A closure implementation with RF drives

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RF/MHD Coupling related to SWIM Slow MHD Campaign

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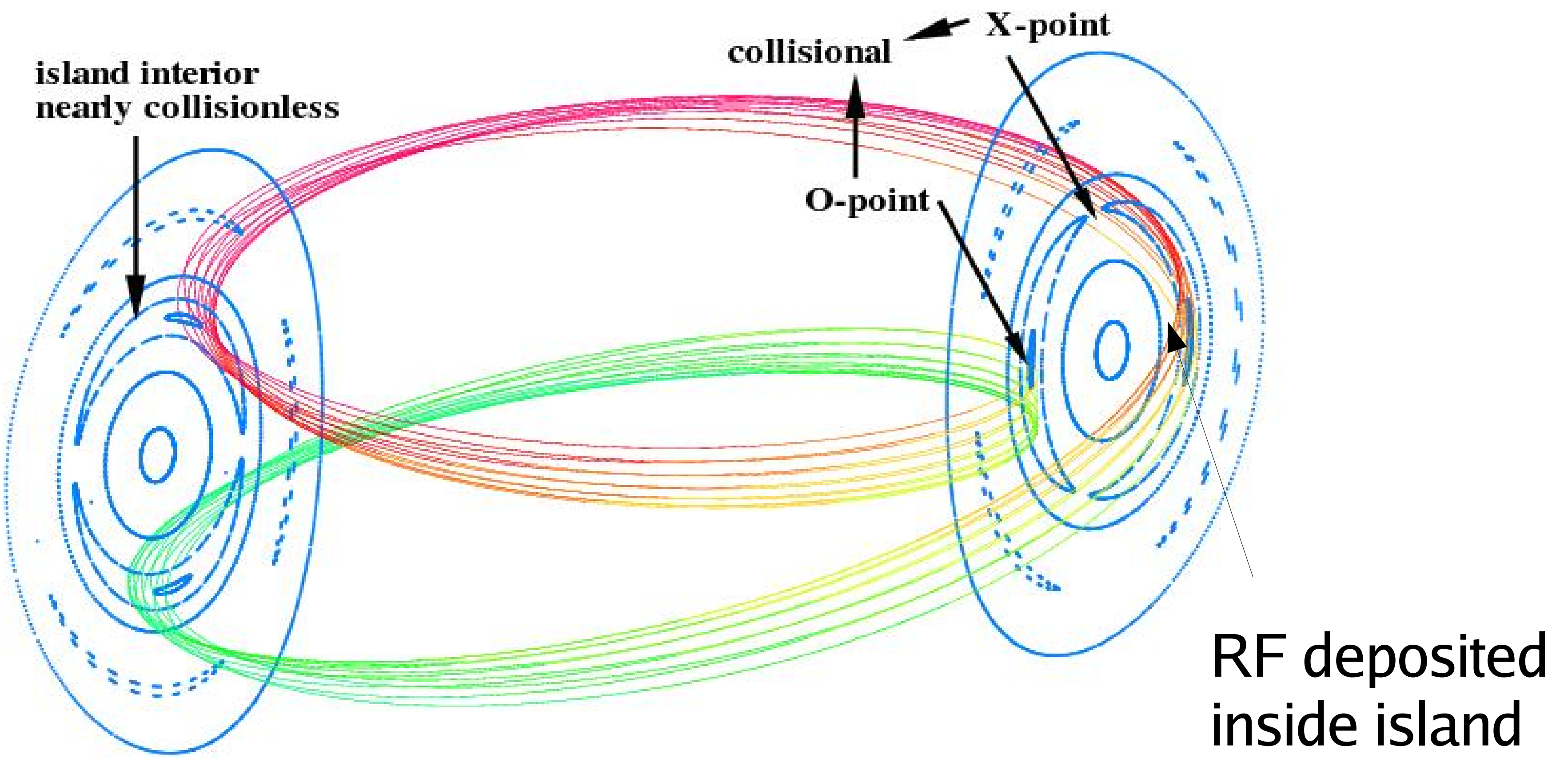
Transport parallel to magnetic field requires kinetic calculation.



