The SWIM “Slow” MHD Campaign: Interaction of RF with MHD

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SWIM “Slow” MHD Campaign

- Long Term Physics goal: Demonstrate RF stabilization of NTM in toroidal geometry, with time-dependent RF source
- Long Term Integration Goal: Demonstrate efficient coupling between state-of-art MHD and RF codes on a time-dependent, self-consistent problem

Technical Approach

- Recognize that problem is additive
  - Modified Rutherford equation:

$$\frac{dw}{dt} = \frac{\eta_{nc}}{\mu_o} k_1 [\underbrace{\Delta' + \Delta_{nc}(w) + \ldots + \Delta_{RF}(w)}_{\text{Physics is additive}}]$$

- Can approach problems in parallel
- Don’t need to get NTM right before attacking RF
  - Can start with RF/tearing coupling

Implementation Plan (MHD)

- I: Add RF source module and interface to NIMROD
- II: Define “simple” RF closure
- III: *ad hoc* analytic source term (force on electrons) in Ohm’s law
  - Tearing mode stabilization => proof of principle
- IV:Evolutionary equation for RF source
- V:Revisit NTM calculations
  - Kruger/Hegna heuristic closure?
  - Collisional Braginskii nonlinear electron viscous stress tensor?
- V: Couple to RF codes
- VI: Throughout, refine theoretical closure models and implementations

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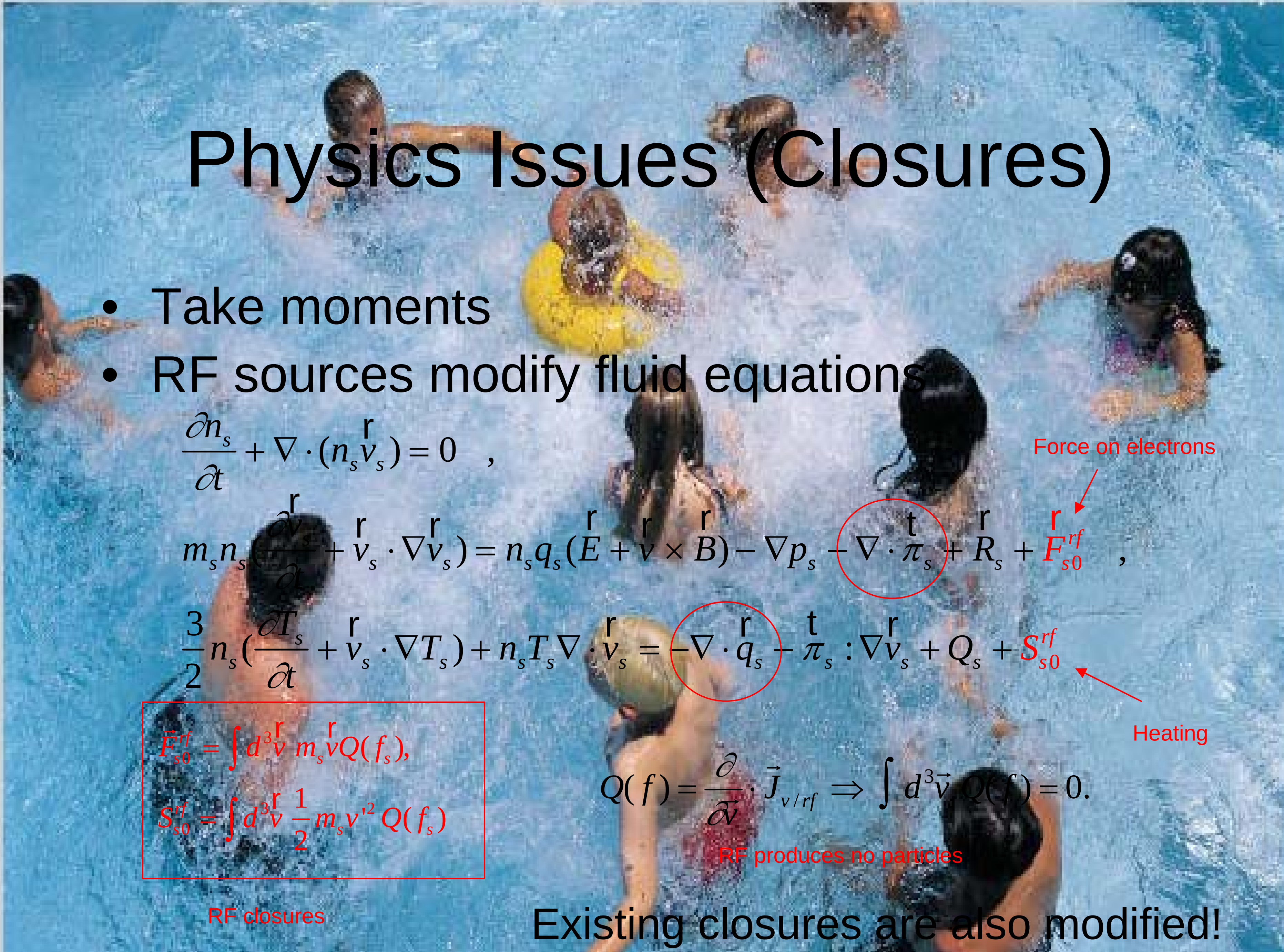
Physics Issues (Kinetic Equation)

