Progress and plans for NTM simulations
(using NIMROD, GENRAY, and the SWIM IPS framework)

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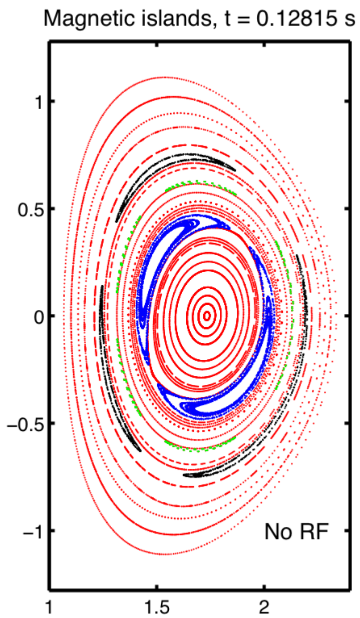
The problem: mitigation and control of tearing modes (magnetic islands) by electron cyclotron current drive (ECCD)



•Neoclassical (or resistive) tearing modes generate magnetic islands in tokamaks. Experimentally, RF waves resonant with electron cyclotron motion can drive currents that alter the island structure. We want to model this process.

•RF effects enter the kinetic equation as a quasilinear operator

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

•Velocity moments of $Q(f_\alpha)$ modify the MHD equations, and appear in closure calculations for ***q*** and **Π**. We want to get $Q(f_\alpha)$ from an RF code (not from NIMROD). Code interaction via IPS.

$$\nabla\cdot\mathbf{B} = 0 \qquad \nabla\times\mathbf{B} = \mu_0\mathbf{J}$$

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \qquad \frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{u}) = 0 \qquad \mathbf{E}+\mathbf{u}\times\mathbf{B} = \eta\mathbf{J} + \frac{\mathbf{F}^{rf}_{e0}}{n|q_e|}$$

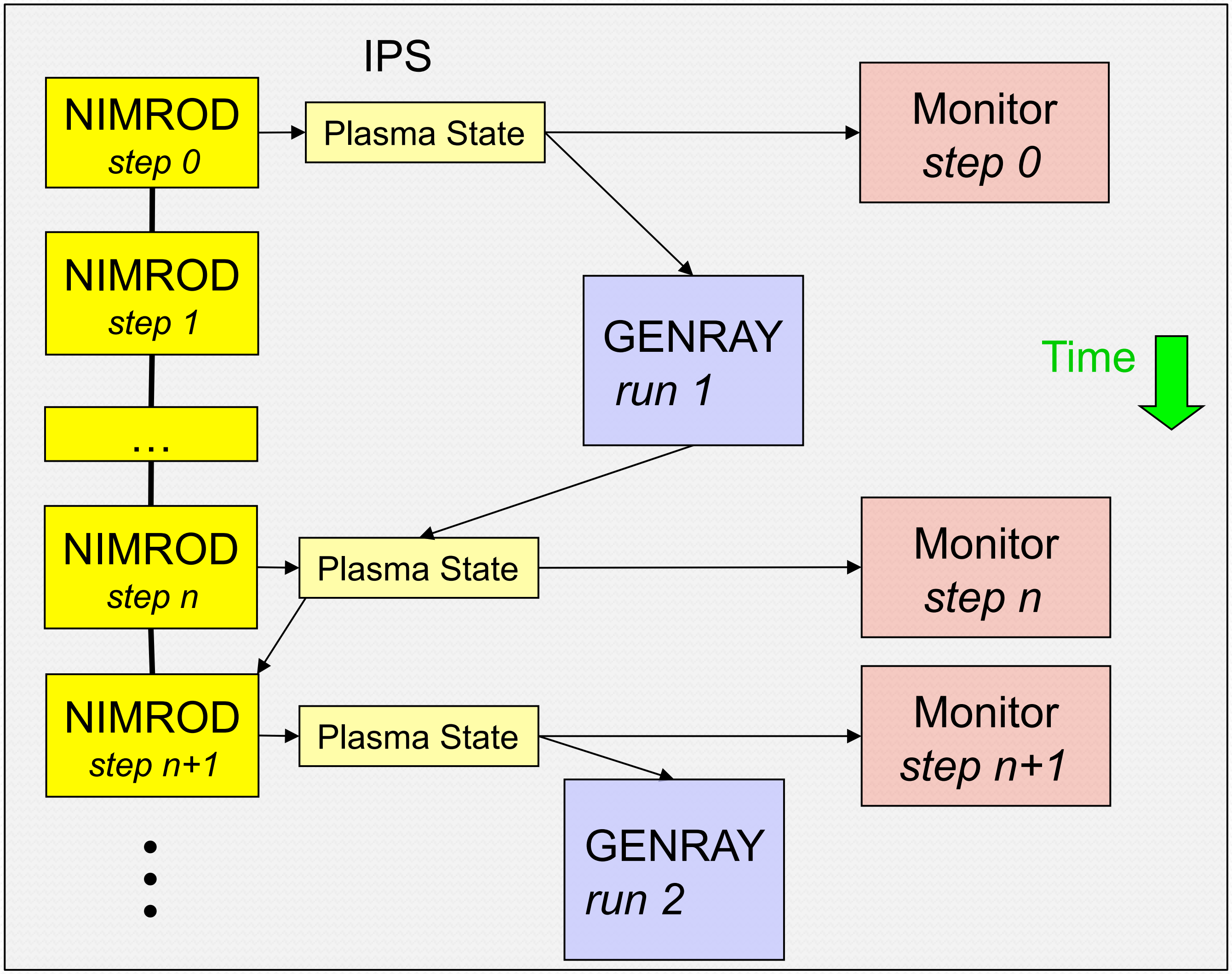
$$\rho\frac{\partial\mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + \mathbf{J}\times\mathbf{B} - \nabla\cdot\mathbf{\Pi} + \sum_\alpha \mathbf{F}^{rf}_{\alpha0}$$