Need closures for NTM physics when RF is in play.

$$\frac{\partial n}{\partial t} + \vec{\nabla} \cdot \left(n \vec{u} \right) = 0,$$

$$m n \left[\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} \right] = n q \left(\vec{E} + \vec{u} \, \boldsymbol{x} \, \vec{B} \right) - \vec{\nabla} \left(n T \right) - \vec{\nabla} \cdot \boldsymbol{\Pi} + \vec{R} + F_0^{rf},$$

$$\frac{3}{2} n \left[\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla} T \right] = - n T \vec{\nabla} \cdot \vec{u} - \vec{\nabla} \cdot \vec{q} - \boldsymbol{\Pi} : \vec{\nabla} \vec{u} + Q + S_0^{rf}.$$

0. RF stabilization of resistive tearing mode with steady-state RF.

$$0 = nq\left(\vec{E} + \vec{u}\,\boldsymbol{x}\,\vec{B}\right) - \vec{\nabla} p + \vec{R} + F_0^{rf}\left(\delta f_{RF}\right),$$

Zeroth-order coupling: MHD code computes moments of Q^{rf} supplied by RF codes which use equilibrium, axisymmetric fields.

$$\frac{3}{2} n \left[\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla} T\right] = -nT\,\vec{\nabla} \cdot \vec{u} + S_0^{rf}\left(\delta f_{RF}\right).$$

1. RF stabilization of resistive tearing mode with t-dependent RF.

$$0 = nq\left(\vec{E} + \vec{u}\,\boldsymbol{x}\,\vec{B}\right) - \vec{\nabla}p + \vec{R} + F_0^{rf}\left(\delta f_{RF}\right),$$

First-order coupling: MHD code computes moments of Q^{rf} supplied by RF codes which use equilibrium + evolving n=0 fields.

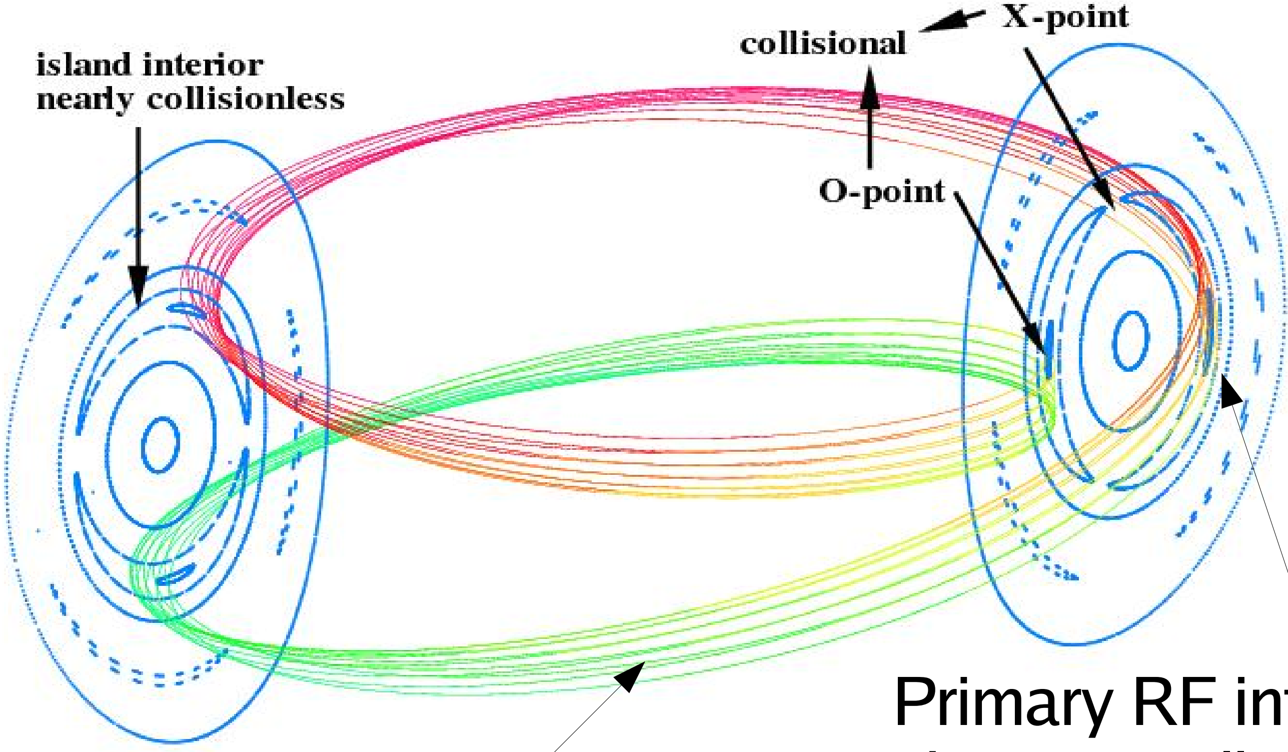
$$\frac{3}{2}n\left[\frac{\partial T}{\partial t} + \vec{u}\cdot\vec{\nabla}T\right] = -nT\,\vec{\nabla}\cdot\vec{u} + S_0^{rf}\left(\delta f_{RF}\right).$$

What will this accomplish?

