Progress on non-linear MHD simulations of ITER Shattered Pellet Injection

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Introduction & Overview

- Unmitigated disruption is **intolerable** for ITER.
- Shattered Pellet Injection (SPI) the present baseline scheme for disruption mitigation.
- While more simplified model useful, complicated interplay between MHD modes and the injected materials necessitates 3D non-linear simulation of SPI.
- Multiple numerical investigations are ongoing or planned concerning both the thermal quench (TQ) and current quench (CQ) mitigation by SPI involving **JOREK**, **NIMROD** and **M3D-C1** (*see talk by Lyons et al. for V&V details*).
- At present the works done focus on the **pre-TQ SPI**, with future possible investigations of post-TQ SPIs.

The JOREK mono- and dual-SPI simulation for ITER plasma with mixed species

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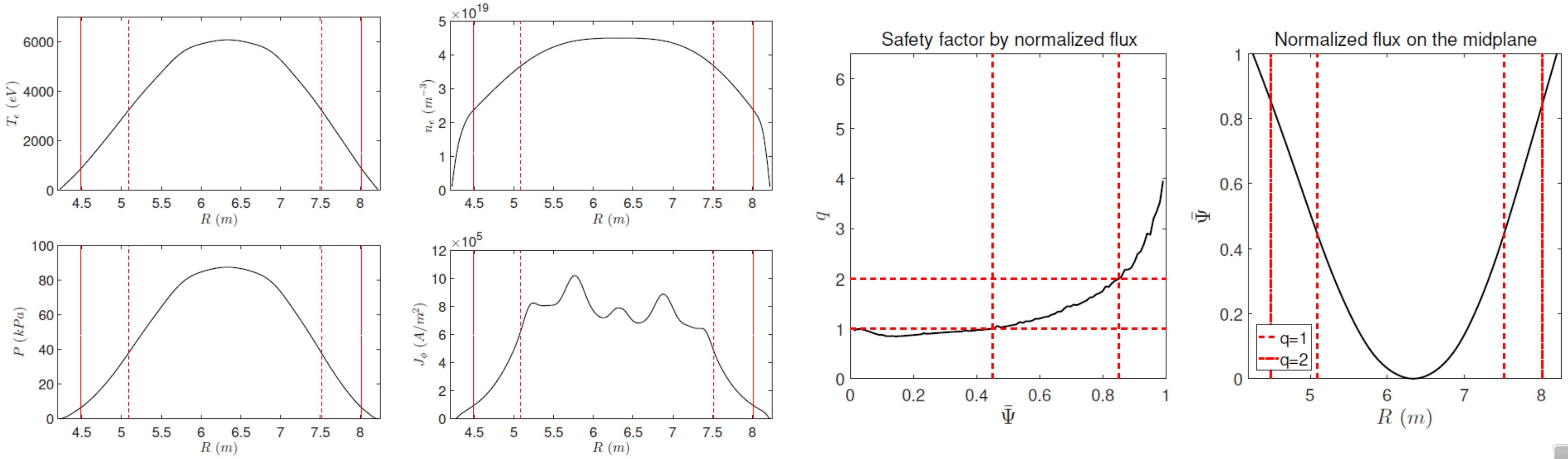
JOREK capability & limit

- JOREK uses the **reduced MHD** model for SPI simulation, all species are assumed to share the same velocity field.
- Ablation treated as density source around each individual fragment, its strength according to **NGS-like ablation law** calculated using local plasma parameter.
- The ablation cloud is **artificially elongated** along the toroidal direction due to limited harmonic resolution.
- Free choice of fragment size distribution.
- Spitzer η and Braginskii $\kappa_{\parallel}$, with a floor level for η to ensure resolution and a upper limit for $\kappa_{\parallel}$ to represent the flow limited conduction.
- Can either treat both electron and ion with a single temperature or treat them separately.
- Coronal equilibrium is assumed when treating impurity charge state distribution, a more realistic representation of the self-consistently evolving non-equilibrium charge state distribution is underway.

