Update on M3D-C1 Disruption Mitigation Modeling

by

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ITER DMS Task Force - 3D MHD Modeling Meeting

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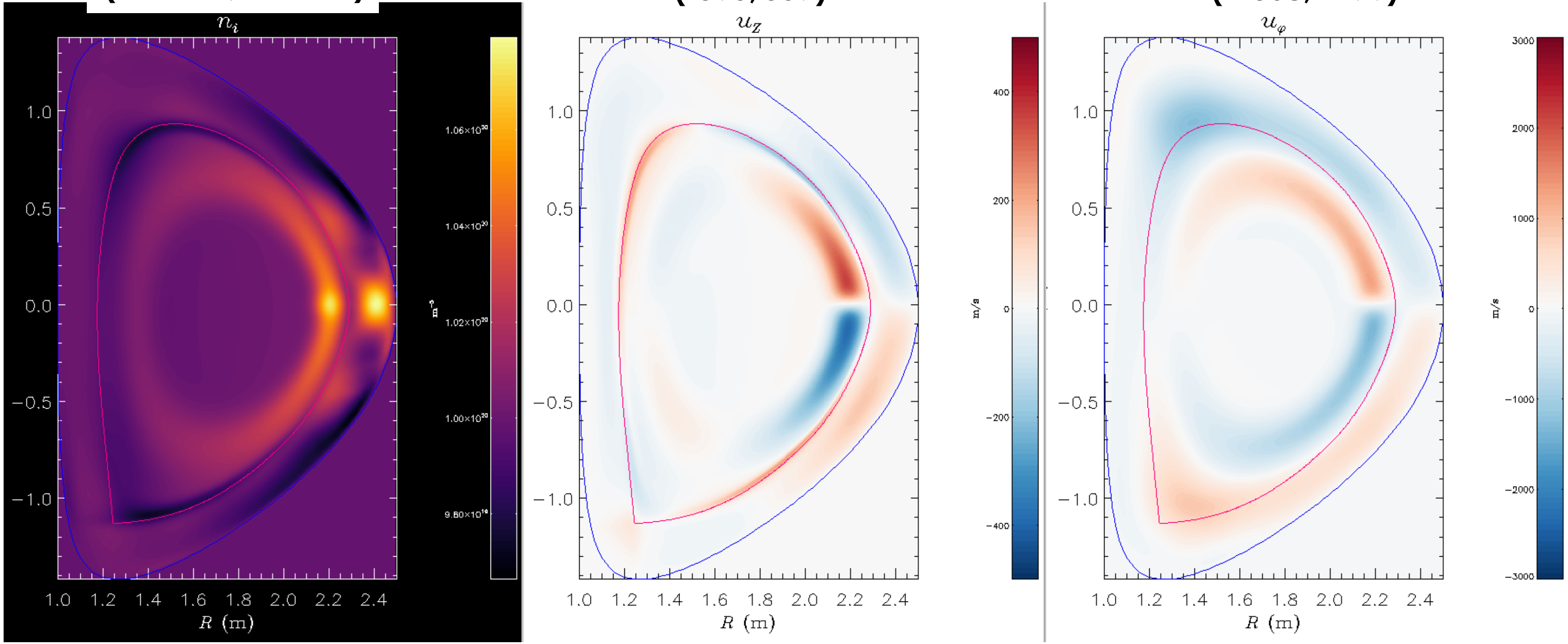
GENERAL ATOMICS

Velocity Boundary Conditions

First Seen in Pellet Benchmark, M3D-C1 & NIMROD Seeing Different Flow Patterns with Strong Density Source

M3D-C1: Strong parallel outflow from source, but return flow near X-points & in OFLR

(9.66e19, 1.08e20) **(-390, 357)** **(-1368, 1279)**



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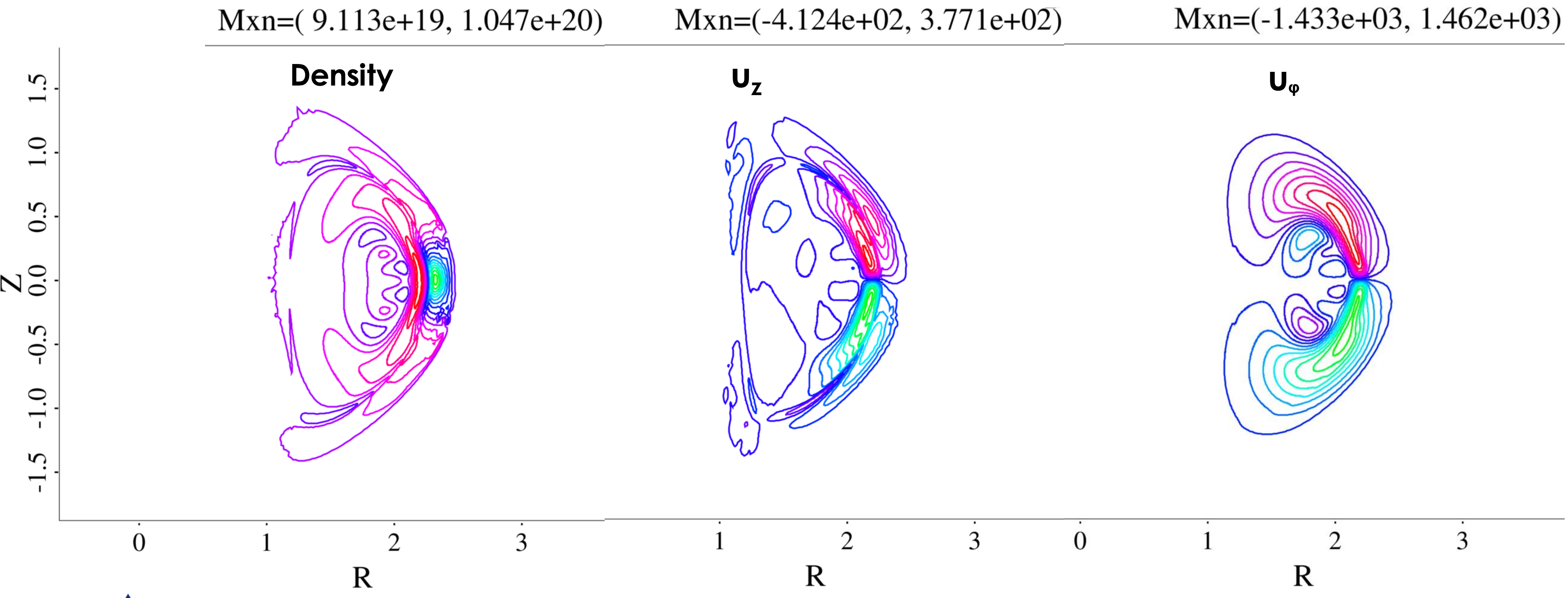
First Seen in Pellet Benchmark, M3D-C1 & NIMROD Seeing Different Flow Patterns with Strong Density Source

NIMROD: Similar outflow magnitude, but no return flow (same direction in OFLR)



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M3D-C1 No-Flow Boundary Conditions Force Vorticity and Compression Components of Velocity to Zero Separately

- **M3D-C1 use a potential formulation for velocity**

$$\vec{u} = R^2 \nabla U \times \nabla \varphi + R^2 \omega \nabla \varphi + \frac{1}{R^2} \nabla_\perp \chi$$

- **Boundary conditions come from components of this**
  - No toroidal slipping (`inoslip_tor=1`): $\omega = 0$
  - No poloidal slipping: $R\frac{\partial U}{\partial n} + \frac{1}{R^2}\frac{\partial \chi}{\partial \tau} = 0$
  - No normal flow (`inonormalflow=1`): $-R\frac{\partial U}{\partial \tau} + \frac{1}{R^2}\frac{\partial \chi}{\partial n} = 0$
- **The second two are currently implemented such that each term is zero, not the sum**
  - No poloidal slipping (`inoslip_pol=1`): $\partial U/\partial n = 0 \quad \text{and} \quad \chi = 0$
  - No normal flow (`inonormalflow=1`): $U = 0 \quad \text{and} \quad \partial \chi/\partial n = 0$
- **This was likely unseen before because χ typically small**

