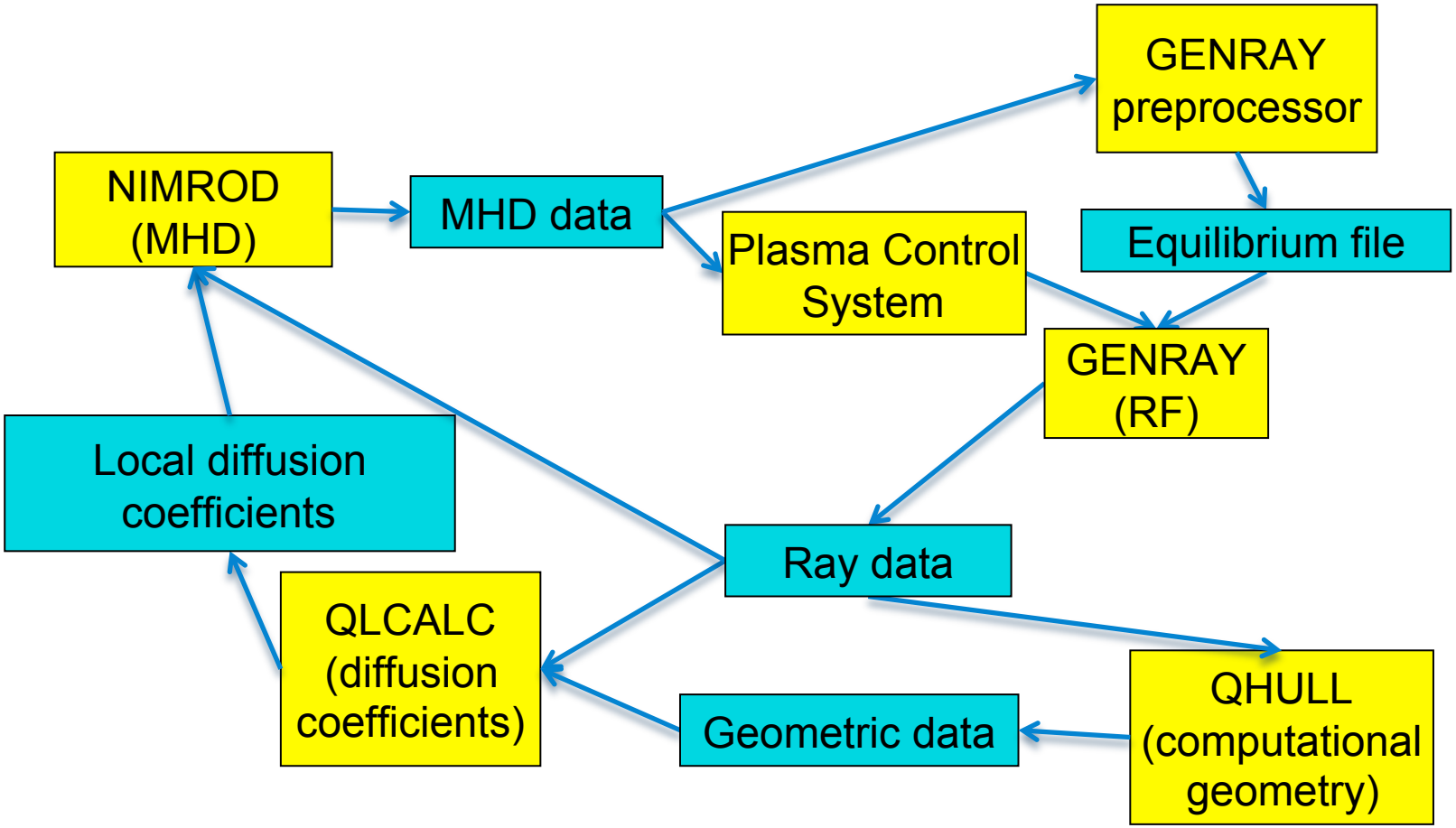
The numerical Plasma Control System reads data from NIMROD synthetic diagnostics (Mirnov coils)



Can also add time modulation of RF source (for rotating plasmas). NIMROD reads ON or OFF status and ramps up RF power on a timescale comparable to physical gyrotron ramp times.