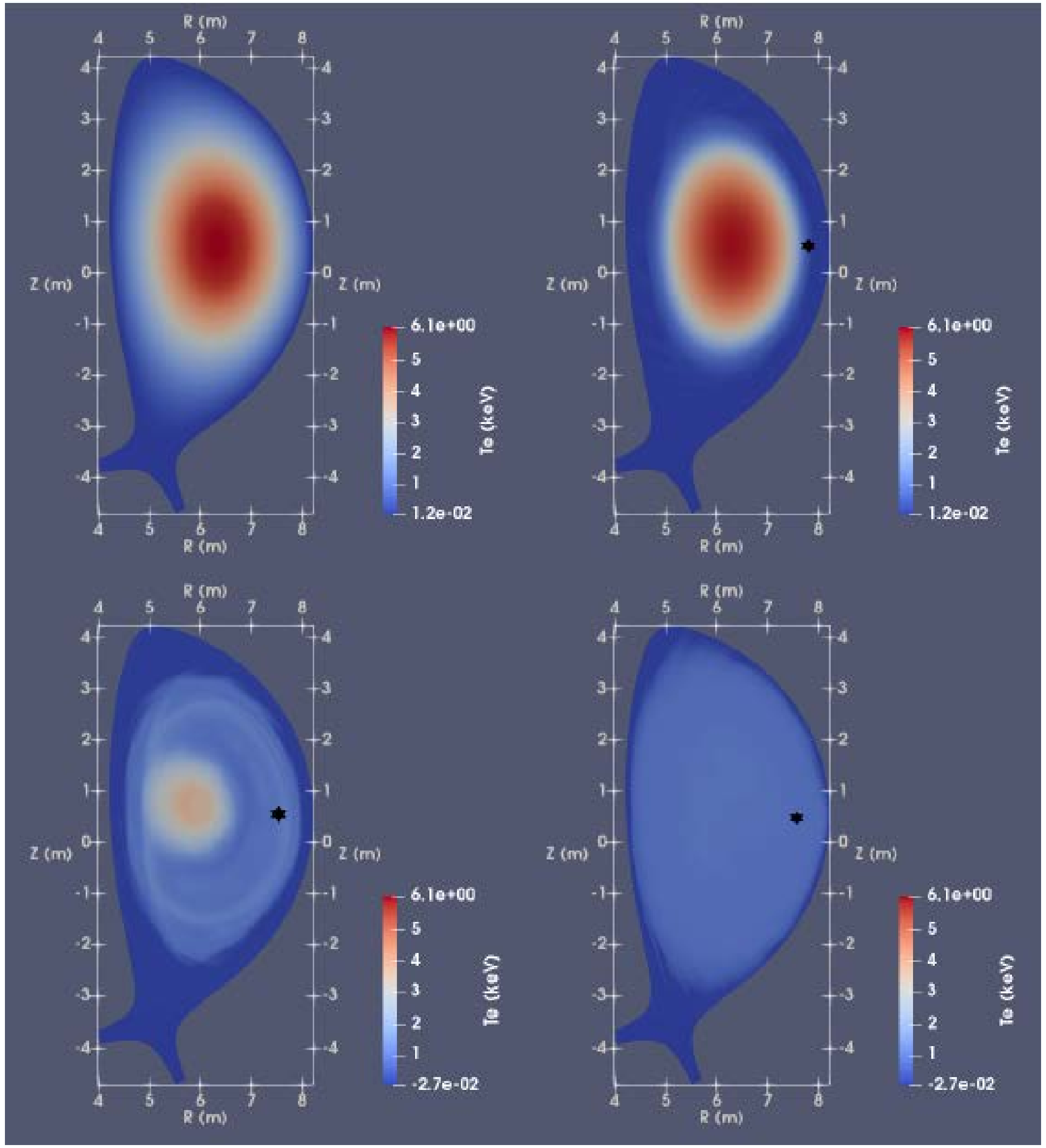
Target equilibrium

- An ITER $7.5MA/2.65T$ Hydrogen L-mode plasma is used as the target equilibrium ("Case 10"). The initial thermal energy is $33.3MJ$.
- Axis q_0 slightly above unity but with a weak reverse shear, meaning significant $q = 1$ surface.
- Numerical investigation indicate intrinsic 1/1 stability within our timescale of interest (probably due to low β).



Cooling & de-comfinement

- A $4 \times 10^{21}/3.6 \times 10^{22}$ **two temperature** neon/hydrogen SPI is used to demonstrate the profile evolution.
- The temperature profiles are shown for $0.00ms$, $2.67ms$, $3.50ms$(During the TQ) & $3.57ms$, respectively.
- Before the TQ, the temperature in the wake of the fragments are down to the order of 10 eVs, until the TQ occurs and the outgoing heat flux re-heat the plasma.



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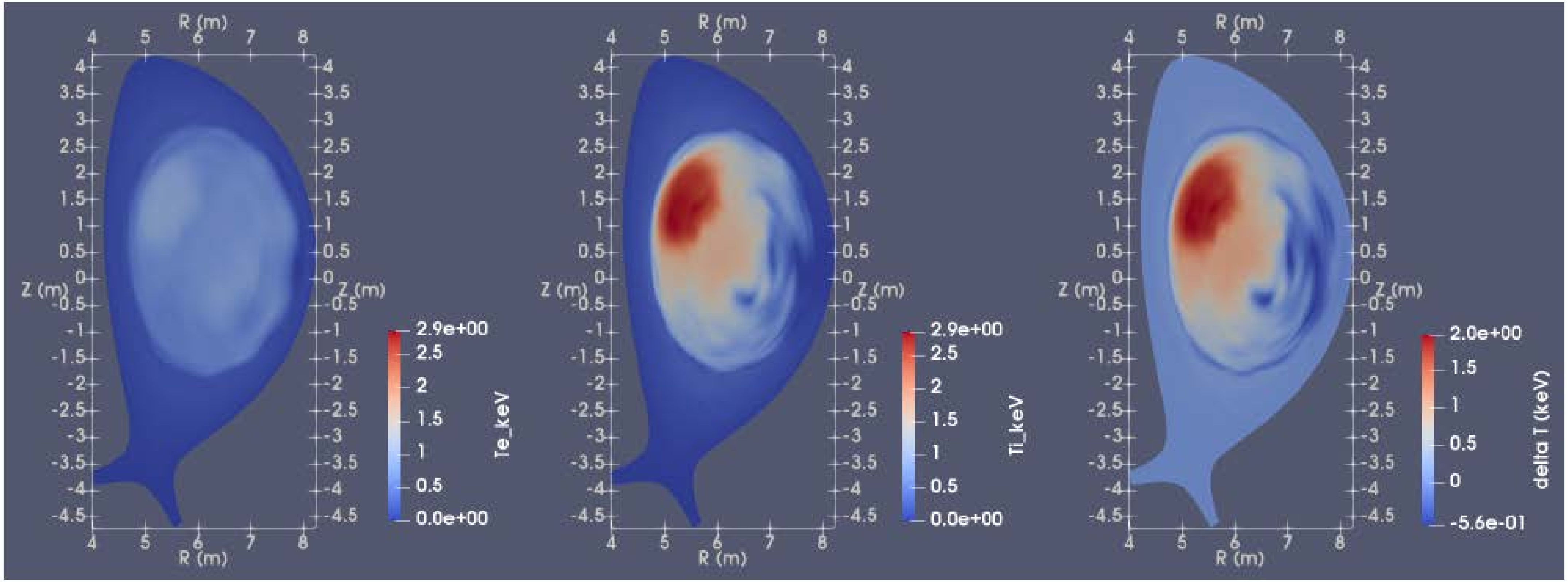
Electron & ion temperature deviation

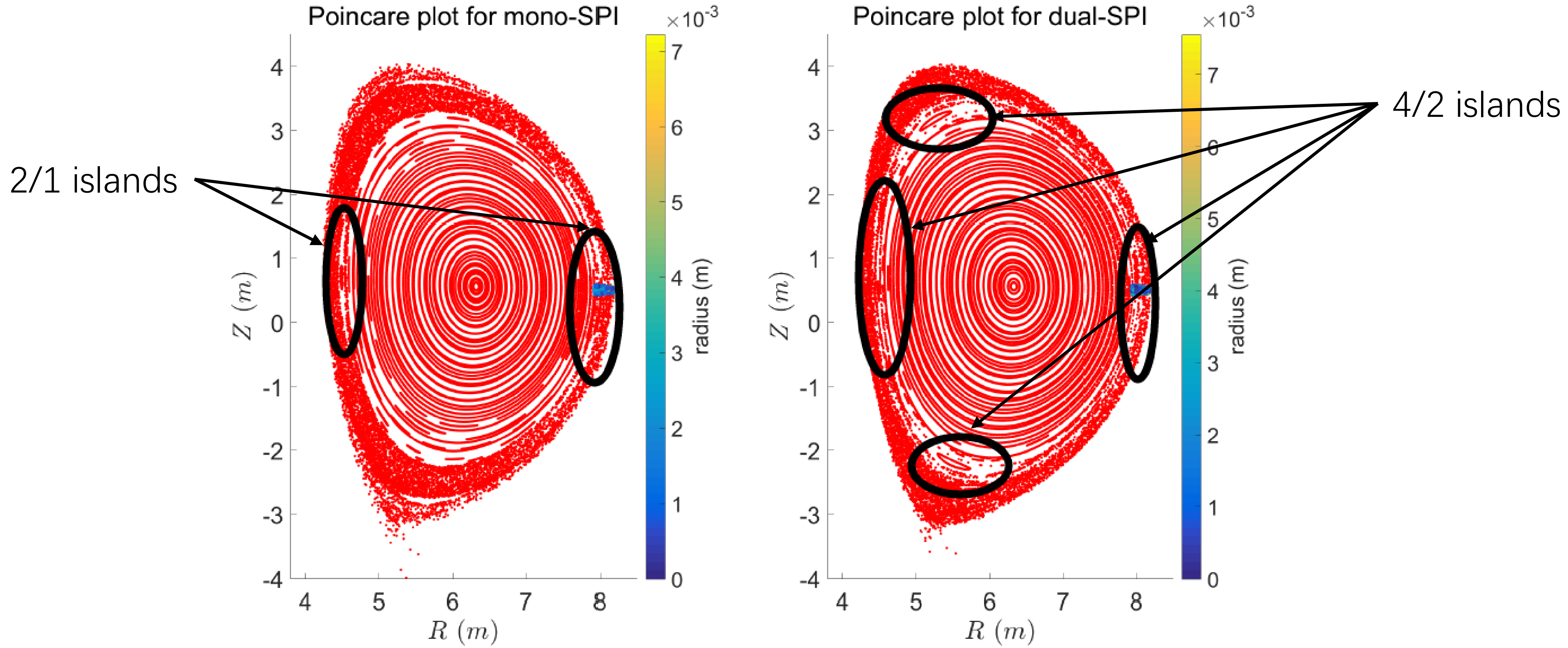
- Electron and ion temperature show strongest deviation right after the occurrence of the TQ.
- The parallel thermal conduction of the two species differs by a factor of the **square root of the mass ratio** for both Braginskii and flow-limited case.