New, Correct Boundary Conditions Implemented, but Not Robust

- **Summed boundary conditions implemented as `inoslip_pol=2` and `inonormalflow=2`**
- **Using both is unstable (perhaps not enough constraints?)**
- **`inoslip_pol=2` and `inonormalflow=1` is sometimes stable**
  - Amounts to 3 BCs: $R\frac{\partial U}{\partial n} + \frac{1}{R^2}\frac{\partial \chi}{\partial \tau} = 0$, $U = 0$ and $\partial\chi/\partial n = 0$
  - Value of χ not fixed
  - Requires stronger regularization

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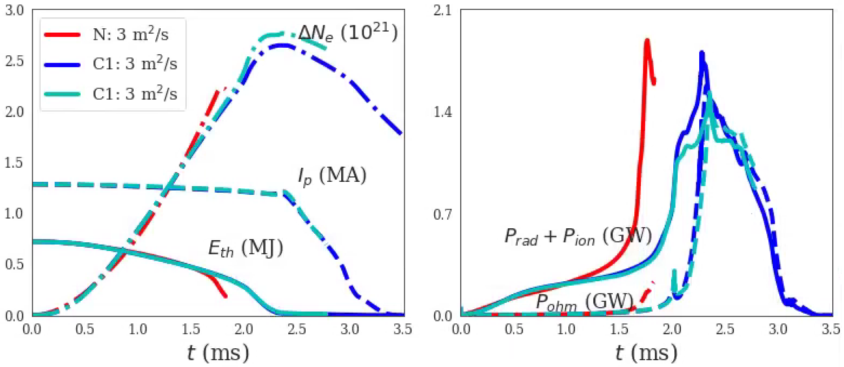
New Poloidal Flow Boundary Condition Does Not Significantly Change 3D Benchmark Results

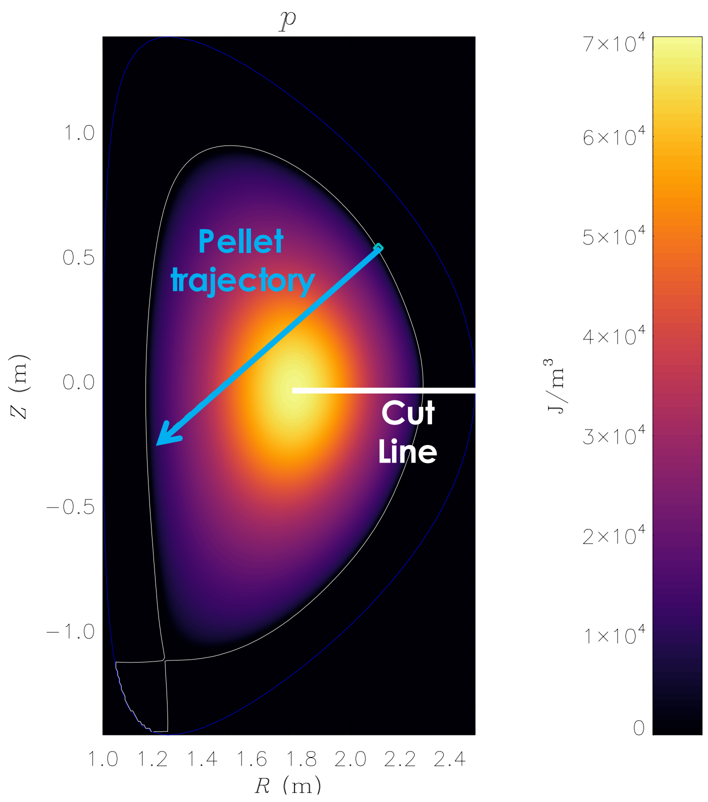
- Reran with old normal flow condition but new poloidal flow condition
- Increased regularization
- Near identical time histories, despite change in velocity profiles (see following slides)

Old (inoslip_pol=1)
New (inoslip_pol=2)



Comparison of Midplane Cuts

- Cuts are taken through midplane
- Downstream of pellet location
- R components roughly normal
- Z components roughly poloidal



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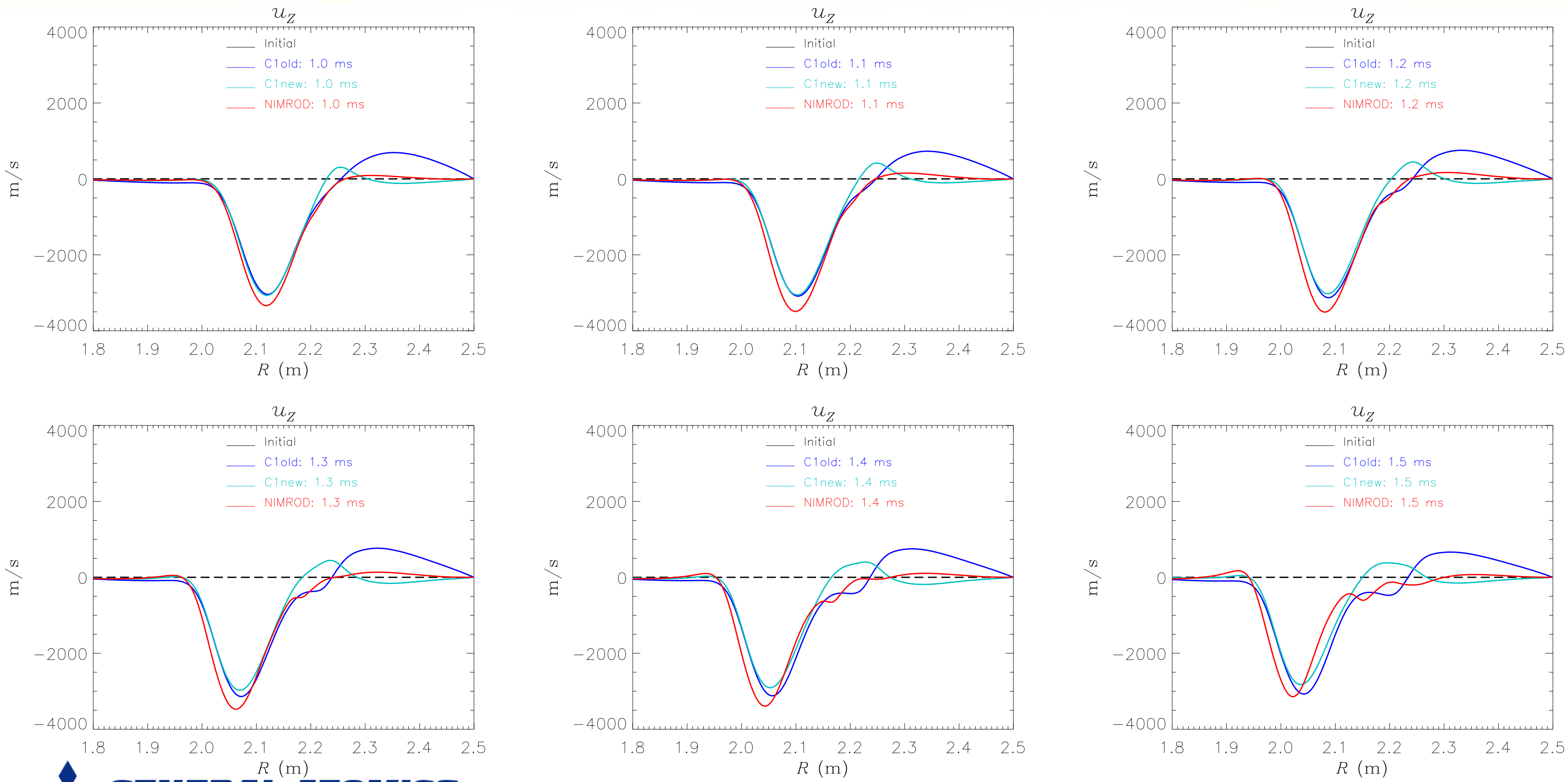
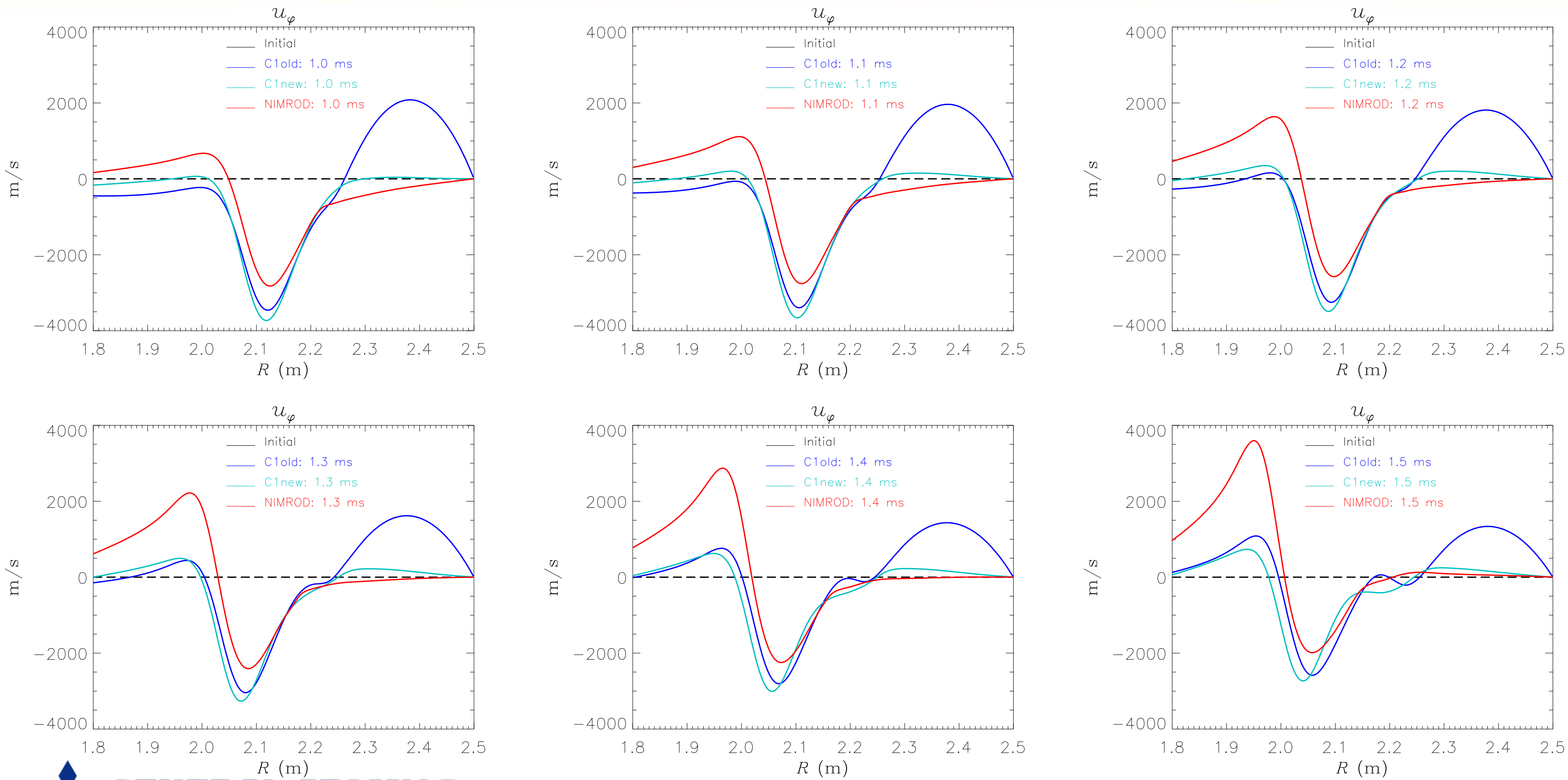
Poloidal Flow Better but Not Perfect