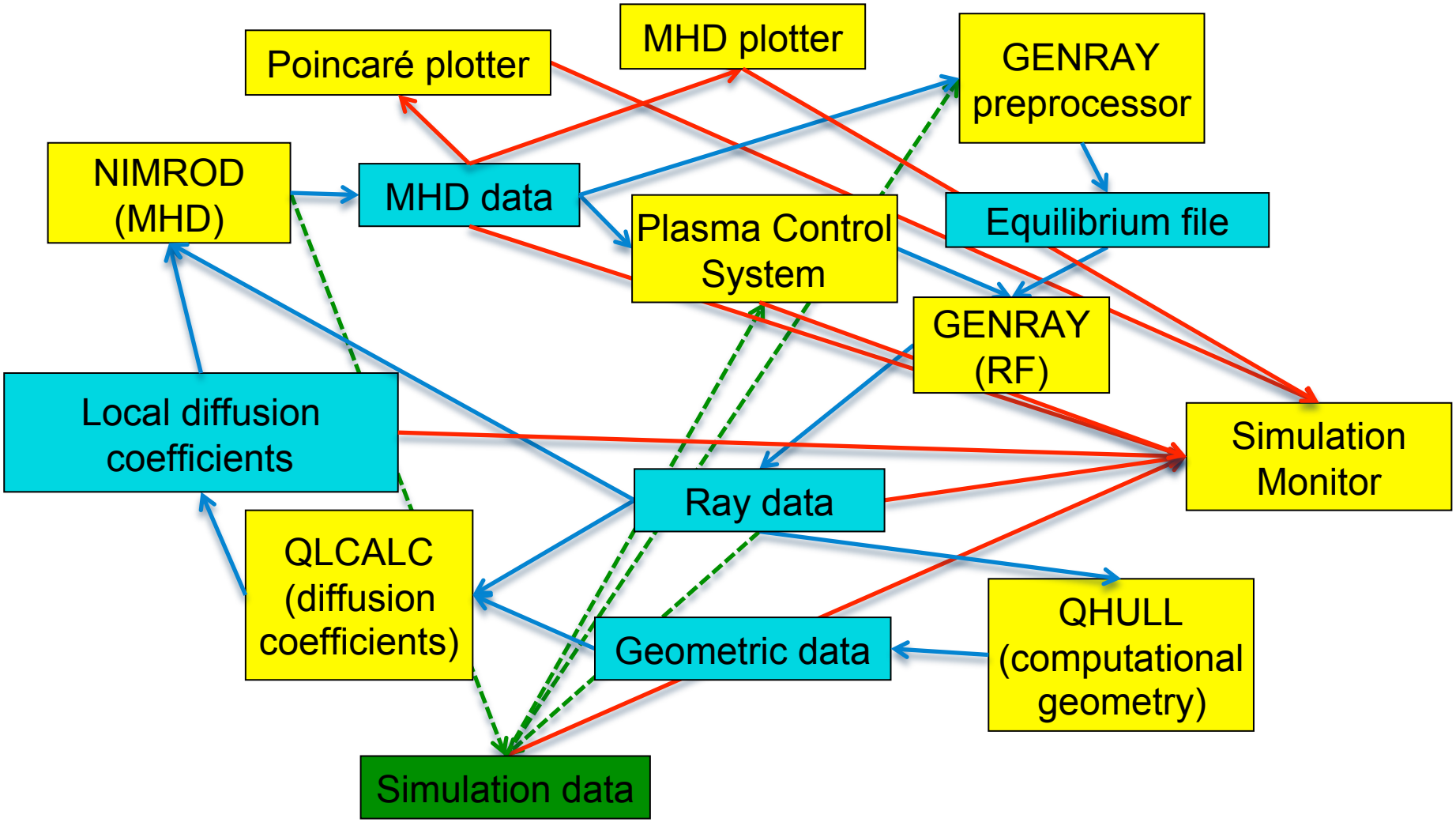
Workflow for coupled simulations is complicated

•Getting the quasilinear diffusion coefficients into NIMROD is a multistep process using several codes and moving several files...