The electron temperature, ion temperature and their difference during the TQ ($3.52ms$).

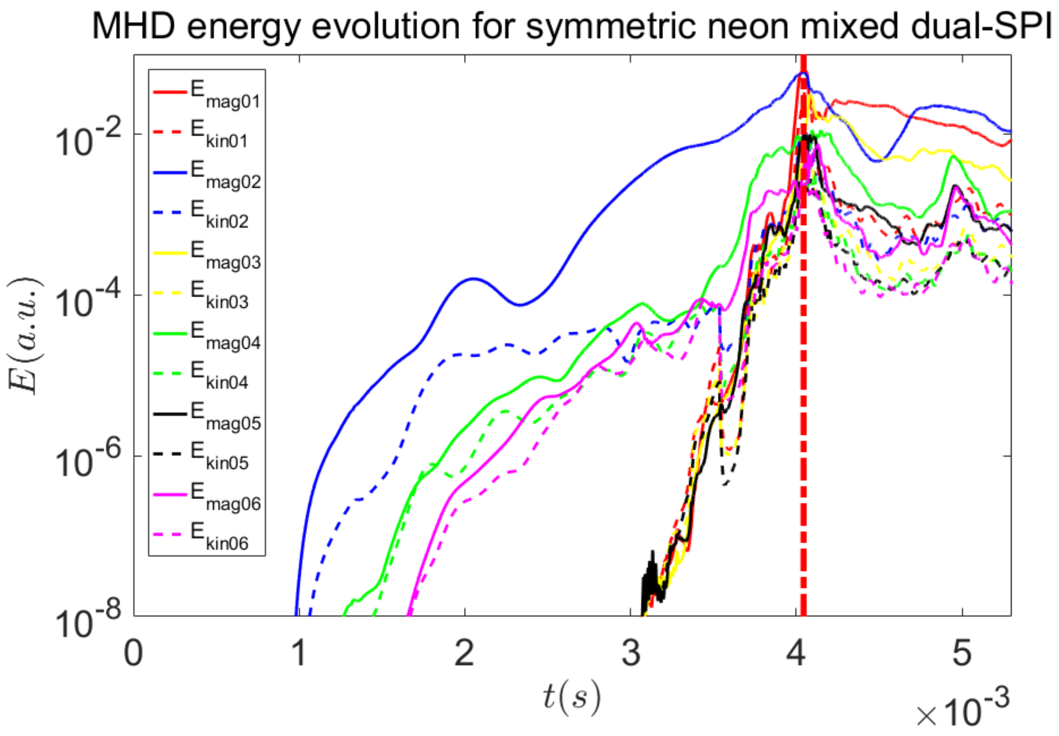
MHD excitation by mono- and dual-SPI

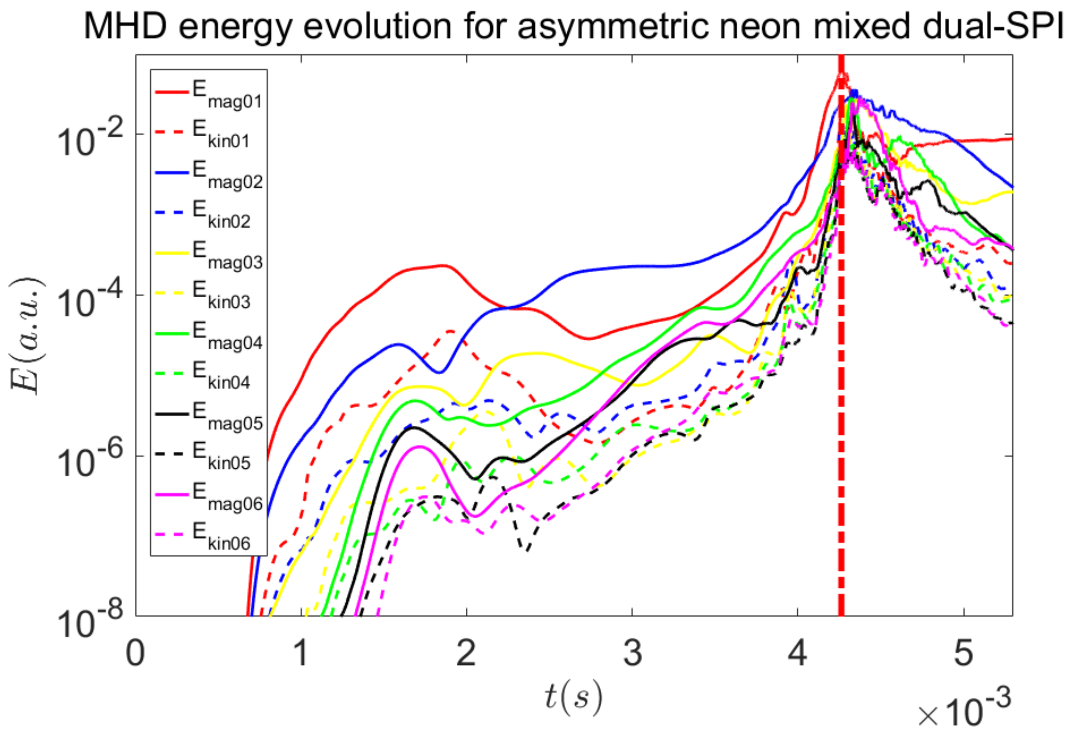
- **Symmetric dual-SPI excites higher harmonics** (n = 2) of magnetic modes compared with that of the mono-SPI.
- Indication that the **helical effect** plays a significant role here.