Toroidal Flow Better in Edge, but Differs in Core



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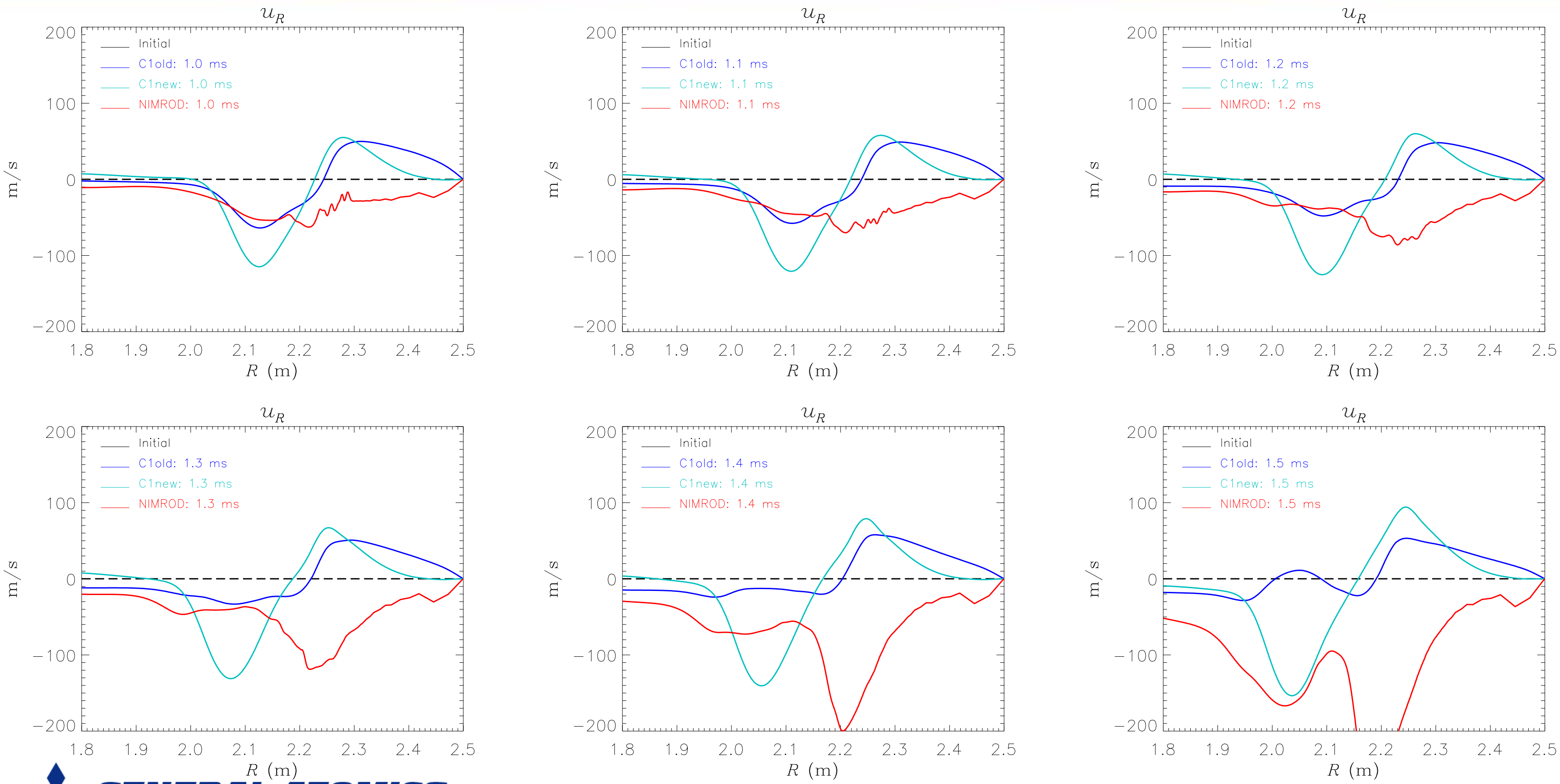
Radial Flow Still Very Different (NIMROD Has Single Sign)