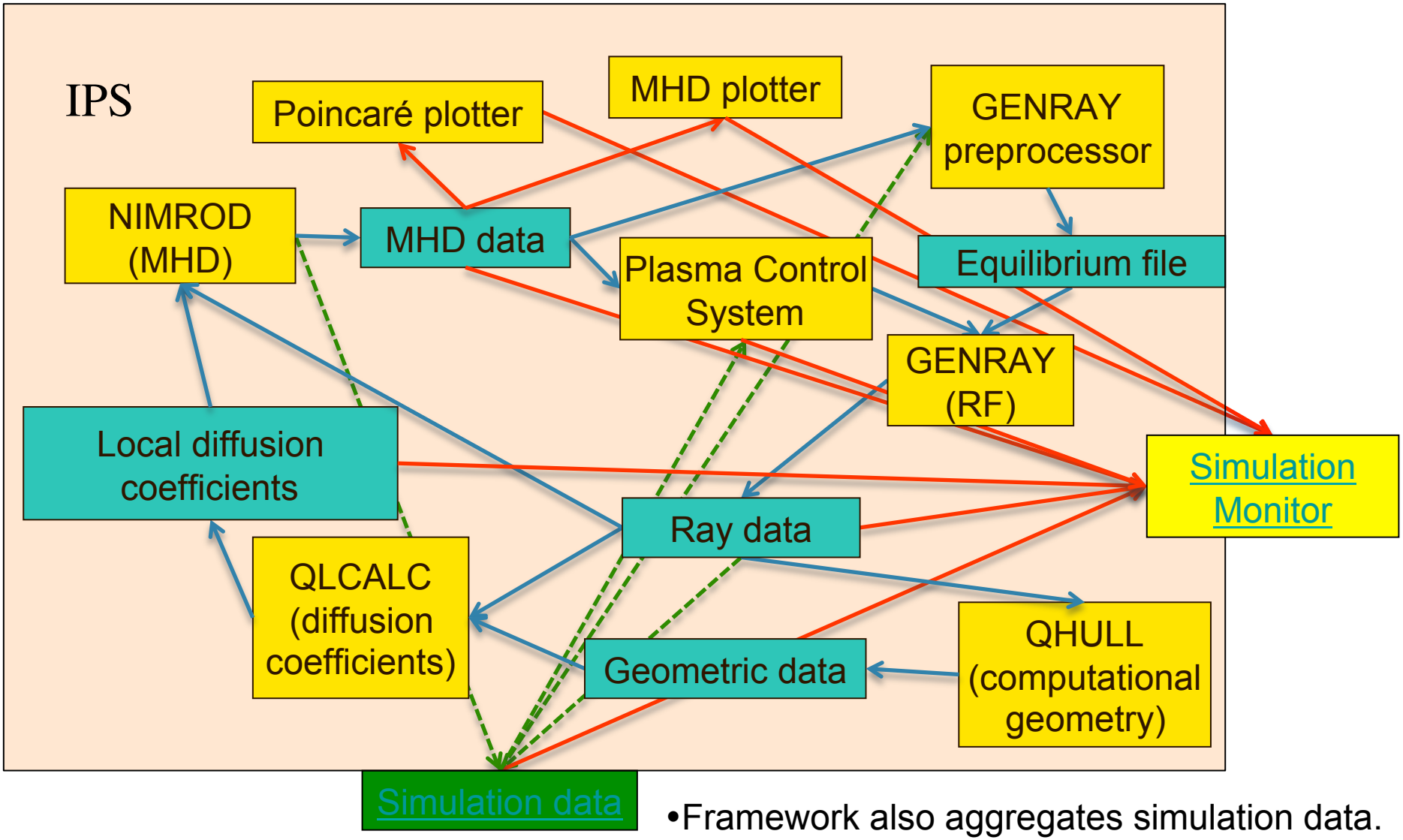
Workflow for coupled simulations is complicated

•Getting the quasilinear diffusion coefficients into NIMROD is a multistep process using several codes and moving several files... Comprehensive monitoring of the simulation makes things even more complex.