MHD response for dual-SPI

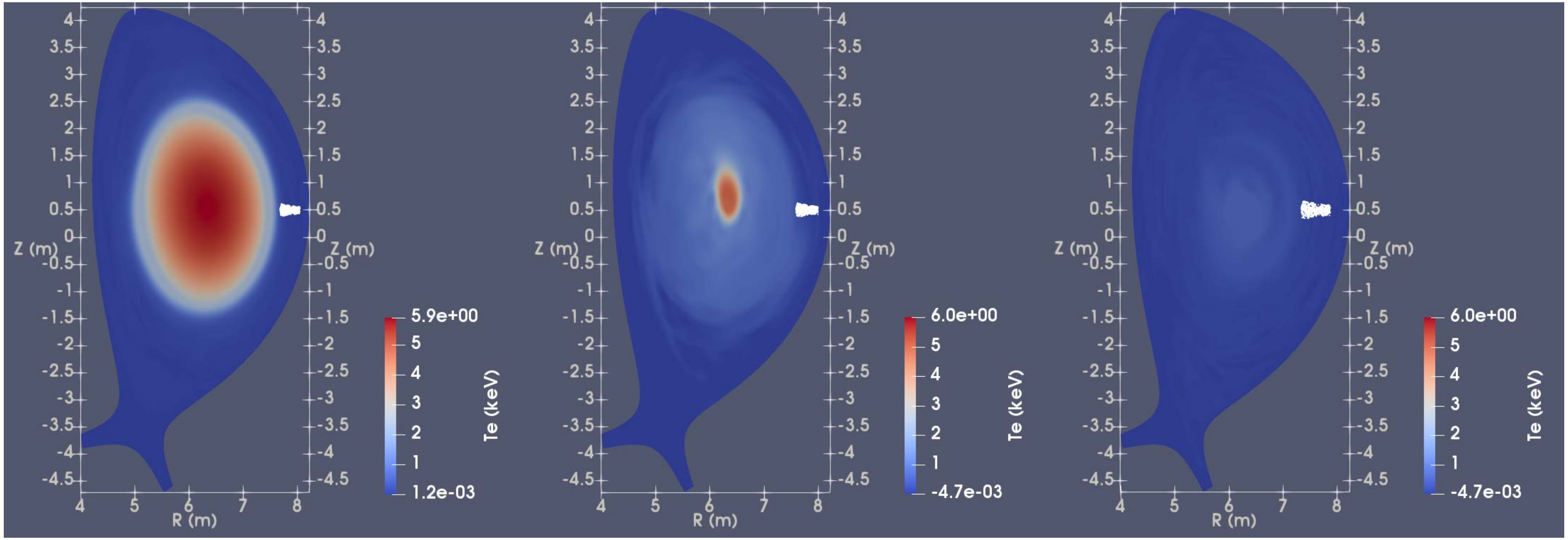
- For the **symmetric dual-SPI**, **even modes** dominate as would be expected.
- For the **asymmetric dual-SPI**, the **odd modes** dominate at beginning, even modes play a significant role later, both combined cause TQ.



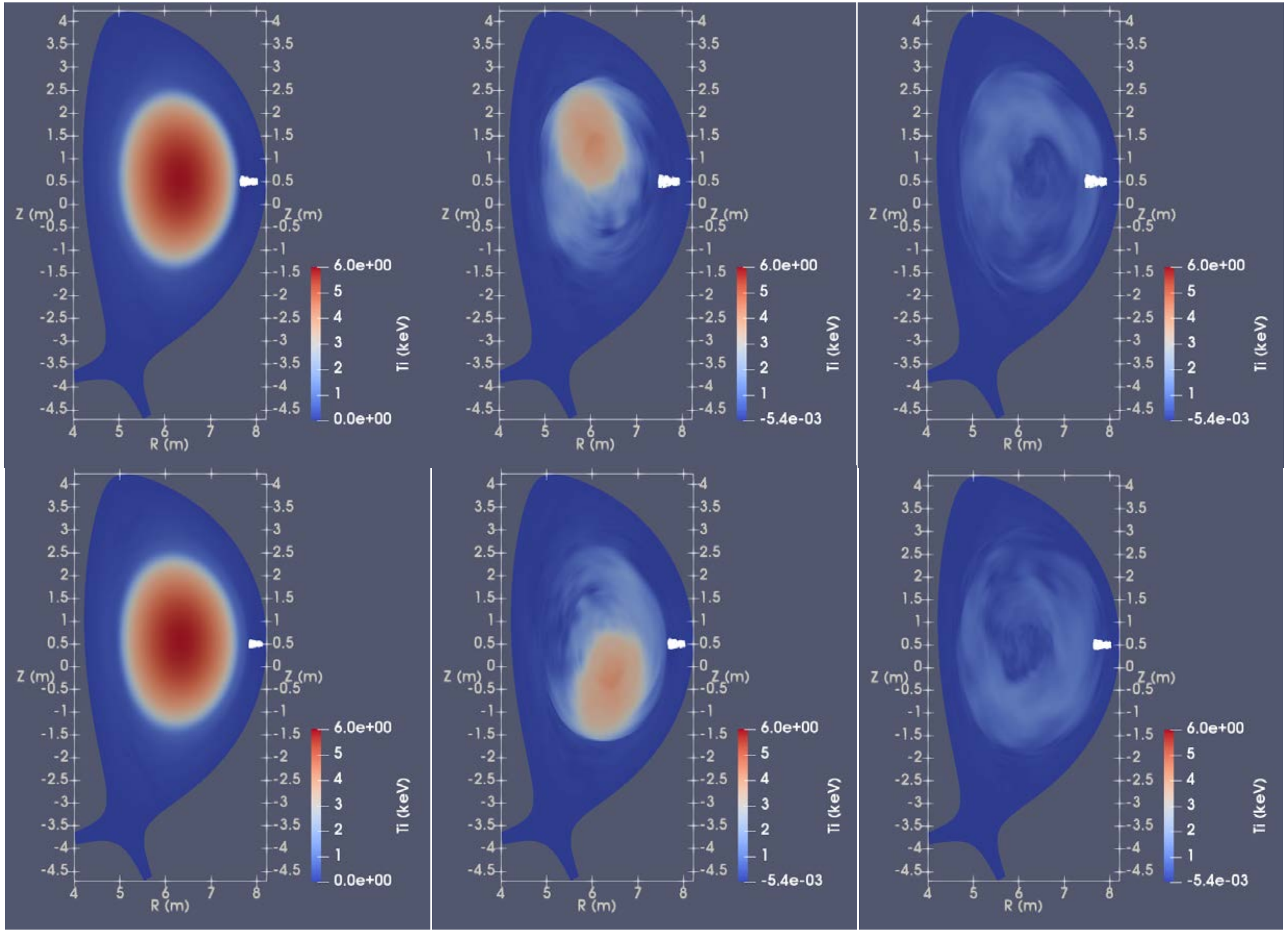


MHD response for symmetric dual-SPI

- The symmetric SPI: The core temperature collapse happens as fragments reach q=1 surface.
- The TQ seems to be dominated by even modes, **no significant 1/1 kink motion observed**.