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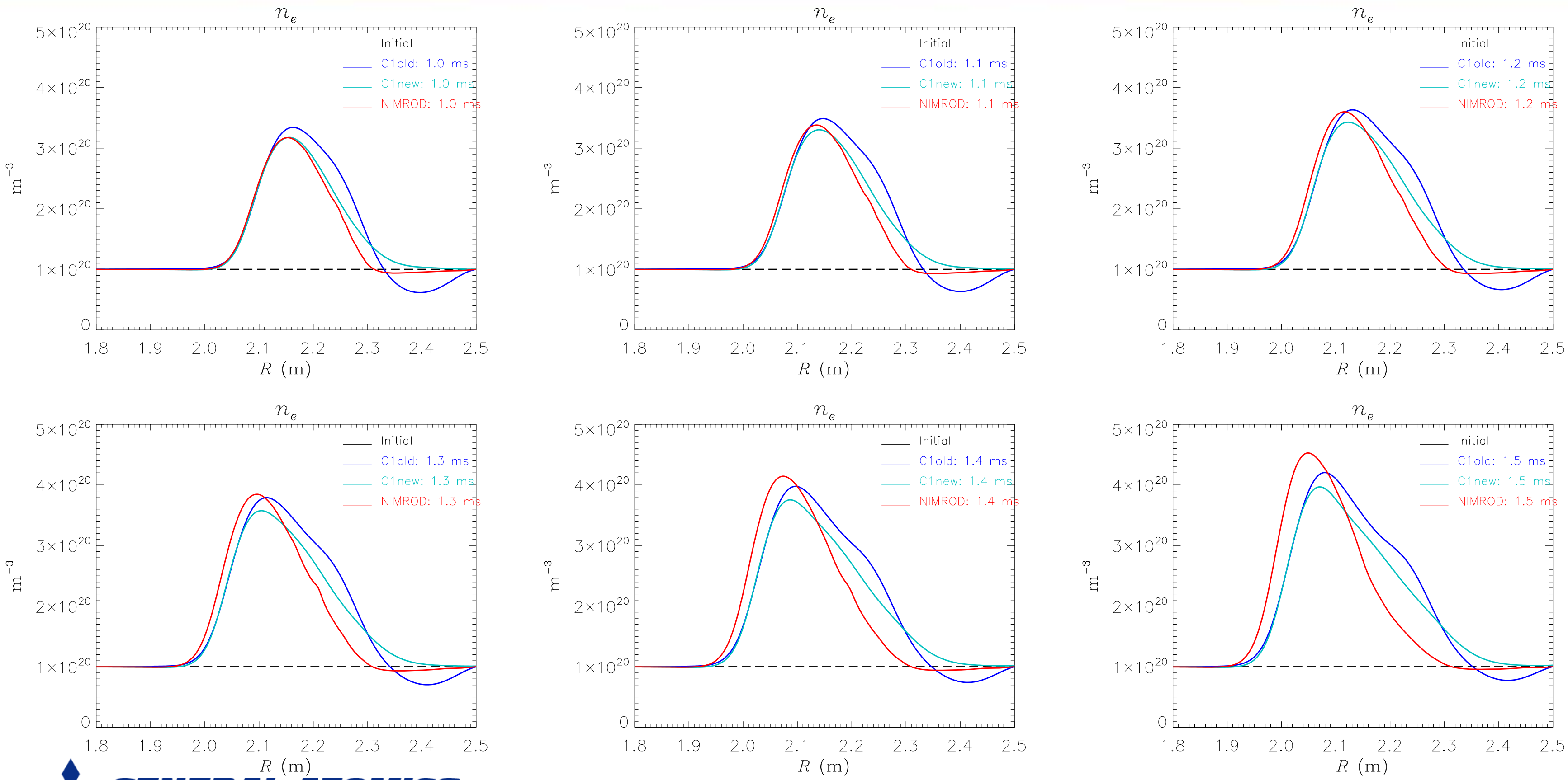
Electron Density in Good Agreement Early, But Diverges



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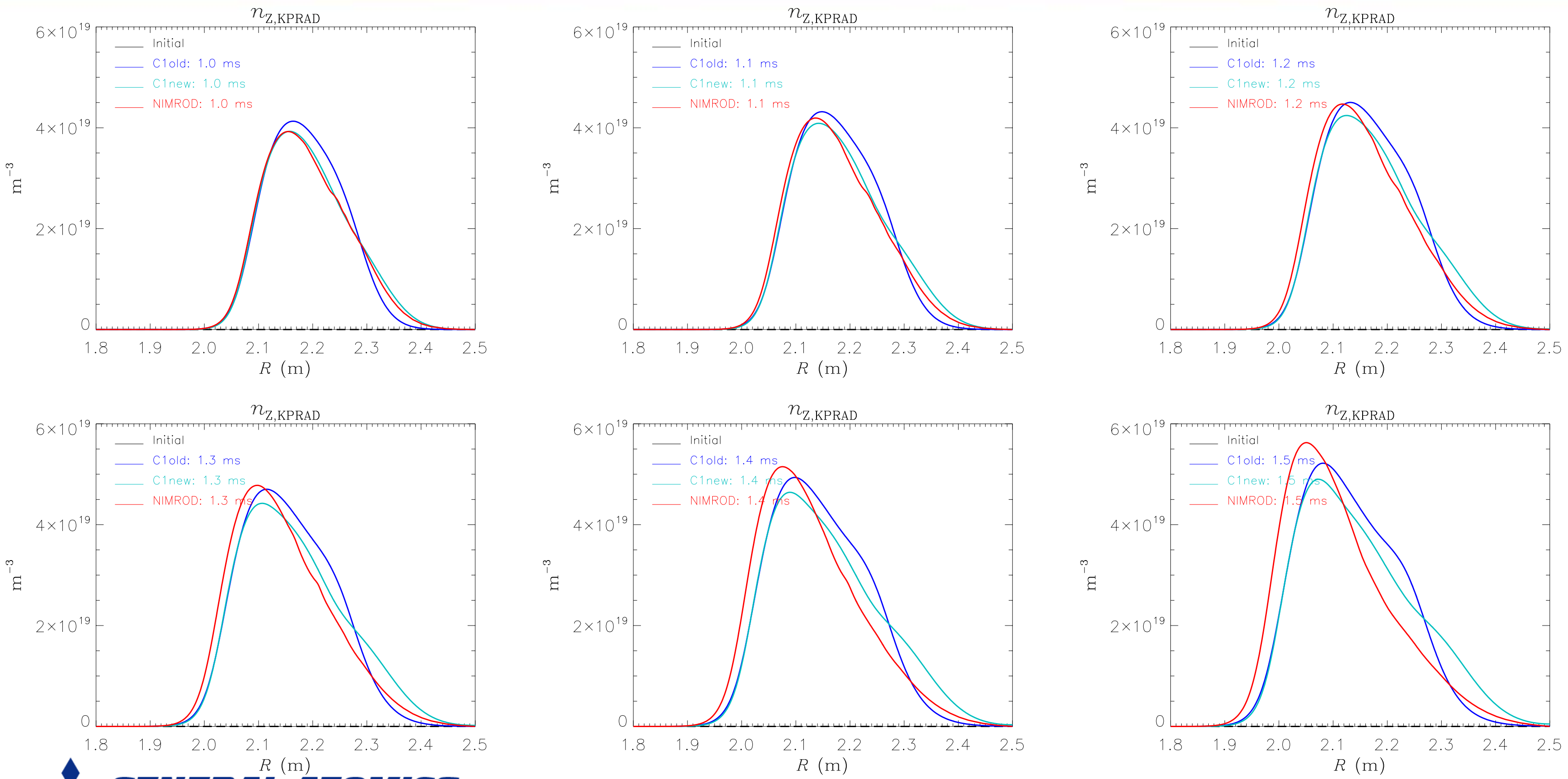
Impurity Density in Even Better Agreement Early, But Diverges