- Requires simple moments of perturbed distribution function generated by RF codes (CQL3D + Toray, GENRAY), $f = f_M(MHD) + \delta f(RF)$.
- Demonstrates loose (steady-state) and tight (evolving n=0) coupling of MHD code with RF physics.
- Permits rapid scans of antenna geometry and different RF deposition scenarios.

- For ECCD, CQL3D solves "zero-banana-width" drift kinetic equation with rf ray-tracing source and quasilinear/collisional effects to determine bounce-averaged f as function of, u, $\theta_{,}$ and, ρ (radial flux coordinate).
- Does it make sense to use results from electron transport/RF codes that do not "see" magnetic island?

RF produces local E. Let quasineutrality determine how effects spread in island geometry.



Many toroidal transits required to “feel” island geometry.

Primary RF interaction changes collisionality of trapped particles as they bounce through resonance

2. RF stabilization of NTM with heuristic closures.

$$0 = nq\left(\vec{E} + \vec{u}\,\boldsymbol{x}\,\vec{B}\right) - \vec{\nabla}\,p + \vec{R} + F_0^{rf} + \vec{\nabla}\cdot\boldsymbol{\Pi}\,,$$

Heuristic flow damping closure for electron stress, perturbed bootstrap current. Anisotropic conduction flattens T across island.

$$\frac{3}{2}n\left[\frac{\partial T}{\partial t} + \vec{u}\cdot\vec{\nabla}\,T\right] = -nT\,\vec{\nabla}\cdot\vec{u} - \vec{\nabla}\cdot\vec{q} + S_0^{rf}\,.$$

3. Serious NTM/RF closures solve kinetic equation with RF drives in 3D magnetic geometry.

$$\frac{\partial F}{\partial t} + \vec{v}\cdot\vec{\nabla} F + \vec{a}\cdot\vec{\nabla}_{\vec{v}} F - C(f) = Q^{rf}(f_M)$$

$$- L_1^{(1/2)}\left(\boldsymbol{\Pi} : \vec{\nabla}\vec{u} + \vec{\nabla}\cdot\vec{q} - Q - S_0^{rf}\right)\frac{f_M}{p}$$

$$+ \vec{v}\,'\cdot\left(\vec{\nabla}\cdot\boldsymbol{\Pi} - \vec{R} - F_0^{rf}\right)\frac{f_M}{p}$$

$$- L_1^{(3/2)}\vec{v}\,'\cdot\vec{\nabla} T\frac{f_M}{T} - \frac{m}{T}\left(\vec{v}\,'\vec{v}\,' - \frac{v'^2}{3}\boldsymbol{I}\right) : \vec{\nabla}\vec{u}\, f_M$$

Solve gyroaveraged equation.

- *In zero-banana-width, low-flow limit we have:*

$$\left[\frac{\partial}{\partial t}+v_{\|}\nabla_{\|}+\frac{v_{\|}}{v}\left(q\frac{E_{\|}}{m}\right)\frac{\partial}{\partial v}\right]\bar{F}-\left\langle C\left(f_M+\bar{F}\right)\right\rangle=$$

$$Q^{rf}(f_M)+L_1^{1/2}\left(\partial_t \ln T+(2/3)\vec{\nabla}\cdot\vec{u}\right)f_M$$

$$+v_{\|}\hat{b}\cdot\left(\vec{\nabla}\cdot\boldsymbol{\Pi}_{\|}-\vec{R}-F_0^{rf}\right)\frac{f_M}{p}-L_1^{3/2}v_{\|}\nabla_{\|}\ln T\, f_M$$

$$-\frac{m}{T}v^2P_2\left(\hat{b}\hat{b}-\frac{\boldsymbol{I}}{3}\right):\vec{\nabla}\vec{u}\, f_{M}.$$

Consider diagonalizing operator acting on F in CEL-DKE.

- In past, diagonalized free-streaming and Lorentz pitch-angle scattering only:

$$\left[v_{||} \nabla_{||} \right] \bar{F} - \left\langle L(f_M + \bar{F}) \right\rangle$$

- Recent improvements permit simultaneous diagonalization of time derivative and part of collision operator:

$$\left[\frac{\partial}{\partial t} + v_{||} \nabla_{||} + \frac{v_{||}}{v} (q \frac{E_{||}}{m}) \frac{\partial}{\partial v} \right] \bar{F} - \left\langle C(f_M + \bar{F}) \right\rangle$$

island part survives bounce average