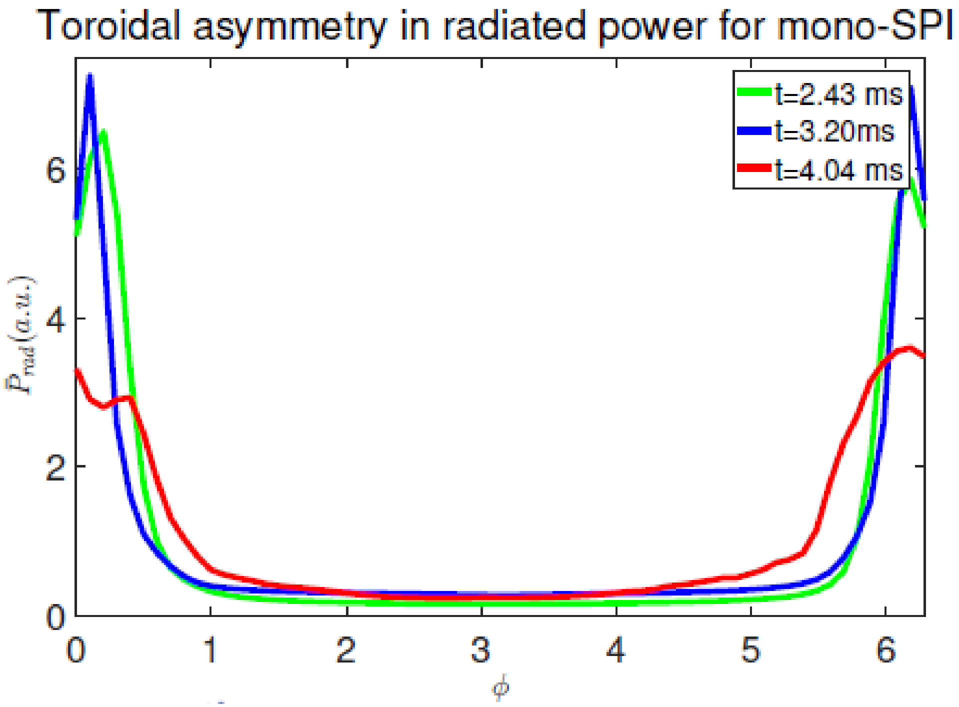
MHD response for asymmetric dual-SPI

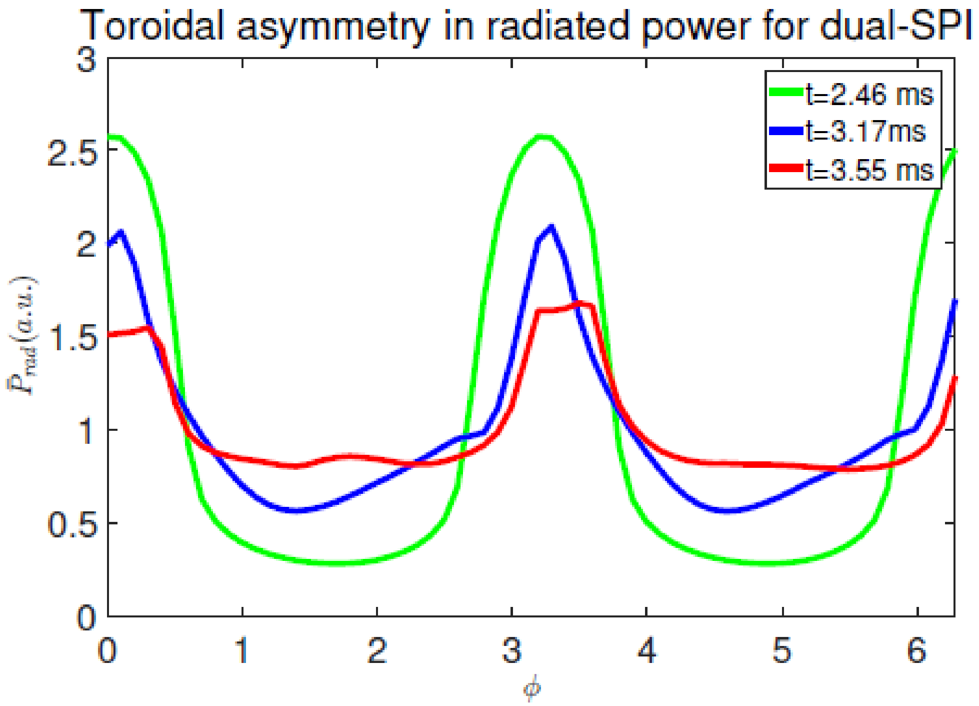


- The asymmetric SPI ($\phi = 0$ for the upper figures and $\phi = \pi$ for the lower): **Some 1/1 kink motion is observed** despite strong even mode amplitude.
- Better core penetration due to more obvious kink motion?

Radiation peaking factor

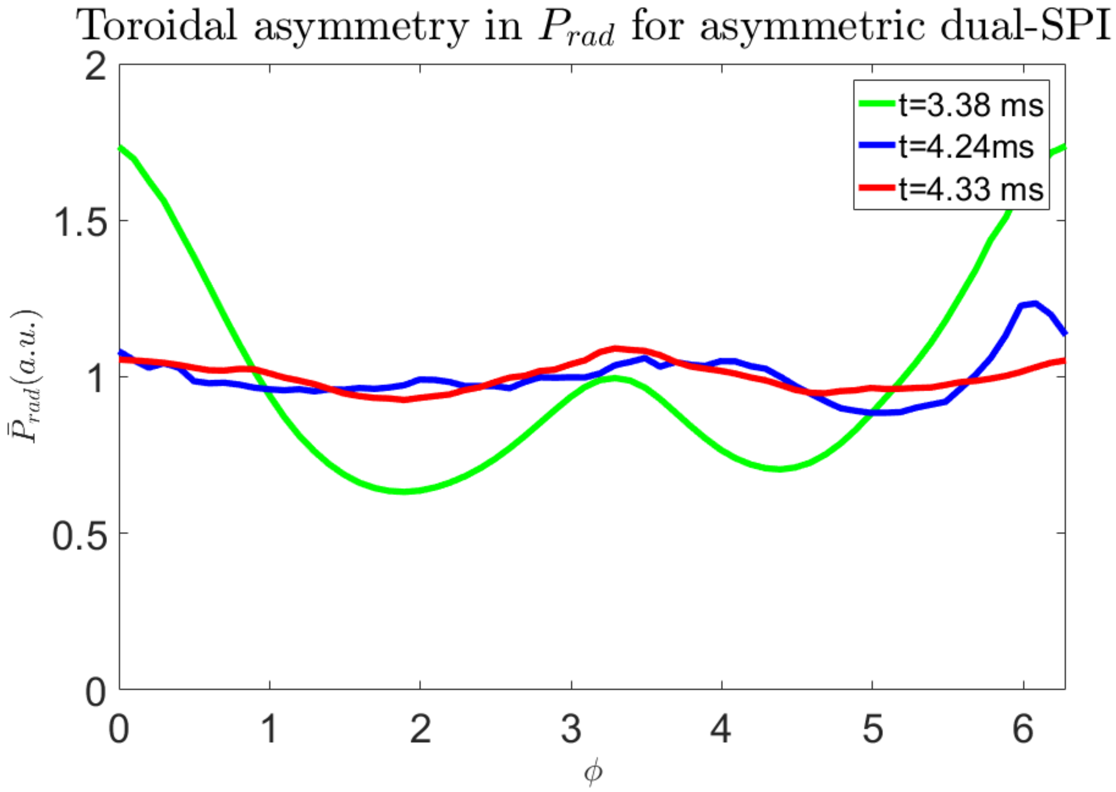
- Compare the radiation asymmetry for a mono-SPI and a dual-SPI with $2.6 \times 10^{22}/2.1 \times 10^{24}$ neon/hydrogen mixed SPI. Both dual-SPI injectors are located at the outer-mid-plane.
- The asymmetry is evidently mitigated by the dual-SPI configuration, although some toroidal asymmetry still persist.
- The asymmetry is artificially mitigated by toroidal elongation of impurity deposition which is Gaussian-like with half-width radian 1.