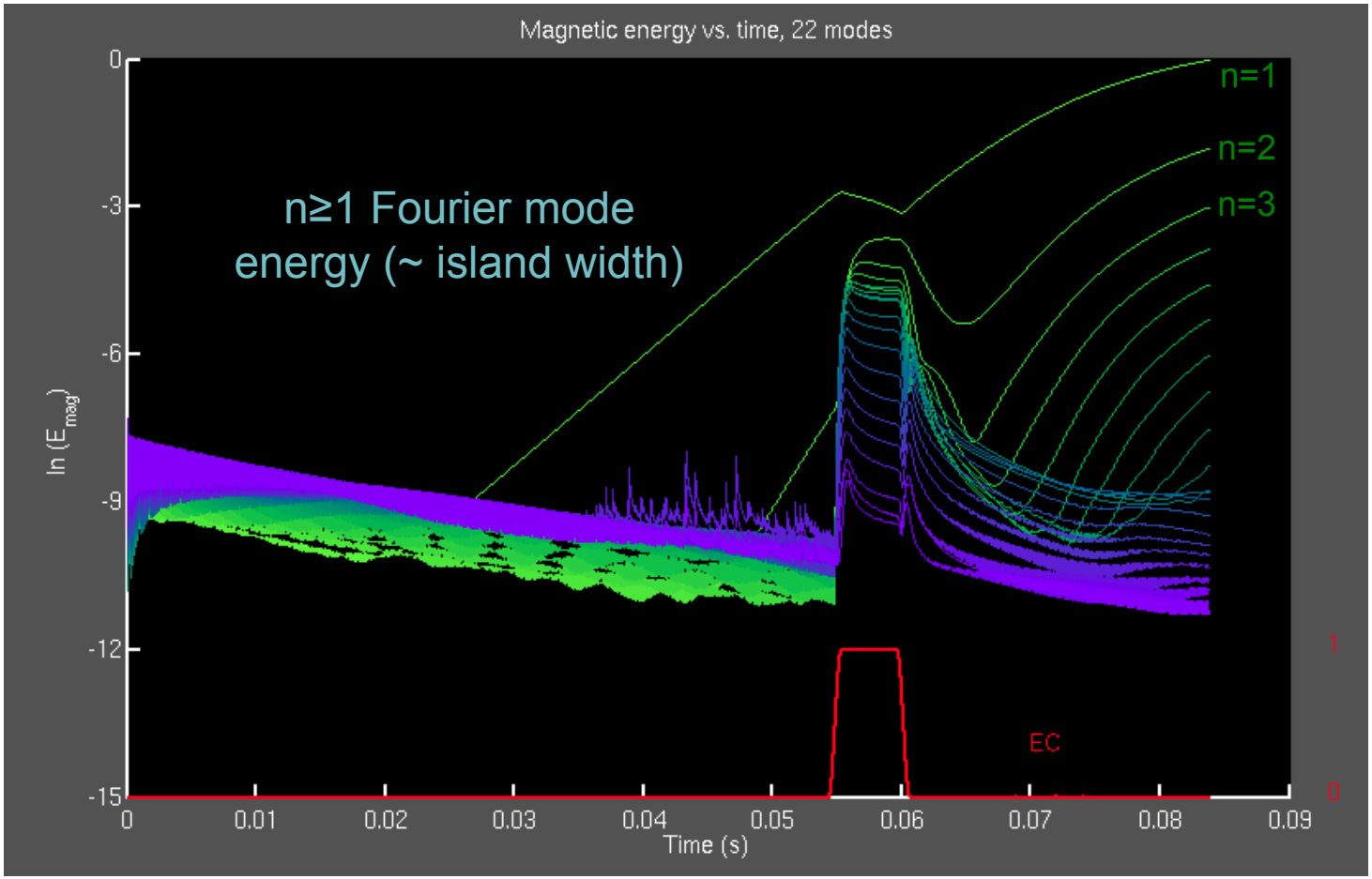
Workflow issues are managed by IPS, enabling better focus on the relevant physics

- The IPS framework handles the details of data transfer between codes.



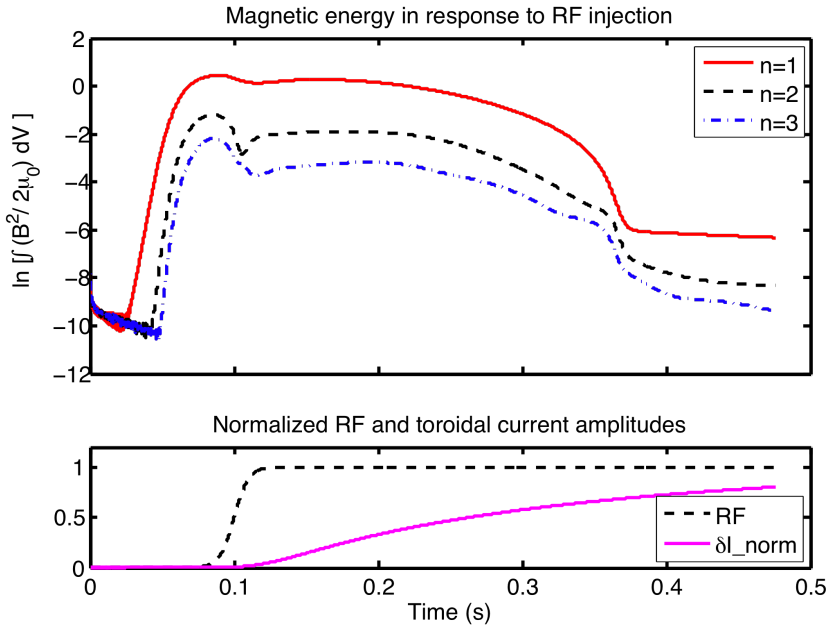
- Framework also aggregates simulation data.