- How to incorporate RF effects into fluid models?
- Start with kinetic equation

$$\frac{df}{dt} = \underbrace{C(f)}_{\text{Collisional}} + \underbrace{Q(f)}_{\text{RF quasi-linear operator}} , \qquad \frac{d}{dt} = \frac{\partial}{\partial t} + \vec{v}\cdot\nabla + \frac{q_s}{m_s}(\vec{E} + \vec{v}\times\vec{B})\frac{\partial}{\partial \vec{v}}$$

$$Q(f) = \frac{\partial}{\partial \vec{v}} \cdot \overleftrightarrow{D} \cdot \frac{\partial f}{\partial \vec{v}},$$

Quasi-linear diffusion tensor
Output of RF codes



Physics Issues (Closures)

- Take moments
- RF sources modify fluid equations

$$\frac{\partial n_s}{\partial t} + \nabla\cdot(n_s\vec{v}_s) = 0 \quad ,$$

$$m_s n_s\left(\frac{\partial \vec{v}_s}{\partial t} + \vec{v}_s\cdot\nabla\vec{v}_s\right) = n_s q_s(\vec{E} + \vec{v}\times\vec{B}) - \nabla p_s - \nabla\cdot\overleftrightarrow{\pi}_s + \vec{R}_s + \vec{F}^{rf}_{s0} \quad ,$$

Force on electrons

$$\frac{3}{2} n_s\left(\frac{\partial T_s}{\partial t} + \vec{v}_s\cdot\nabla T_s\right) + n_s T_s\nabla\cdot\vec{v}_s = -\nabla\cdot\vec{q}_s - \overleftrightarrow{\pi}_s : \nabla\vec{v}_s + Q_s + S^{rf}_{s0}$$

Heating

$$\vec{F}^{rf}_{s0} = \int d^3\vec{v}\, m_s\vec{v}\,Q(f_s),$$

$$S^{rf}_{s0} = \int d^3\vec{v}\,\frac{1}{2} m_s v'^2 Q(f_s)$$

RF closures

$$Q(f) = \frac{\partial}{\partial\vec{v}}\cdot\vec{J}_{v/rf} \Rightarrow \int d^3\vec{v}\,Q(f) = 0.$$

RF produces no particles

Existing closures are also modified!

Information (RF <==> MHD)

- Chapman-Enskog-Like theory can produce closures, i.e.,

Maxwellian

$$\vec{F}^{rf}_{s0} = \int d^3\vec{v}\; m_s \vec{v}\, Q(f_s) \cong \int d^3\vec{v}\; m_s \vec{v}\, Q(f_{Ms}),$$

$$S^{rf}_{s0} = \int d^3\vec{v}\; \frac{1}{2} m_s v'^2 Q(f_s) \cong \int d^3\vec{v}\; \frac{1}{2} m_s v'^2 Q(f_{Ms})$$

- Moments can be computed by numerical integration in velocity space once **D**$_{QL}$ is specified
- **D**$_{QL}$(v) produced at each mesh point by RF codes