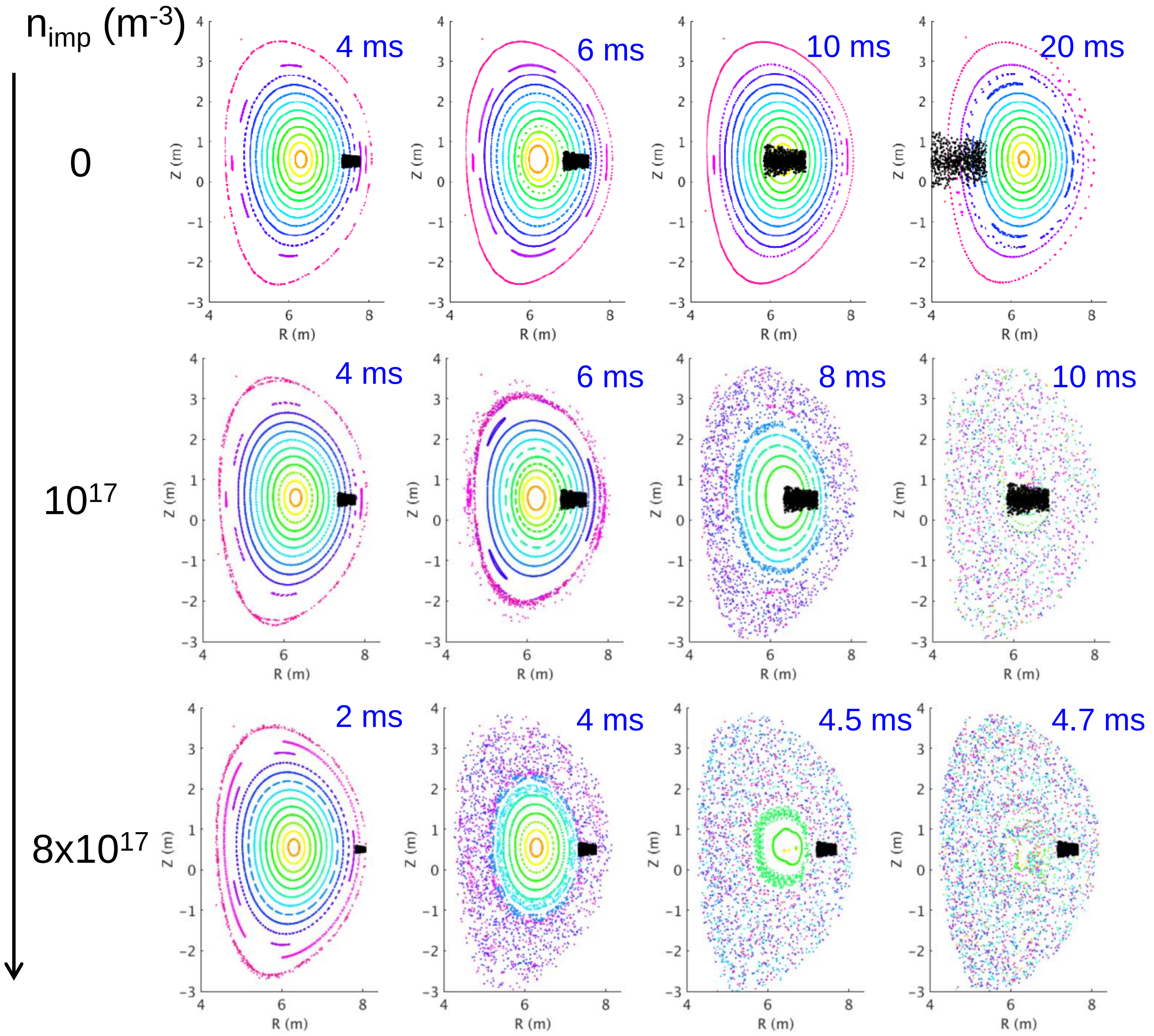
Radiation peaking factor

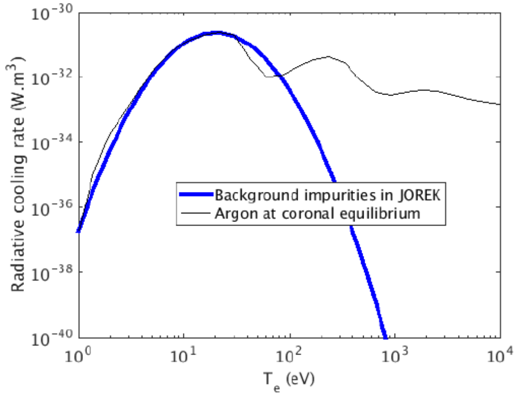
- The asymmetric dual-SPI is investigated by keeping a 1ms time difference between the two injection times.
- Despite stronger radiation peaking before the TQ, the radiation peaking during the TQ is sufficiently mitigated even for non-synchronized SPI.
- Further time difference may change this conclusion, need to look deeper.

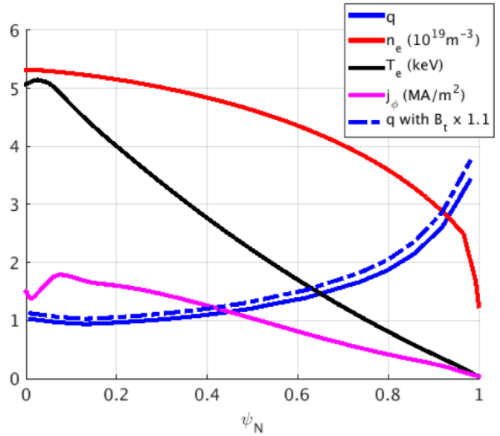


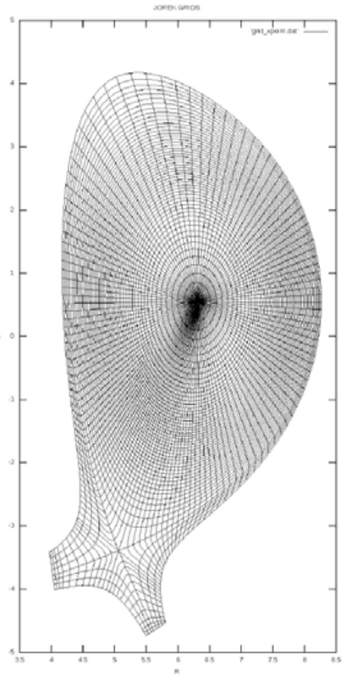
NOVEL INJECTION SCHEMES FOR ITER RUNAWAY ELECTRON SUPPRESSION

Plasma can be strongly diluted without causing an MHD crash… below a certain background impurity density