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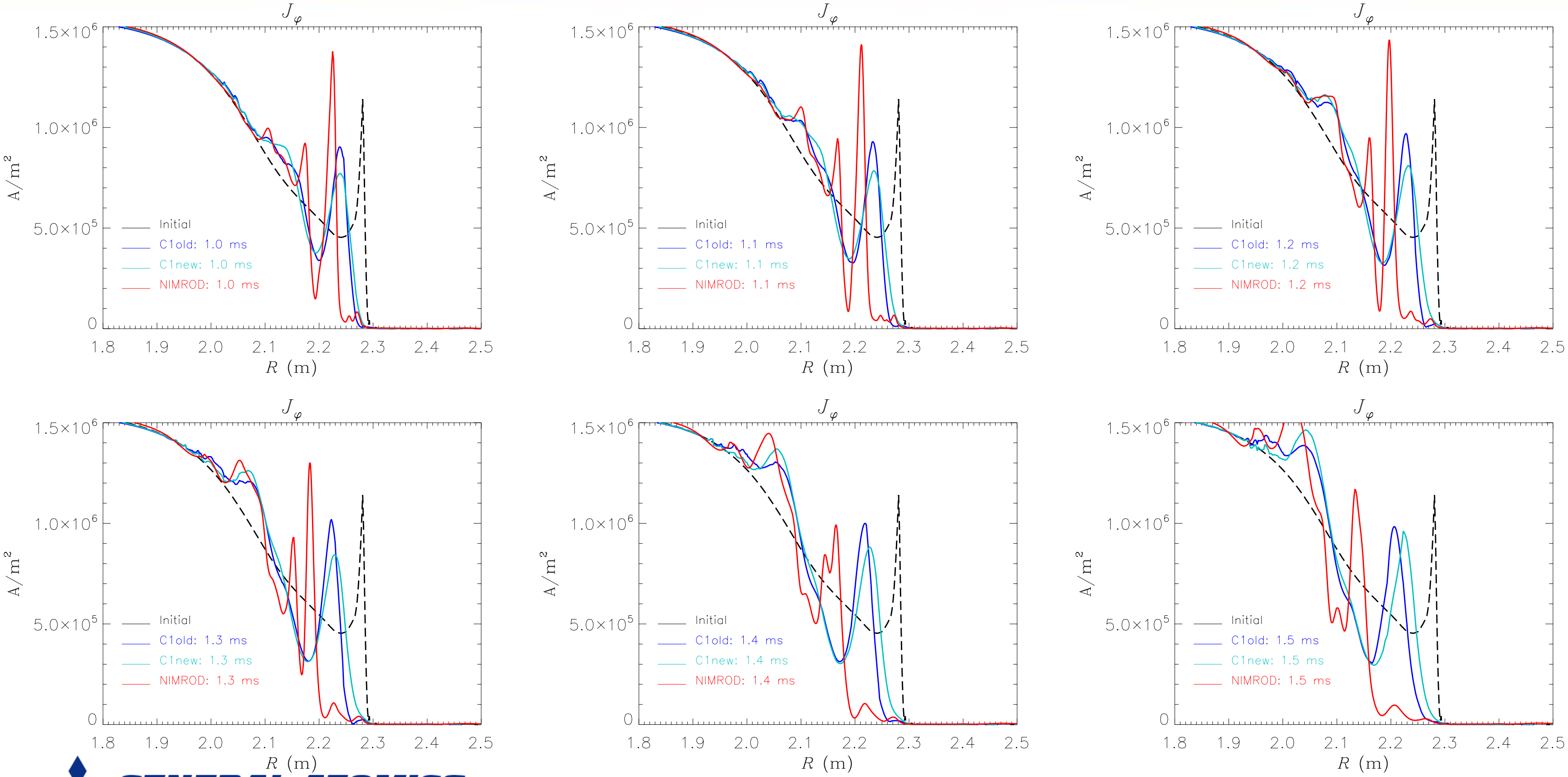
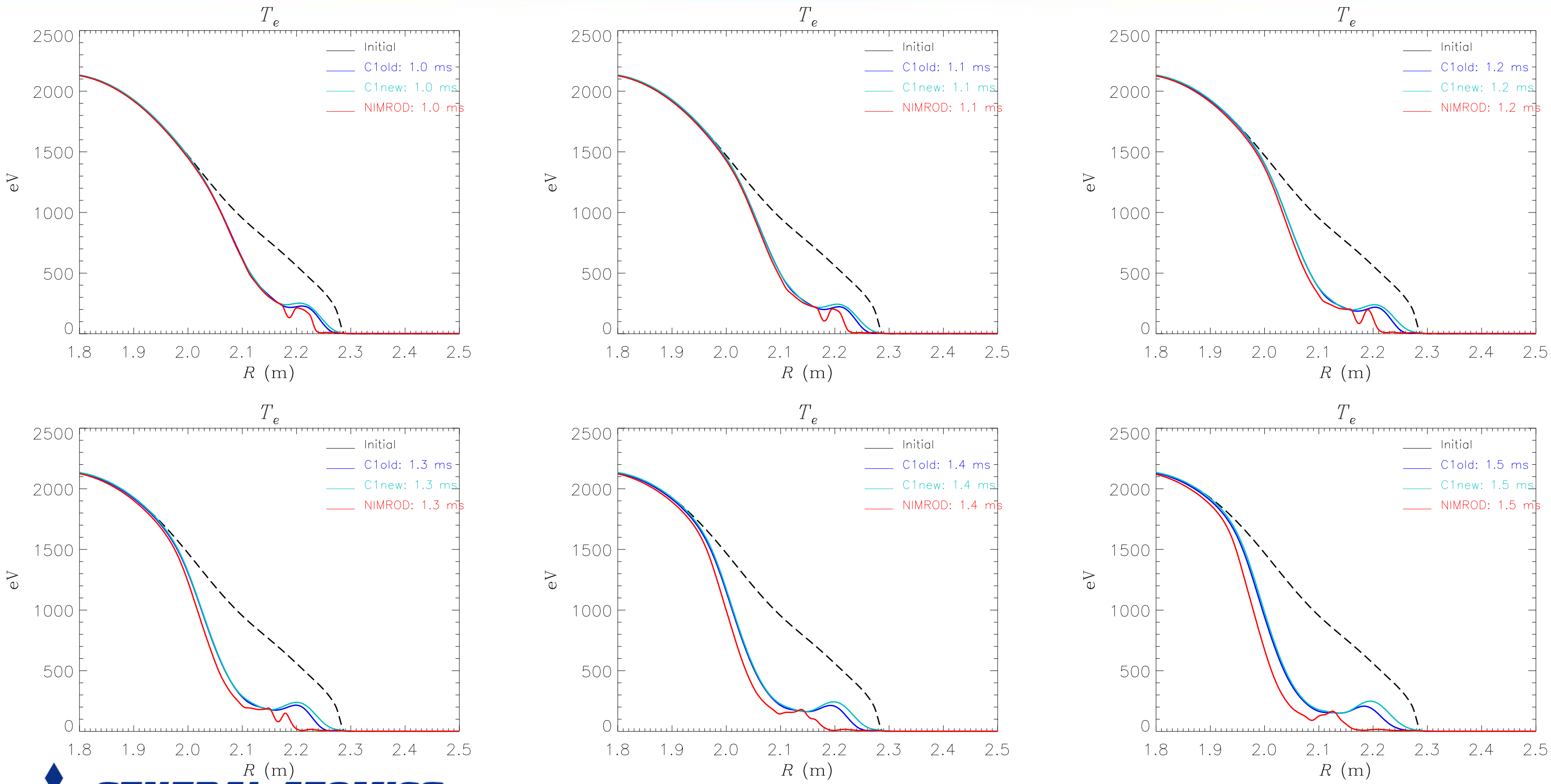
Toroidal Current Density Still Very Different