$$\frac{3}{2}n\left(\frac{\partial T}{\partial t} + (\mathbf{u}\cdot\nabla)T\right) + p\nabla\cdot\mathbf{u} = -\nabla\cdot\mathbf{q} - \mathbf{\Pi}:\nabla\mathbf{u} + Q + \sum_\alpha S^{rf}_{\alpha0}$$

$$S^{rf}_{\alpha0} \equiv \int \frac{1}{2}m_\alpha v^2 Q(f_\alpha)d\mathbf{v}$$

$$\mathbf{F}^{rf}_{\alpha0} \equiv \int m_\alpha \mathbf{v} Q(f_\alpha)d\mathbf{v}$$

Schematic NIMROD/GENRAY coupling under IPS



- For RF/MHD problem, NIMROD exports magnetic geometry and n,T profiles to Plasma State
- Using NIMROD's profiles, GENRAY then calculates RF propagation and power deposition; exporting these quantities to the Plasma State
- NIMROD converts GENRAY data into momentum and energy source terms.

•Coupling depends on |B|, and is thus relatively weak.

Issues for coupled simulations

-Once we have NIMROD and GENRAY exchanging data, need to worry about wave accessibility (will we hit cutoffs?), power deposition (are energy and momentum actually transferred to the plasma? What is the optimal level of RF input power?), and localization (is the power going where we need it to, and can we keep it from places where we don't want it?)

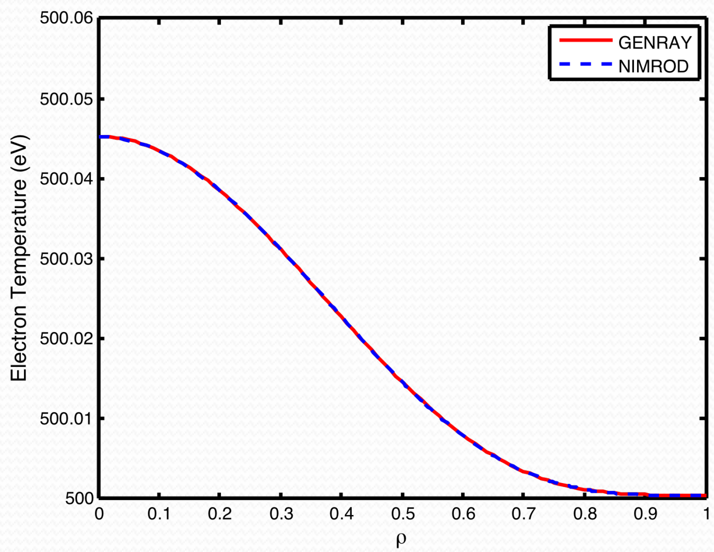
-Also, need to worry about numerical issues: resolution (are we using enough toroidal Fourier modes to adequately capture the toroidally localized RF interaction?), code coupling (how often should NIMROD and GENRAY exchange data?), etc.