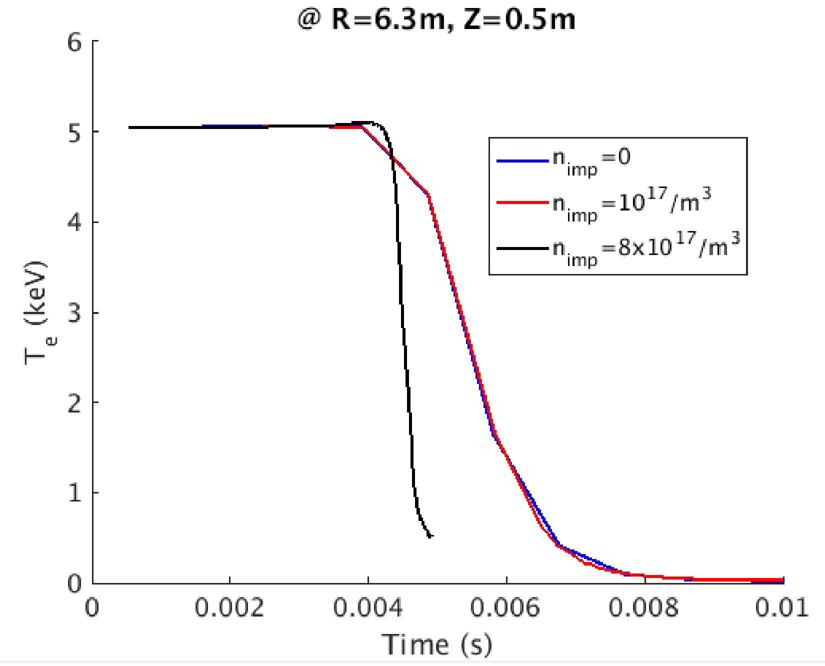


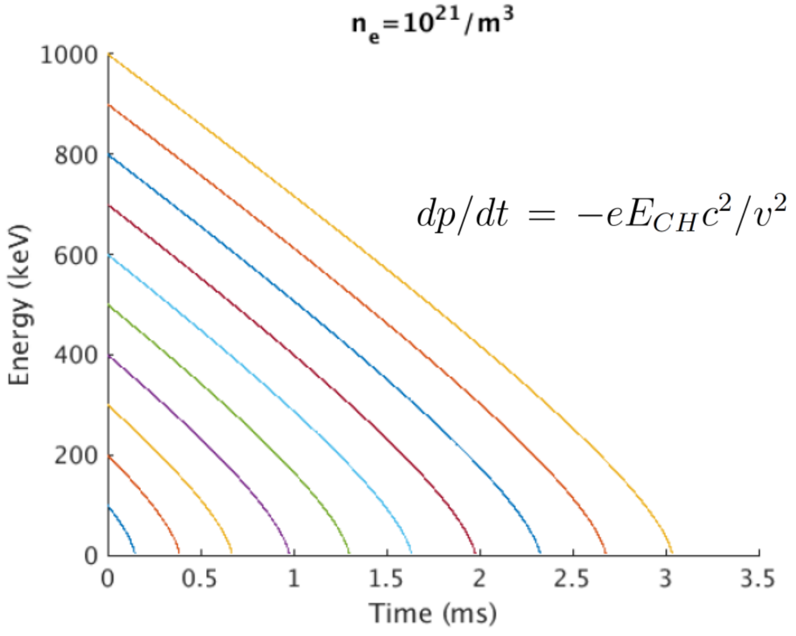




⇒ Motivates further studies with a more realistic description of background impurities

Effect on hot tail generation





- At low n_{imp}, dilution cooling in the core takes place on a multi-ms timescale, allowing the electron distribution to remain Maxwellian
  - Note that $E < E_{CH}$ should hold as long as $T_e > \sim 1$ keV
- Hot tail generation during the TQ is very sensitive to τ_e/τ_{TQ}
- Electron collision time $\tau_e \sim T_e^{3/2}/n_e \sim D^{-5/2}$, where D = dilution factor
- TQ duration (radiative collapse) $\tau_{TQ} \sim 1/n_e \sim 1/D$

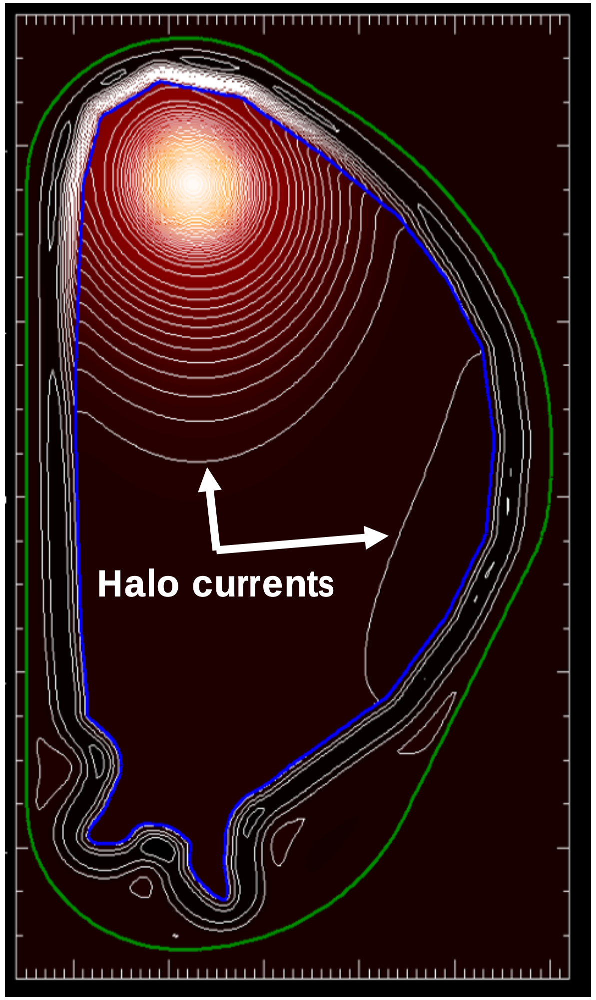
$\Rightarrow$ $\tau_e/\tau_{TQ} \sim D^{-3/2}$, i.e. dilution may dramatically reduce hot tail generation (*see talk by Nardon et al.*)

M3D-C1 status and plan for ITER simulation

GENERAL ATOMICS

M3D-C1 is Prepared to Model ITER SPI Scenarios with Unique Capabilities (Lyons, Clauser, Ferraro, & Jardin)