Temperature Consistent with Current Discrepancies



Some Thoughts

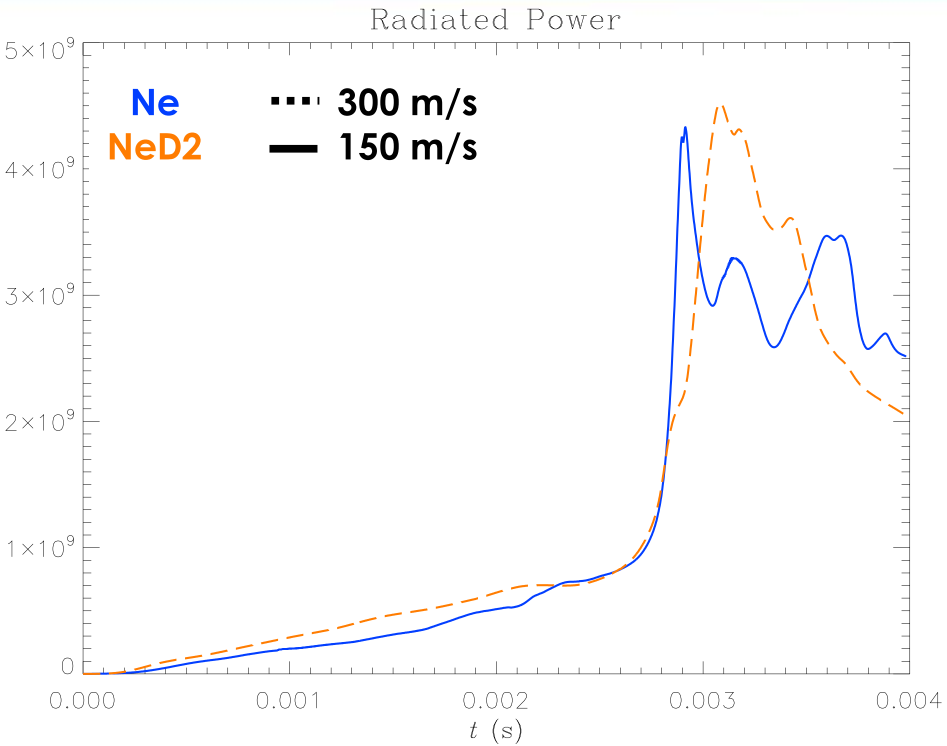
- **Radial flow is small but clearly very different**
  - NIMROD radial flow has single sign, and grows in amplitude
  - Early kinking of plasma inward at φ=0?
- **Charlson pointed out that the gradient of the flow at the boundary appears opposite between M3D-C1 and NIMROD**
- **Maybe we do need to get the normal flow condition correct, but how to do it stably?**
- **Maybe the difference in edge temperature and current is unrelated?**

JET Plume Modeling

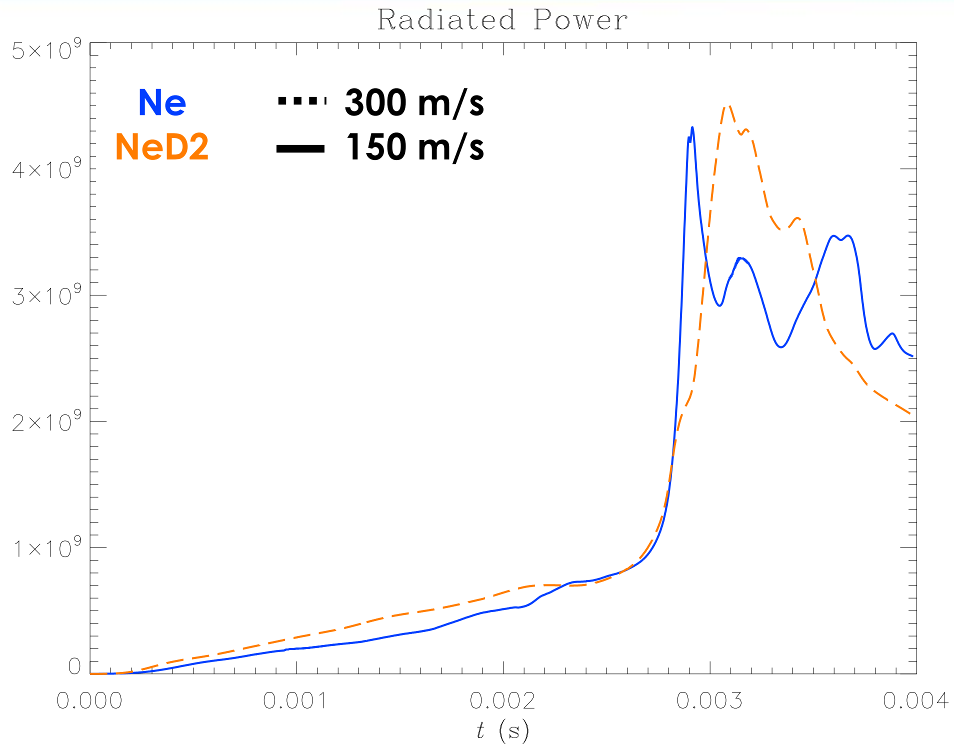
M3D-C1 JET modeling of realistic plumes underway

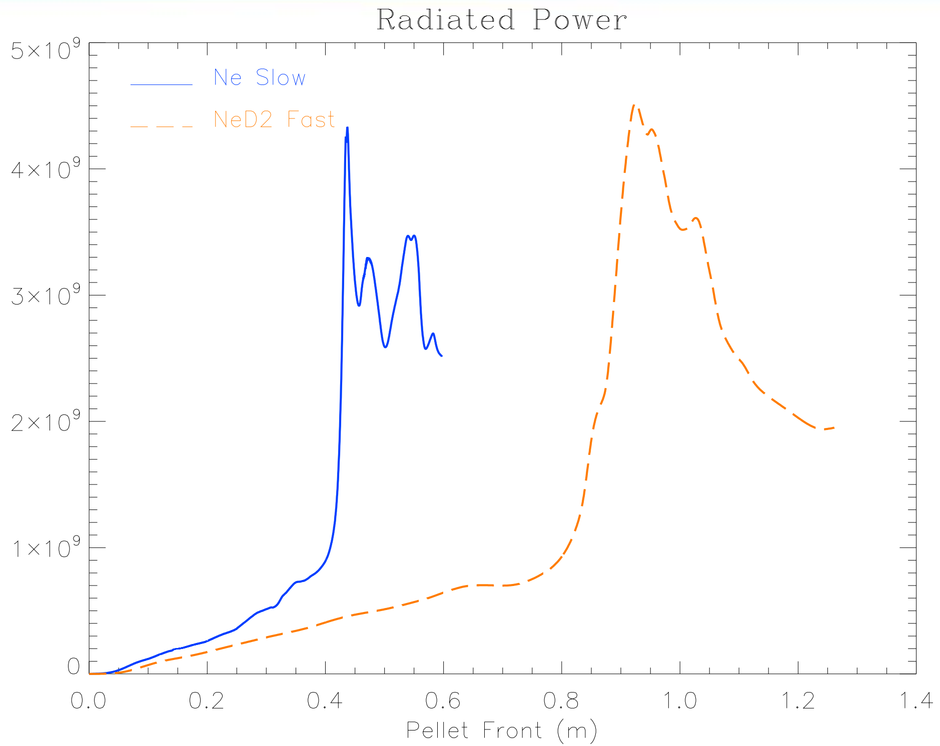
- **Consider two refence plumes emailed to task force**
  - JET pure neon:
    - 30 fragments with 1.71 mm radius
    - 150 m/s speed
  - JET 5% Ne/ 95% D
    - 85 fragments with 1.21 mm radius
    - 300 m/s
- **Pure neon is slower due to greater mass of pellet**

With Realistic Speeds, Both Plume Induce Instability at Same Time



With Realistic Speeds, Both Plume Induce Instability at Same Time, But Faster, Mixed Pellet Gets Much Father Into Plasma