RF/MHD Coupling

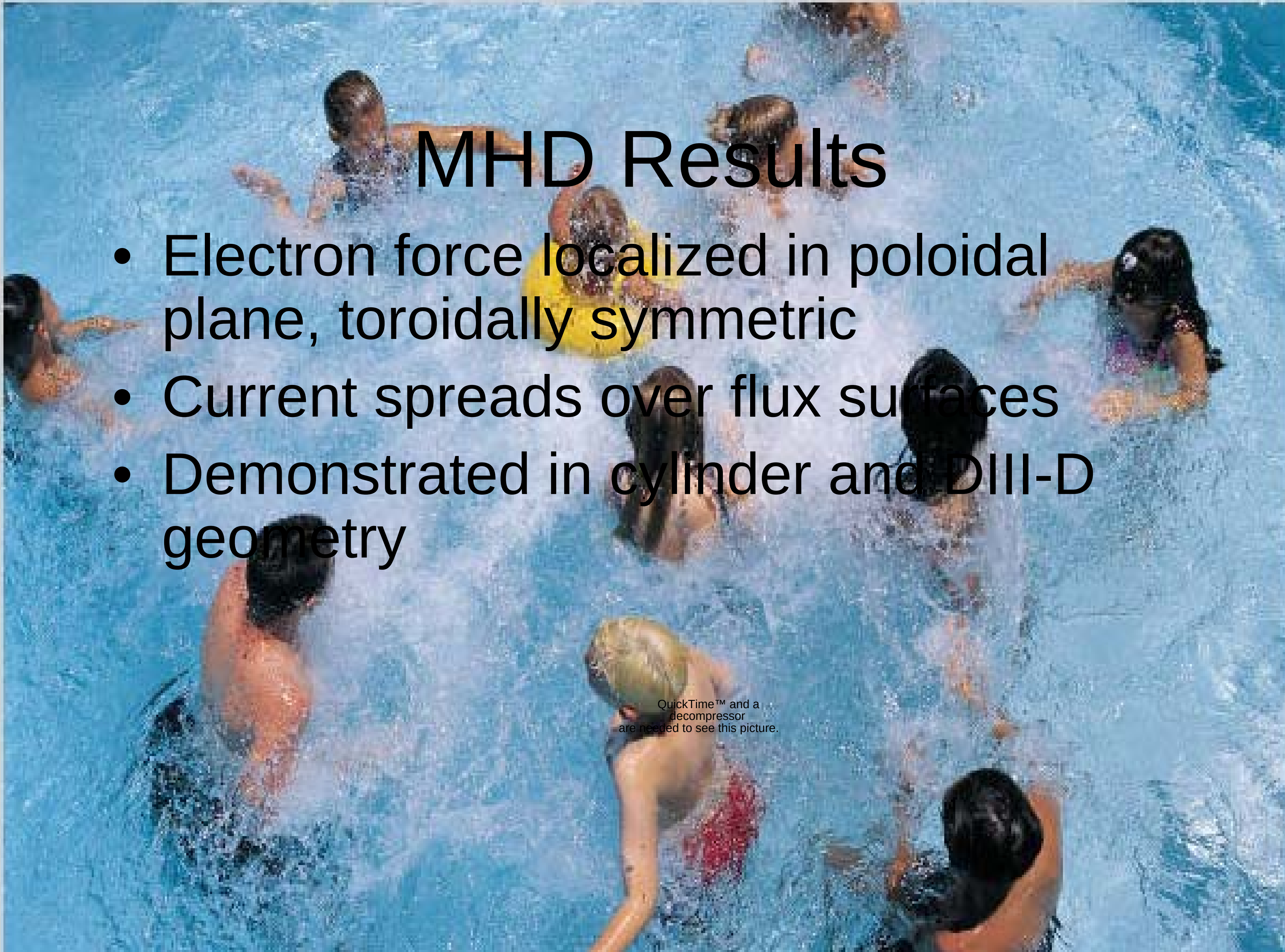
- NIMROD produces $n(\mathbf{r},t)$, $T(\mathbf{r},t)$, $\mathbf{B}(\mathbf{r},t)$ => RF codes
- RF codes produce $\mathbf{D}_{QL}(\mathbf{r},\mathbf{v})$ on rays => interpolated to NIMROD grid
- NIMROD integrates in $\mathbf{v}$ => moments of Q
- NIMROD produces $n(\mathbf{r},t+\Delta t)$, $T(\mathbf{r},t+\Delta t)$, $\mathbf{B}(\mathbf{r},t+\Delta t)$

Issues

- What are the most appropriate fluid moments?
- What is the most efficient way to compute them?
- Are there any new numerical stability issues?
- Can NTM growth and saturation be demonstrated?
- How often does RF need to be updated?
- How should data be passed between MHD and RF codes?
- Do RF codes need to be modified (islands, etc)?
- Do we need to go beyond ECCD?
- ???