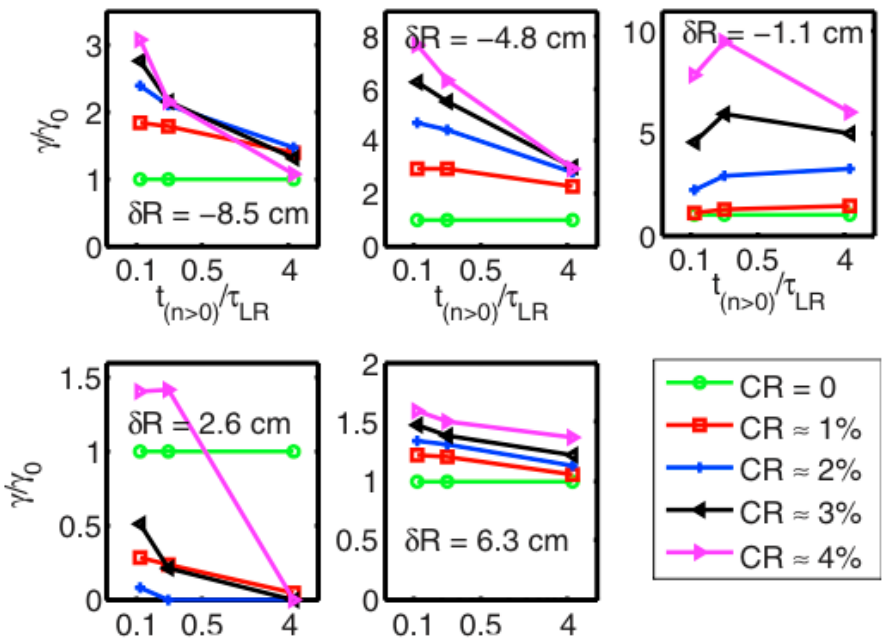
The numerical Plasma Control System can respond to changing conditions of the simulation

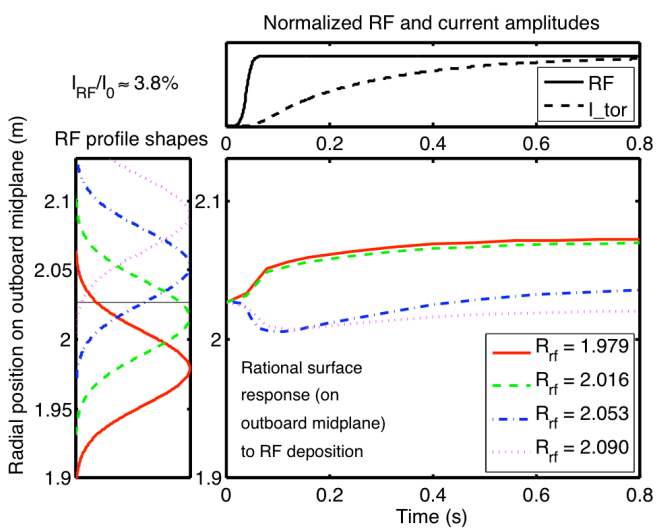


- When mode amplitude exceeds threshold, PCS injects ECCD at island O-point; island shrinks.
- Mode growth resumes when PCS is shut off.

Rational surface motion in response to RF plays an important role in mode stabilization







- Alignment on the outboard side gives better stabilization

- Stabilization affected by rational surface movement

More details in T. G. Jenkins *et al.*, Phys. Plasmas **17**, 012502 (2010).

Present status and plans

•RF-induced quasilinear diffusion coefficients can be constructed from NIMROD and GENRAY data, and these coefficients have been included in NIMROD's fluid equations. Work remains to be done on the self-consistent closure problem – E. Held (Utah State) and J. Ramos (MIT)

•Coupled RF/MHD simulations of ECCD-induced tearing mode stabilization running under IPS are now possible. IPS capabilities in managing complex simulations vastly simplify things for the user.

•For NTM studies we will need better (higher-β) equilibria which are near the stability boundary for the NTM – working with D. Brennan (Tulsa) on this.

•Working with A. Sanderson (Utah) to improve visualization of results (VisIt).

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