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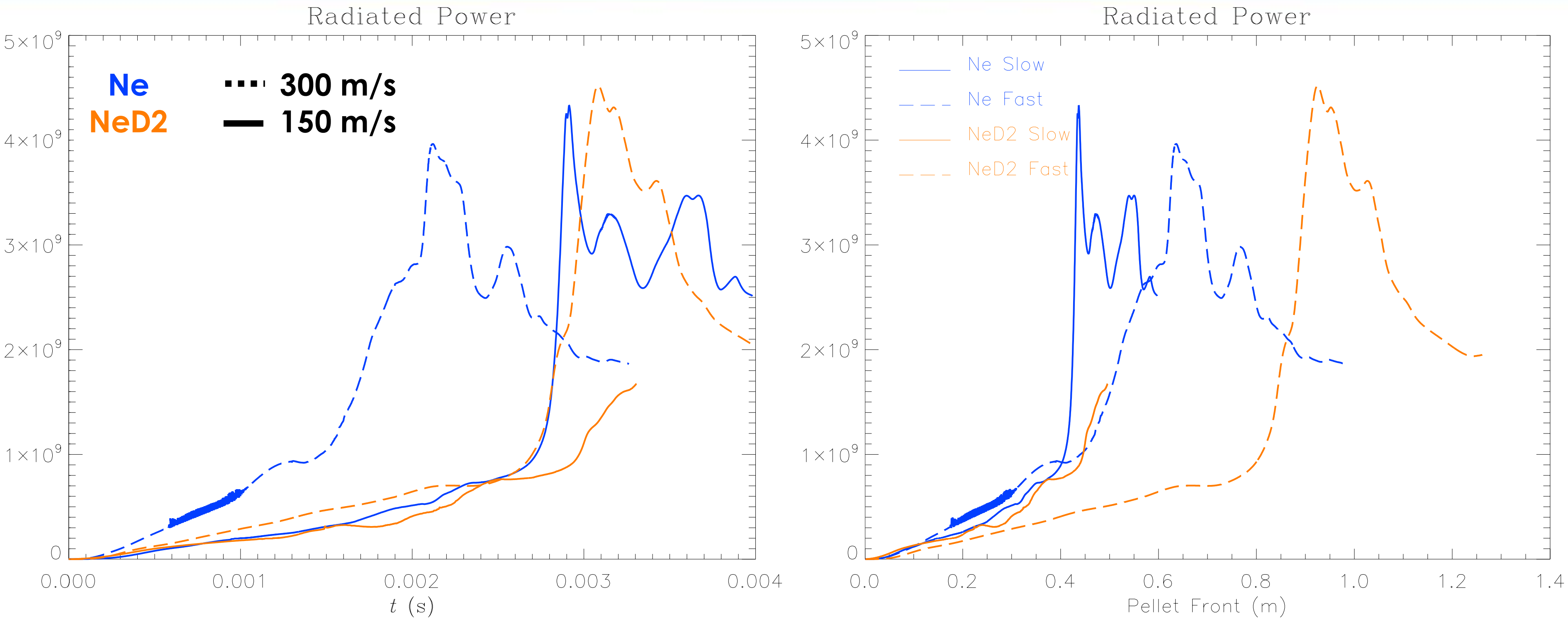
Reversing Speeds Shows Larger Impact For Pure Neon



Fast Ne timescale set by pellet speed, others set by radiative collapse time?

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Future Work

- **JET Simulations**
  - Continue slow, mixed pellet through thermal quench
  - Complete sensitivity scans
  - Reverse number of shards between plumes
  - Detailed radiation asymmetry validation
- **KSTAR plume simulations with multi-injections**

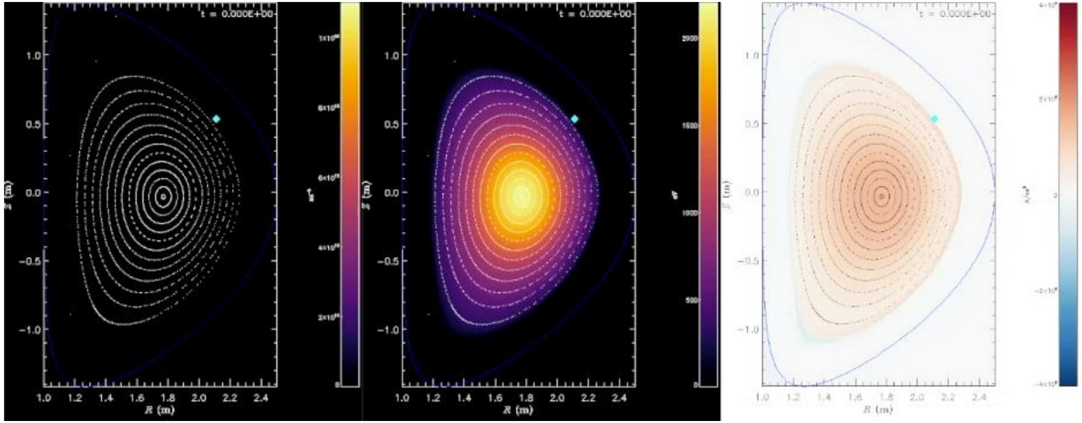
Additional Slides

3D, Nonlinear Benchmark Between M3D-C1 & NIMROD for Realistic, Injected Pellet is Well-Underway

- **Past 2D axisymmetric benchmark achieved excellent agreement: Lyons et al. PPCF 2019**
- **3D nonlinear MHD**
  - Fixed boundary
  - Single-temperature equation
- **Pellet/deposition parameters**
  - 3 mm radius, pure neon
  - 5 cm poloidal and 2.4 m toroidal half-width
  - 200 m/s with realistic trajectory
  - Ablation by local electron density and temperature according to model by Parks
- **Work has motivated code development and provided insight into SPI physics**

M3D-C1 Modeling of DIII-D 160606 @ 2990 ms: 0.7 MJ, 1.28 MA

Impurity Density	Electron Temperature	Toroidal Current Density



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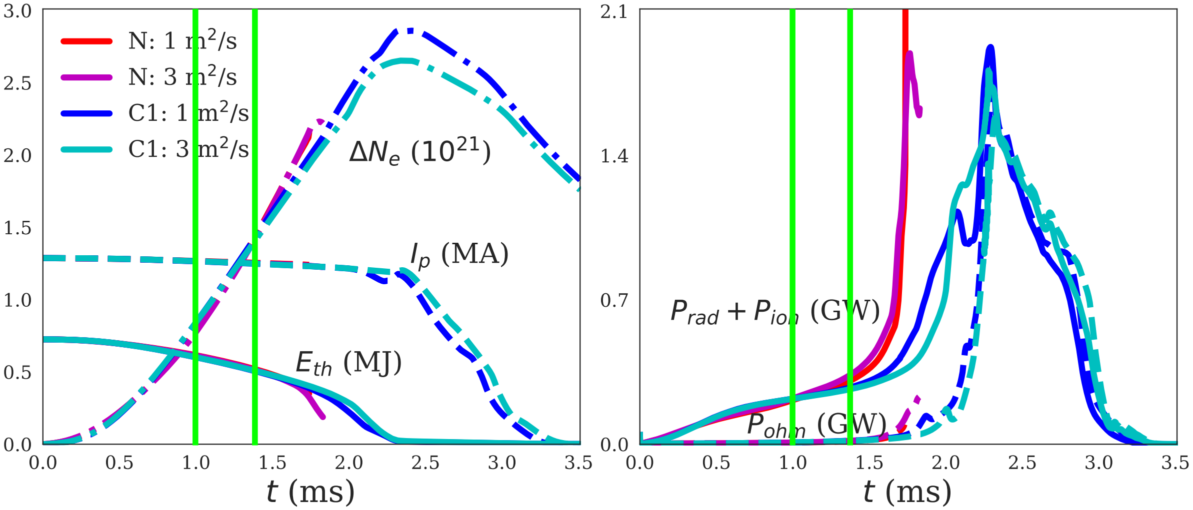
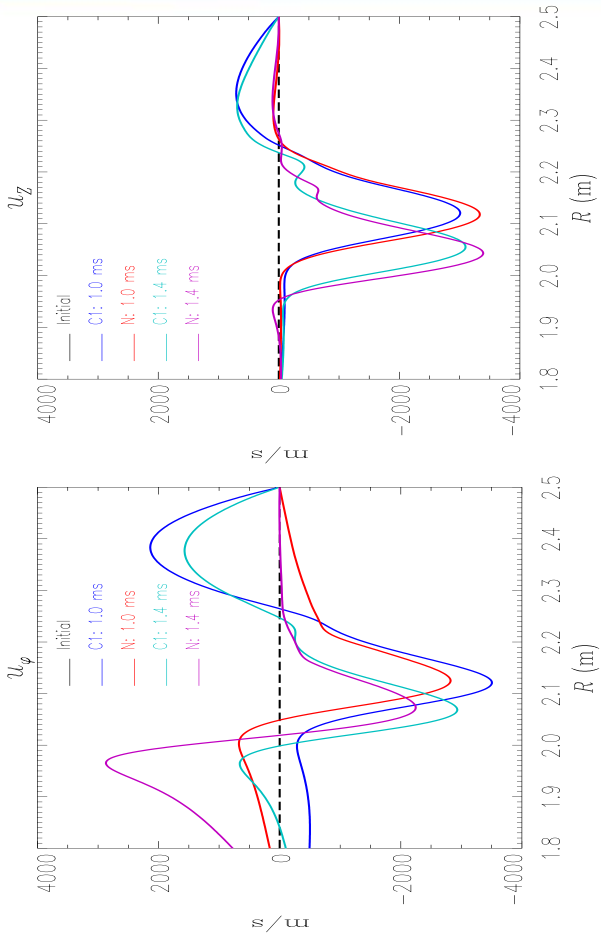
M3D-C1 and NIMROD are Seeing Very Different Flow Patterns