MHD Results

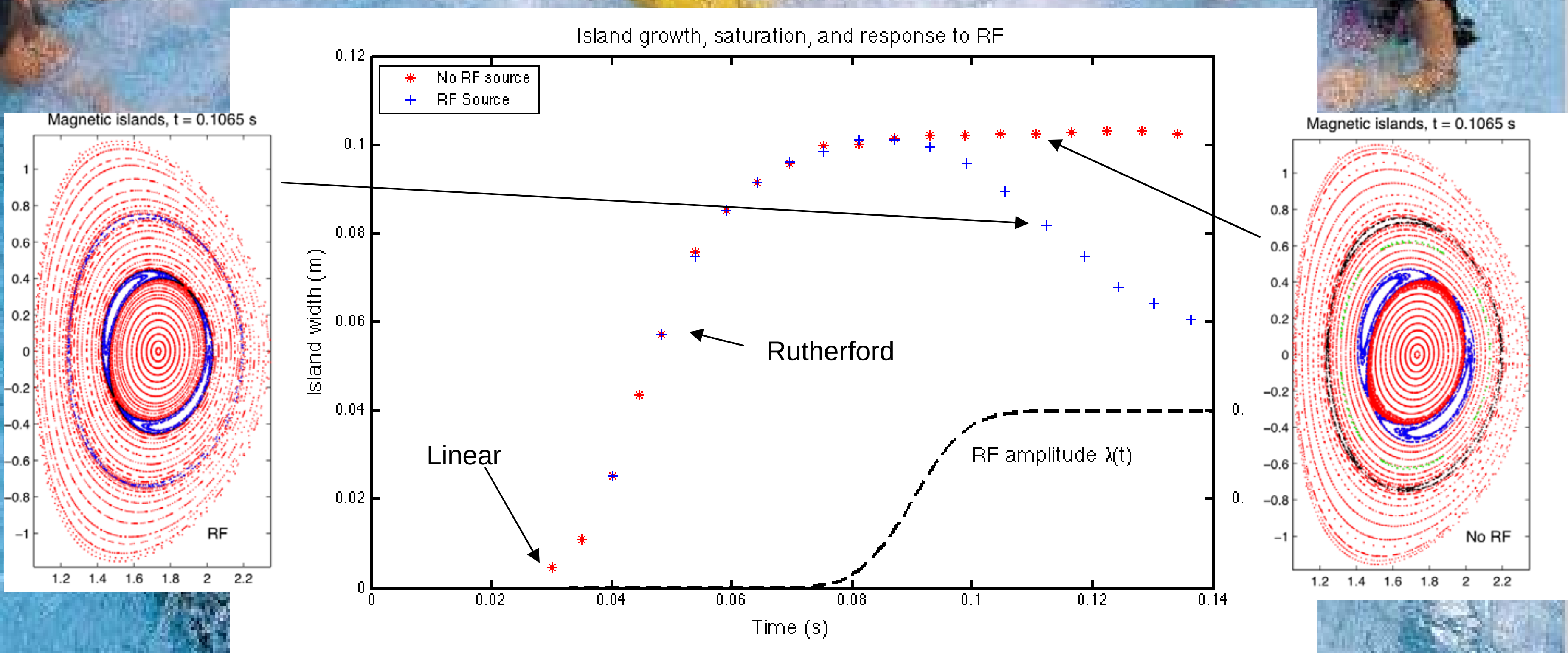
- Electron force localized in poloidal plane, toroidally symmetric
- Current spreads over flux surfaces
- Demonstrated in cylinder and DIII-D geometry



QuickTime™ and a
decompressor
are needed to see this picture.

Tearing Mode Stabilization by RF in DIII-D geometry

(Tom Jenkins)



Status

- Closure procedure defined
- Spitzer-like problem formulated
- Data required from RF modules defined
- General source modules and interfaces added to NIMROD
- Simple axi-symmetric source implemented
- Stabilization of 2/1 resistive tearing mode demonstrated in DIII-D geometry
- Conversations with RF physicists beginning

Workshop

- RF/MHD Workshop - Madison - Dec. 4-6
- Bring together MHD and RF researchers
- Issues:
  - MHD plans, status, and progress
  - RF plan, status, and progress
  - Fluid closures
  - Define critical CS/data issues
  - Develop near term joint implementation plan and time line

The Final Product…..