Progress on RF/MHD coupling
(also: using SWIM’s IPS framework for efficient data analysis in NIMROD)

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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 \( \Pi \). We want to get \( Q(f_\alpha) \) from an RF code (not from NIMROD). Code interaction via IPS.

\[
\nabla \cdot \mathbf{B} = 0 \quad \nabla \times \mathbf{B} = \mu_0 \mathbf{J}
\]
\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad \mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J} + \frac{F^{rf}_{e0}}{n|q_e|}
\]
\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mathbf{J} \times \mathbf{B} - \nabla \cdot \Pi + \sum_\alpha F^{rf}_{\alpha 0}
\]
\[
\frac{3}{2} n \left( \frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T \right) + p \nabla \cdot \mathbf{u} = -\nabla \cdot \mathbf{q} - \Pi : \nabla \mathbf{u} + Q + \sum_\alpha S^{rf}_{\alpha 0}
\]
\[
S^{rf}_{\alpha 0} \equiv \int \frac{1}{2} m_\alpha v^2 Q(f_\alpha) \, dv
\]
\[
F^{rf}_{\alpha 0} \equiv \int m_\alpha v Q(f_\alpha) \, dv
\]
Overview of the Integrated Plasma Simulator (IPS)

• "Management" software – a way to run multiple physics codes concurrently or sequentially, using consistent input parameters

• A way to couple NIMROD to existing codes that model other physical processes, so we can study complicated plasma behavior without extensive NIMROD expansion

• At some level, just a collection of Python scripts that interact in interesting ways
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.
IPS is very flexible with respect to code interactions; it doesn’t care what physics codes we include or how (if?) they interact.

In particular, we can use it to do data analysis as the simulation proceeds (instead of having to do it all at the end); e.g. running nimfl on the dumpfiles as they are produced.

Formally, IPS’s Plasma State is not needed here – just use the run directory for the simulation as a “plasma state”. No interaction of nimfl results with NIMROD, so the coupling only needs to go one way.
- Publish/subscribe model - nimfl component subscribes to the NIMROD “event channel”
- When a dumpfile is produced, NIMROD publishes this event to its event channel.
- nimfl checks the channel for updates; processes dumpfiles as they arrive.
Possible problems with this model

• If nimfl is too slow, we get a backlog of unprocessed dumpfiles (and should allocate more processors to nimfl).

• If nimfl is too fast, processors sit idle…

• A more complicated model – when a large enough backlog is detected, stop NIMROD, use all of its processors to clear the backlog, and restart. (Not difficult in principle, but not implemented yet.)

http://swim.gat.com:8080/display/ and a demo go here.
New nimfl functionality improves island width measurements

q profile at various timeslices

- New q profile diagnostic (M. Schlutt) 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).

- Energy grows by several orders of magnitude before mode becomes visible.
RF effects on island width are more easily quantified

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.
-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 $\beta$. (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 equilibrium 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-$\zeta$ 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 $\Omega_e \sim B \sim 1/R$).
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.

• 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.

• Good 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.

• The flexibility of the IPS enables more rapid data analysis for standalone NIMROD simulations.