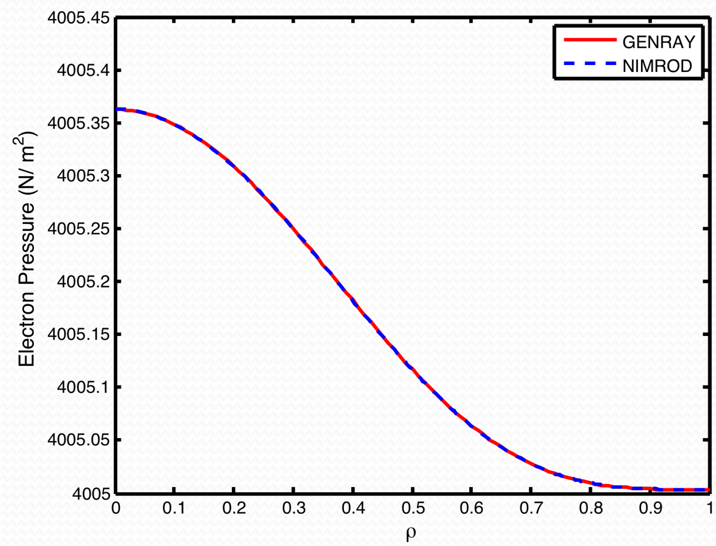
-For experimental comparisons, need to consider time dependence of RF – how do we turn it on; how do we optimally phase it to control island behavior?

-Self-consistency – so far, only have leading-order interaction term (Ohm's law) working. Correction terms in momentum and energy equation coming soon (from transfer of GENRAY's quasilinear diffusion tensor to NIMROD via Plasma State). Closures also need to be calculated self-consistently.

-Neoclassical (as opposed to resistive) tearing modes – need to get plasma equilibria that are sufficiently near marginal stability and have high β. (Difficult.)

