A high-angle photograph of a group of people swimming in a pool. The water is bright blue and splashing. In the center, there is a yellow inflatable ring. Several people are visible, some with their heads above water and others partially submerged. The overall scene is lively and suggests a summer or recreational setting.

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

D. D. Schnack, T. Jenkins, J. Callen, C. Hegna, C.
Sovinec, F. Ebrahimi *University of Wisconsin,
Madison, WI*, E. Held, J.-Y. Ji, *Utah State University,
Logan, UT*, S. Kruger, J. Carlson, *Tech-X Corp.,
Boulder, CO*

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:

$$\frac{dw}{dt} = \frac{\eta_{nc}}{\mu_o} k_1 \left[\Delta' + \Delta_{nc}(w) + \Delta_{RF}(w) \right]$$

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

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

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

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


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

Physics Issues (Kinetic Equation)

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

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

$$Q(f) = \frac{\partial}{\partial \mathbf{v}} \cdot \overset{\text{t}}{\mathbf{D}} \cdot \frac{\partial f}{\partial \mathbf{v}},$$


Quasi-linear diffusion tensor
Output of RF codes

Physics Issues (Closures)

- Take moments
- RF sources modify fluid equations

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

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

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

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

$$S_{s0}^{rf} = \int d^3 \mathbf{v} \, \frac{1}{2} m_s v^2 Q(f_s)$$

RF closures

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

RF produces no particles

Force on electrons

Heating

Existing closures are also modified!

Information (RF \Leftrightarrow MHD)

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

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

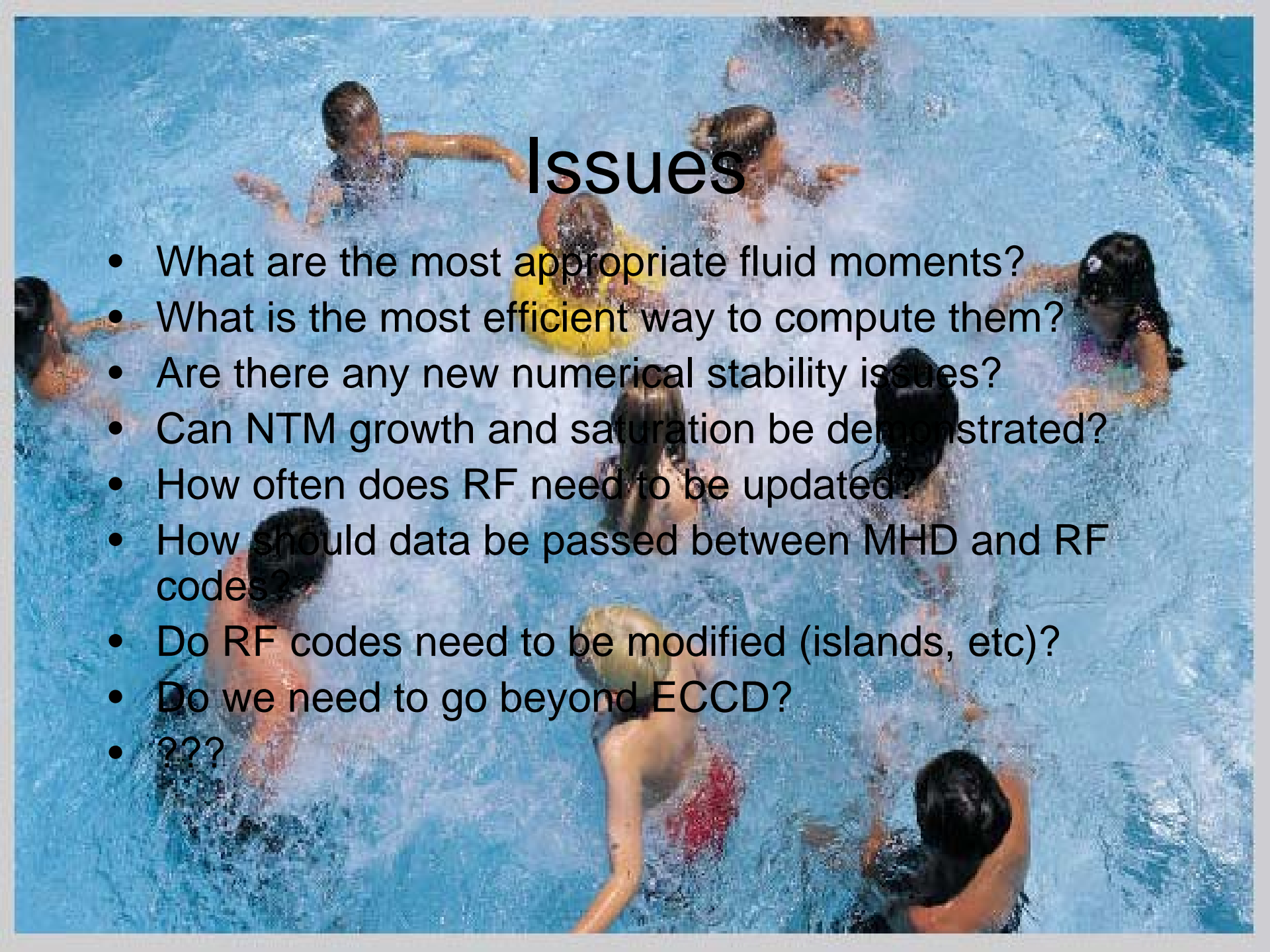
$$S_s^{rf} = \int d^3\vec{v} \, \frac{1}{2} m_s v'^2 Q(f_s) \cong \int d^3\vec{v} \, \frac{1}{2} m_s v'^2 Q(\textcolor{red}{f}_{Ms})$$