- **M3D-C1 no-flow boundary conditions were causing unphysical flows in simulations with large density sources**
  - First observed in 3D pellet benchmark
  - Subsequently seen in simplified tests
- **M3D-C1 observes open-field-line region (OFLR) flow is opposite sign of outflow from source**
- **NIMROD observes flow entrained with outflow from source**

Difference in 3D Pellet Benchmark Likely Caused by Flow

- **M3D-C1 seeing later radiation spike and coincident MHD instability onset**
- **Flow pattern strikingly different even before time traces diverge, especially in open-field-line region (OFLR)**





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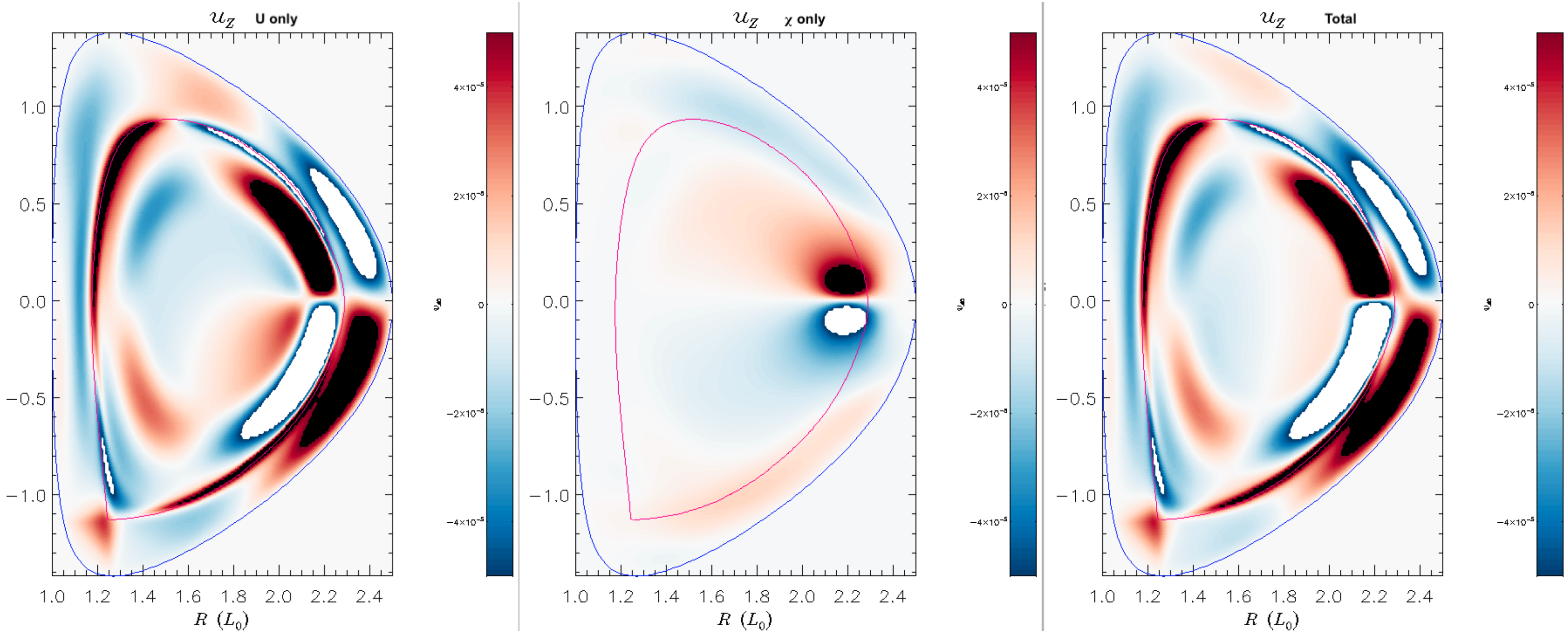
So With No-Slip and No-Normal Flow, Terms are Separately Zero

Flow Components For No-Slip



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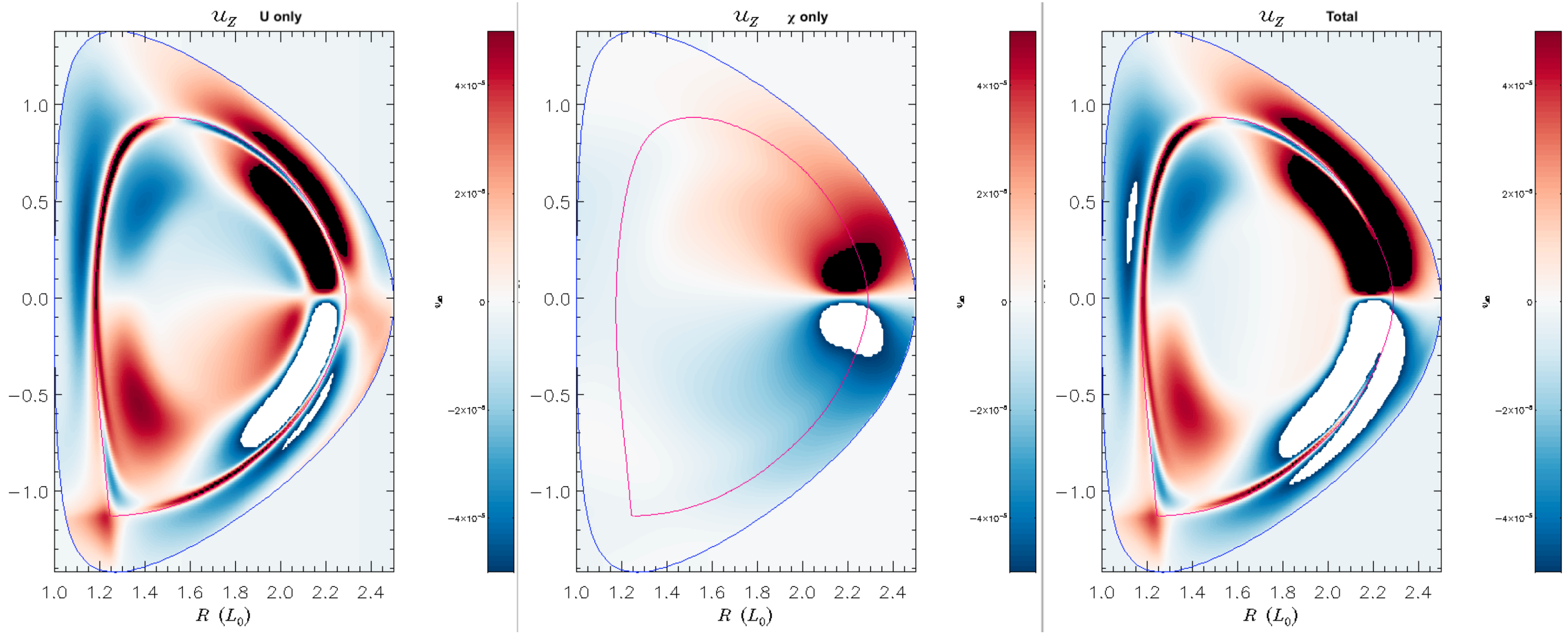
But They Shouldn't Be… Just Their Sum

Flow Components For Slipping



Fix In-Progress, But New Boundary Conditions are Unstable

- **New boundary conditions have been properly coded**
- **Summed condition on normal flow always causes numerical instability**
- **Summed condition on poloidal flow**
  - Can be stable, but not always
  - Requires stronger regularization to maintain reasonable values of χ