Initial NIMROD/GENRAY coupling has been successful

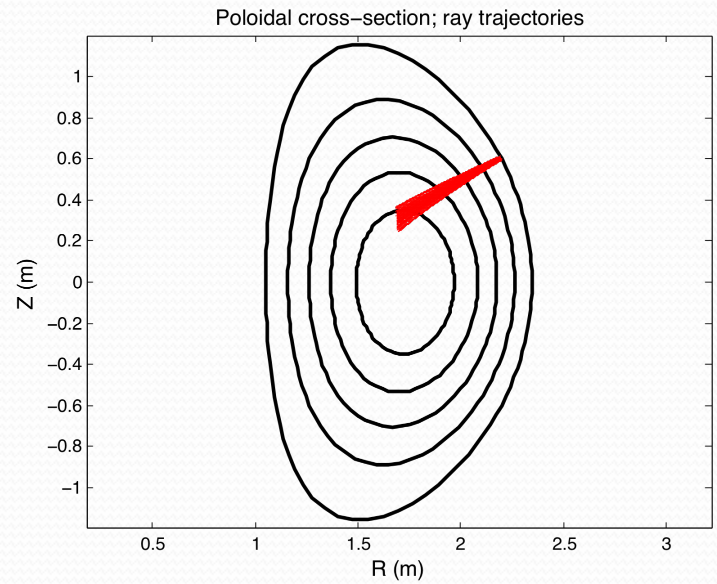


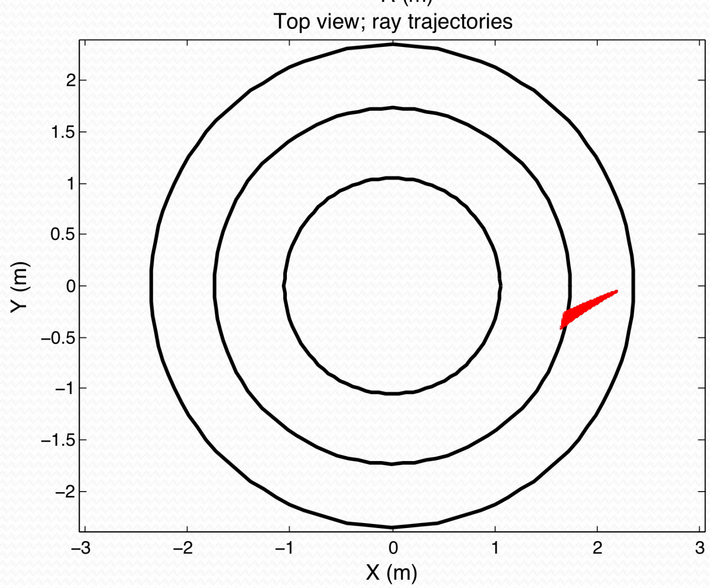


- Using an analytic profile (to begin with). Good agreement between NIMROD and GENRAY data. (Large gauge pressure used in NIMROD to compensate for the low-β equilbrium currently available.)

- In the coupled model, spline fits to the evolving profiles will be transferred to the Plasma State (a work in progress). For the moment, just calculate with the initial profiles.

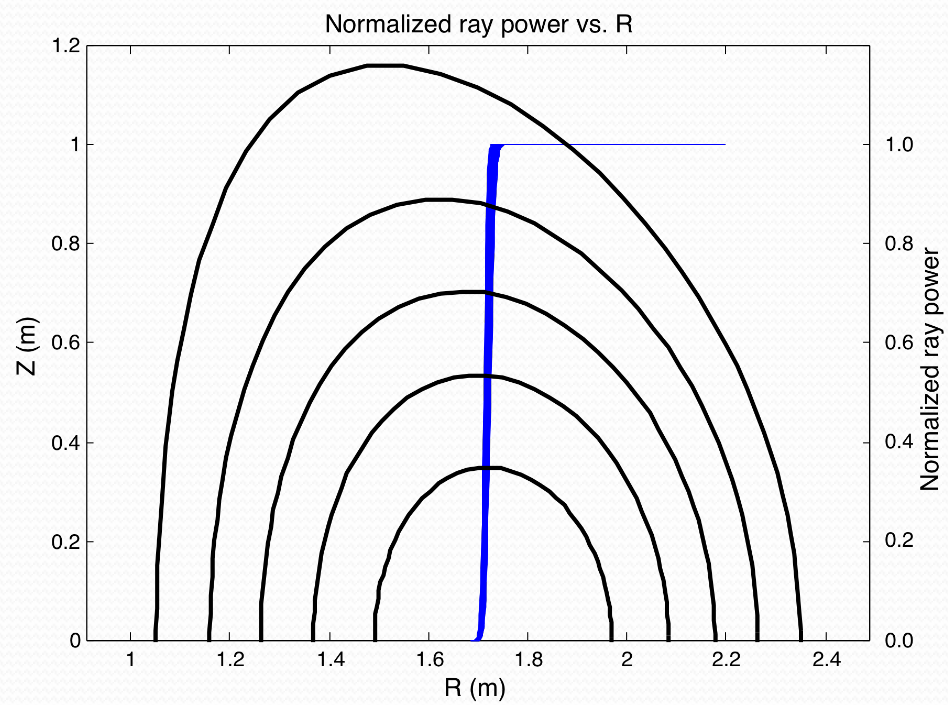
Localized RF deposition has been achieved in GENRAY runs which use NIMROD-generated input files





•Here, 80 ray trajectories are calculated by GENRAY after it receives NIMROD's fields and profiles.

•RF power deposition is highly localized; ray trajectories are nearly straight.