Maxwellian

- Moments can be computed by numerical integration in velocity space once \mathbf{D}_{QL} is specified
- $\mathbf{D}_{QL}(\mathbf{v})$ 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 $n(\mathbf{r}, t+\Delta t)$, $T(\mathbf{r}, t+\Delta t)$,
 $\mathbf{B}(\mathbf{r}, t+\Delta t)$

A group of people are swimming in a pool, with water splashing around them. The word "Issues" is overlaid in large black text in the upper center of the image.

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?
- ???

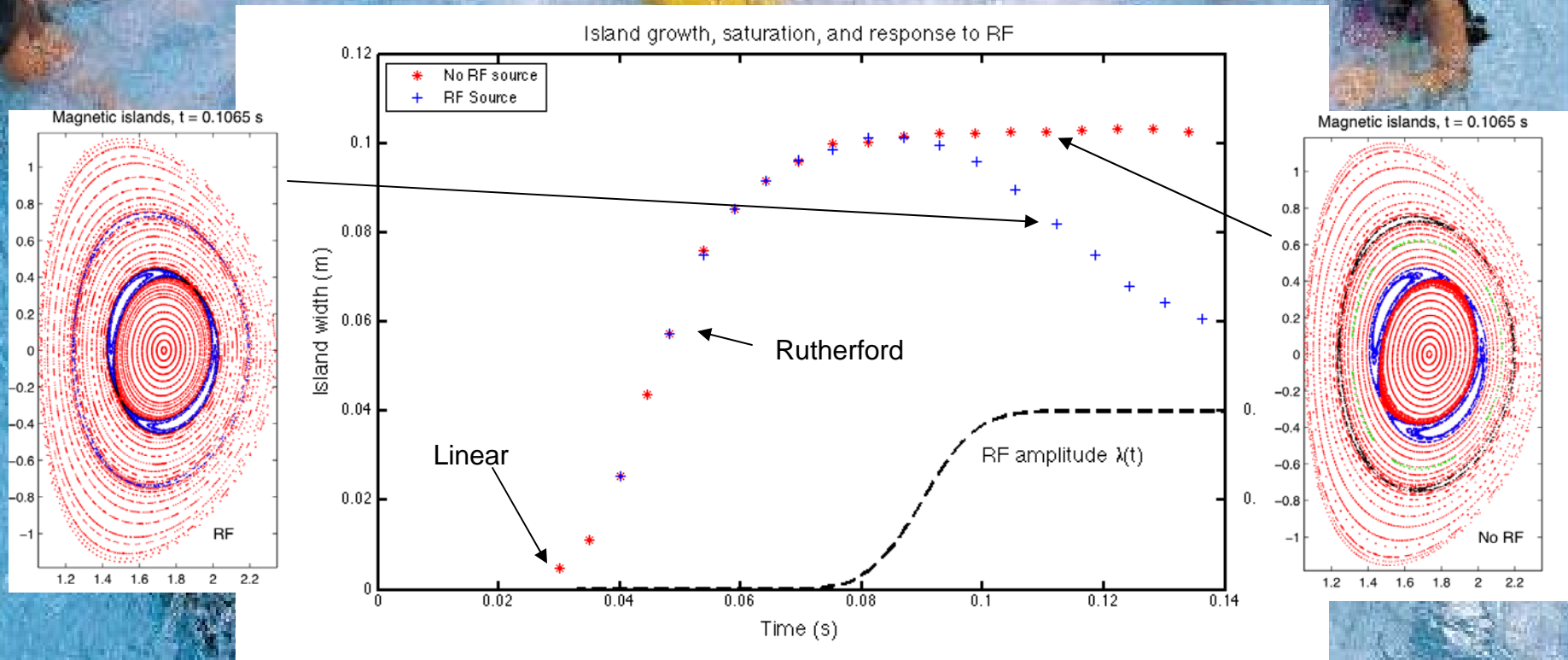
MHD Results

- 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)



A high-angle photograph of a group of people swimming in a blue pool. The water is splashing, and several people are visible, including a man in a blue swimsuit, a woman in a yellow swimsuit, and a woman in a purple swimsuit. The word "Status" is overlaid in large, bold, white sans-serif font in the upper center of the image.

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

A high-angle photograph of a group of people, including children and adults, swimming in a blue pool. The water is splashing, and the scene is lively. Overlaid on the center of the image is the word "Workshop" in a large, bold, black sans-serif font.

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.....