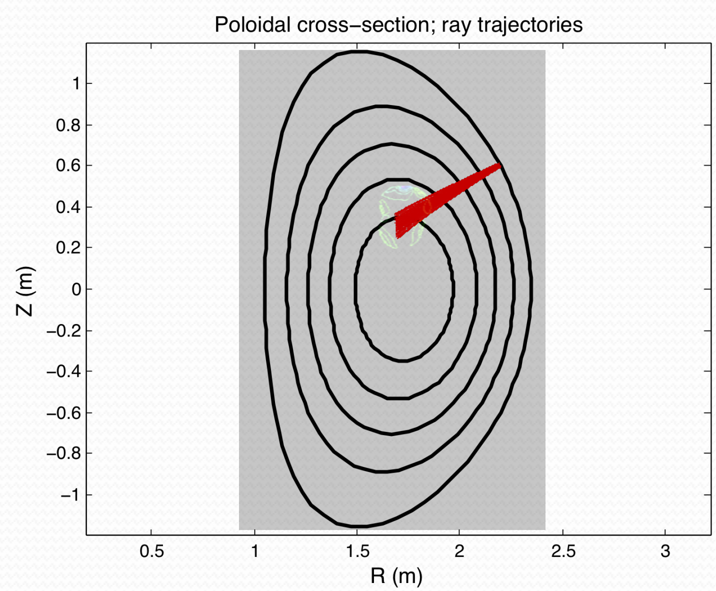


GENRAY data can be used as a source term in NIMROD to simulate effect of localized RF deposition

•GENRAY writes the ray data to a netCDF file which NIMROD can read; the data is linearly interpolated onto constant-ζ planes (corresponding to the number of toroidal Fourier modes), and modified Shepard methods (E. Held) then map the discrete ray points onto NIMROD's finite element basis.

•NIMROD output (local induced current) agrees well with GENRAY input parameters; current is induced near the deposition region.

•Deposition location can be fine-tuned by varying RF wave frequency, which changes the location of the resonance (since $\Omega_e \sim B \sim 1/R$).



Second-order couplings (via energy and momentum equations) involve the quasilinear diffusion tensor

- Currently, only code coupling is in Ohm's law:

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

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

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

- Ultimately, we need the quasilinear diffusion tensor D:

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

$$Q(f_\alpha)=\frac{\partial}{\partial\mathbf{v}}\cdot\mathbf{D}\cdot\frac{\partial f_\alpha}{\partial\mathbf{v}}$$

Assume the distribution function is a local Maxwellian.

- Quasilinear operator [Stix] for infinite, uniform plasma:

$$Q(f_{\alpha 0})=\lim_{V\to\infty}\frac{\pi q_\alpha^2}{m_\alpha^2 V}\sum_{n=-\infty}^{\infty}\int\frac{1}{v_\perp}L\left\{v_\perp\delta(\omega-k_\parallel v_\parallel-n\Omega_\alpha)|\psi_n|^2 L\left\{f_{\alpha 0}\right\}\right\}\,d^3\mathbf{k}$$

$$L\left\{\ldots\right\}=\frac{n\Omega_\alpha}{\omega}\frac{\partial\ldots}{\partial v_\perp}+\frac{k_\parallel v_\perp}{\omega}\frac{\partial\ldots}{\partial v_\parallel}$$

$$\psi_n=\frac{E_x(\mathbf{k})+iE_y(\mathbf{k})}{2}J_{n-1}\left(\frac{k_\perp v_\perp}{\Omega_\alpha}\right)+\frac{E_x(\mathbf{k})-iE_y(\mathbf{k})}{2}J_{n+1}\left(\frac{k_\perp v_\perp}{\Omega_\alpha}\right)+\frac{v_\parallel}{v_\perp}E_z(\mathbf{k})J_n\left(\frac{k_\perp v_\perp}{\Omega_\alpha}\right)$$

GENRAY data can be used to construct the full quasilinear diffusion tensor (work ongoing)

$$Q(f_{\alpha 0}) = \lim_{V\to\infty} \frac{\pi q_\alpha^2}{m_\alpha^2 V} \sum_{n=-\infty}^{\infty} \int \frac{1}{v_\perp} L\left\{ v_\perp \delta(\omega - k_\parallel v_\parallel - n\Omega_\alpha)|\psi_n|^2 L\left\{f_{\alpha 0}\right\}\right\} \, d^3\mathbf{k}$$

$$L\{\ldots\} = \frac{n\Omega_\alpha}{\omega}\frac{\partial \ldots}{\partial v_\perp} + \frac{k_\parallel v_\perp}{\omega}\frac{\partial \ldots}{\partial v_\parallel}$$

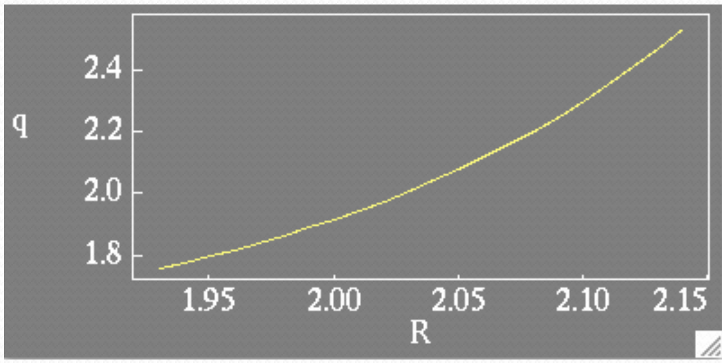
$$\psi_n = \frac{E_x(\mathbf{k}) + iE_y(\mathbf{k})}{2} J_{n-1}\left(\frac{k_\perp v_\perp}{\Omega_\alpha}\right) + \frac{E_x(\mathbf{k}) - iE_y(\mathbf{k})}{2} J_{n+1}\left(\frac{k_\perp v_\perp}{\Omega_\alpha}\right) + \frac{v_\parallel}{v_\perp} E_z(\mathbf{k}) J_n\left(\frac{k_\perp v_\perp}{\Omega_\alpha}\right)$$

•We can get the local values of these quantities (cyclotron frequency, wave number spectrum, electric field polarization, etc.) from GENRAY data.

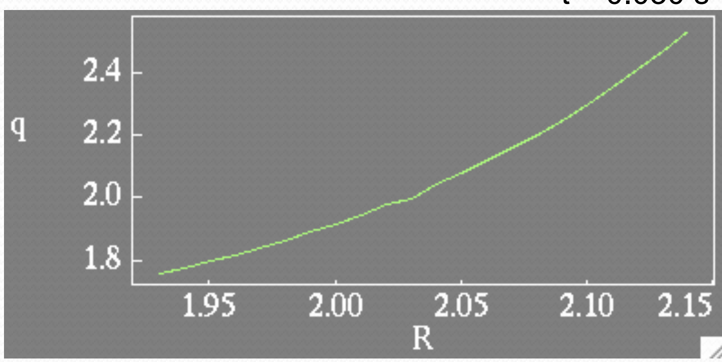
•Plasma is spatially nonuniform; need to verify that we are modifying the operator correctly (eikonal approximation) and that we can obtain numerical convergence in the limit of many rays.

New nimfl functionality improves island width measurements

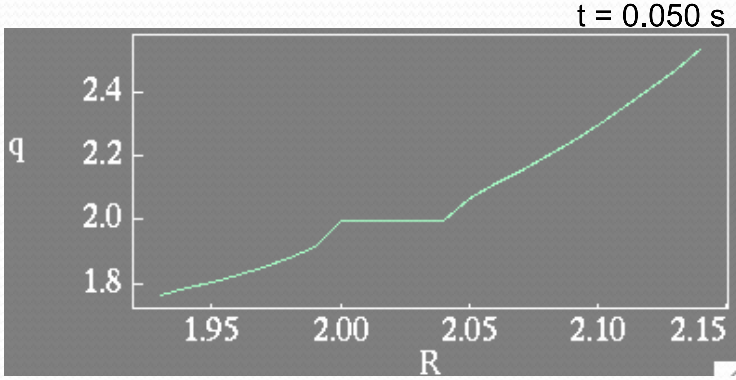
q profile at various timeslices



t = 0.030 s

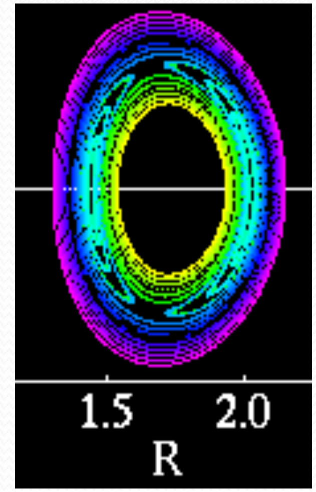


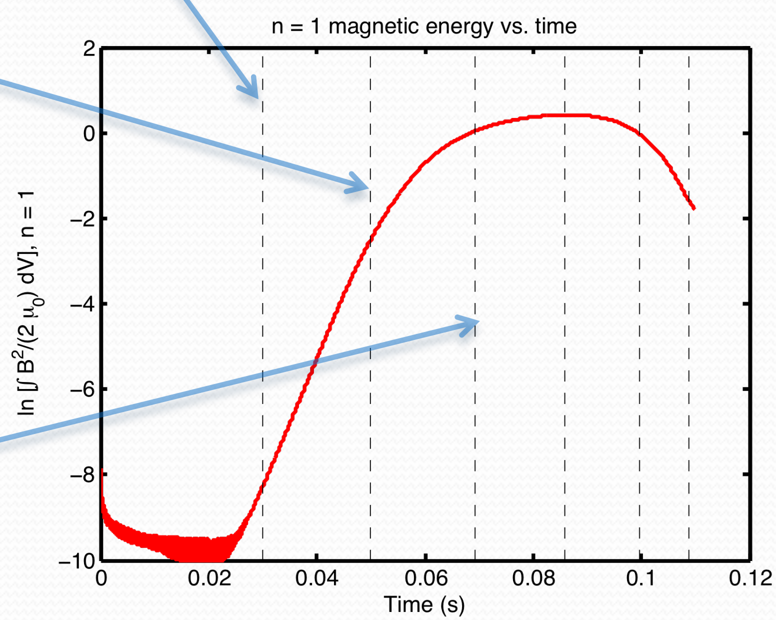
t = 0.050 s



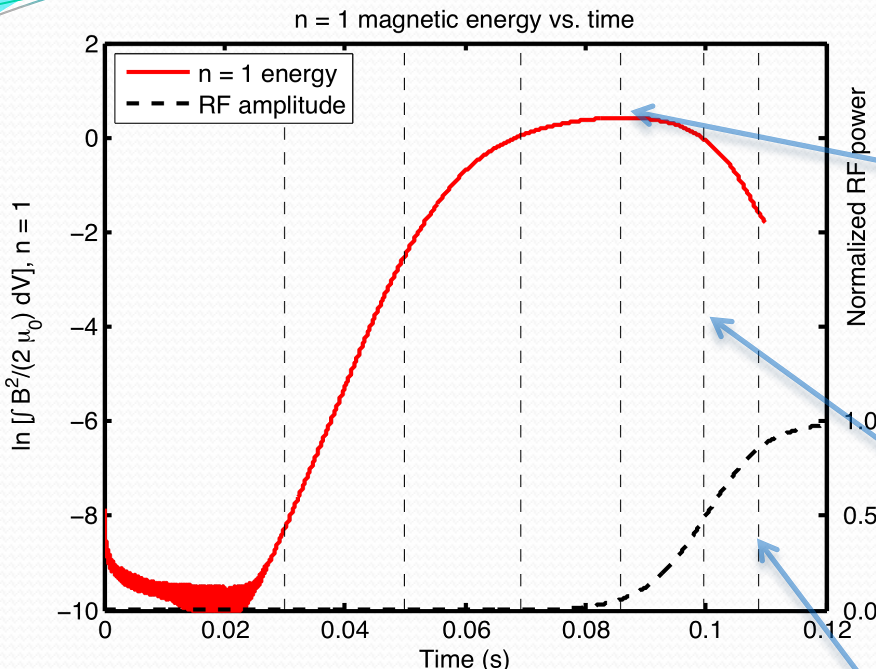
t = 0.069 s

•New q profile diagostic (M. Schlutt, UW) has been very helpful for SWIM simulations; previously, island width obtainable only from Poincaré plots by hand (magnetic energy used as a proxy for island width instead).

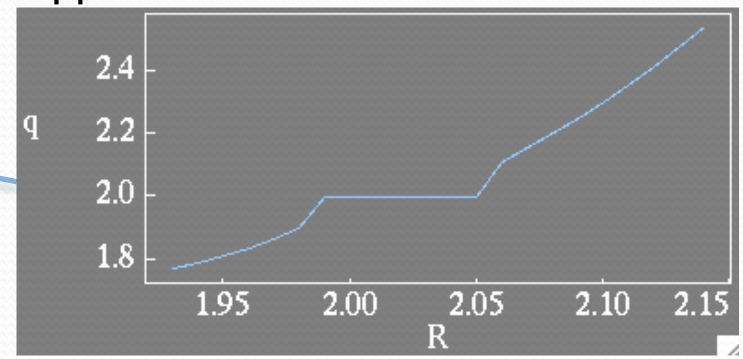




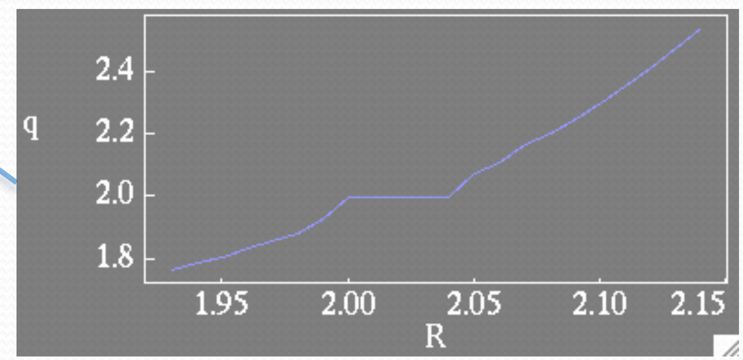
RF effects on island width are more easily quantified



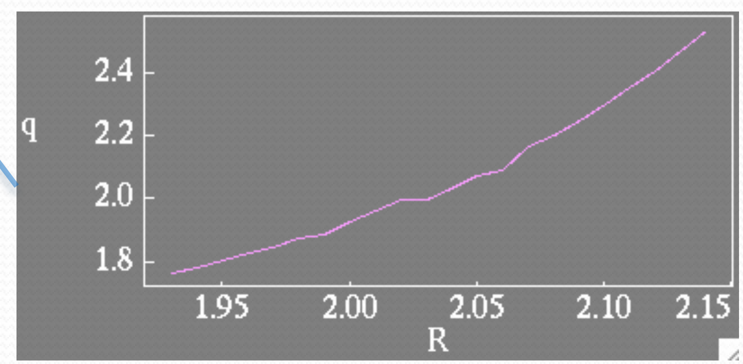
q profile at various timeslices



t = 0.086 s



t = 0.100 s



t = 0.109 s

- Ultimately, we want to implement synthetic diagnostics for use in a ‘search-and-suppress’ control system for NTMs (similar to systems found on DIII-D and other devices). Having rapid diagnostic capability for island widths in this process is very helpful.

Status and upcoming goals

•Ad hoc model for RF deposition is giving interesting results, and is leading to better intuition about physically self-consistent RF models. (I didn't talk about this… come to my poster tomorrow for more information.)

•NIMROD and GENRAY can read datastructures from one another, and the IPS-NIMROD-GENRAY interface is almost complete. Fully coupled runs, wherein the RF-induced current in Ohm's law couples the codes, should be possible within a few weeks.

•Progress has been made on understanding how to construct the quasilinear diffusion operator (for momentum/energy equations, and closures) from GENRAY data. This will enable more self-consistent coupled simulations.

•Toroidal resolution and convergence issues are being investigated.