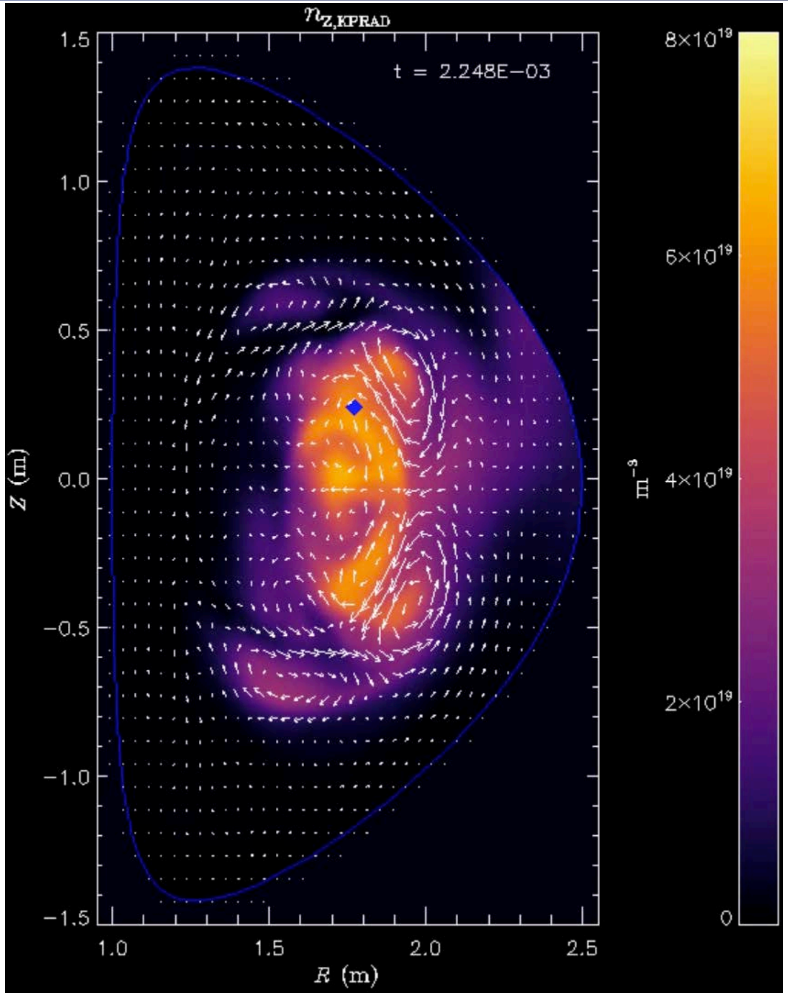
- **M3D-C1 offers a unique collection of capabilities**
  - Solves full, extended MHD equations
  - Toroidal finite elements can be packed to resolve small pellets efficiently
  - Time-dependent, coronal, non-equilibrium model evolves radiation & each charge state
  - Wall model allows arbitrary thickness, anisotropic resistivity, and halo currents
  - Runaway electron model self-consistent with MHD evolution is under development
- **ITER modeling is more challenging than present devices, but no technical hurdles remain**
  - Recent code improvements have allowed M3D-C1 SPI simulations of thermal quench and current quench (*see talk by Lyons et al.*)
  - M3D-C1 already performs high-fidelity ITER modeling of VDEs (*see talk by Jardin et al.*)



Contours of poloidal current during ITER VDE with two-layer resistive wall Courtesy of C. Clauser

M3D-C1 modeling of ITER SPI scenarios will begin in the near future

- **Appropriate equilibria have been obtained**
- **Will explore a variety of configurations**
  - Pellet size, speed, and composition
  - Multiple, simultaneous injection
  - Plasma scenarios
- **Work will be**
  - Guided by the needs of the DMS Task Force
  - Synergistic with ongoing NIMROD modeling



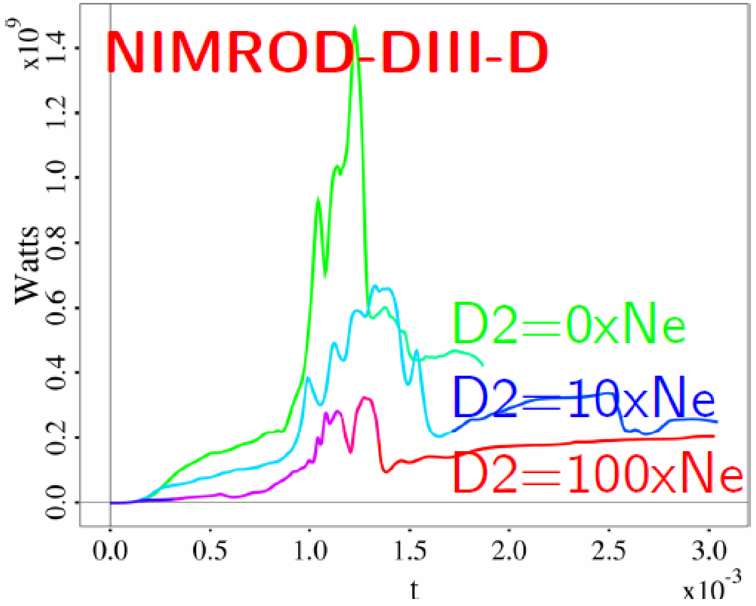
Impurity density and poloidal flow field just after thermal quench in DIII-D SPI
Courtesy of B.C. Lyons

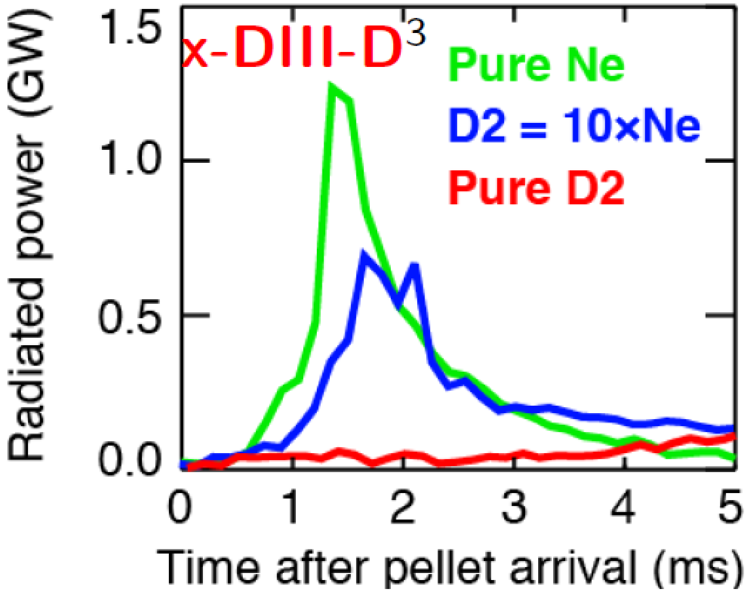
GENERAL ATOMICS

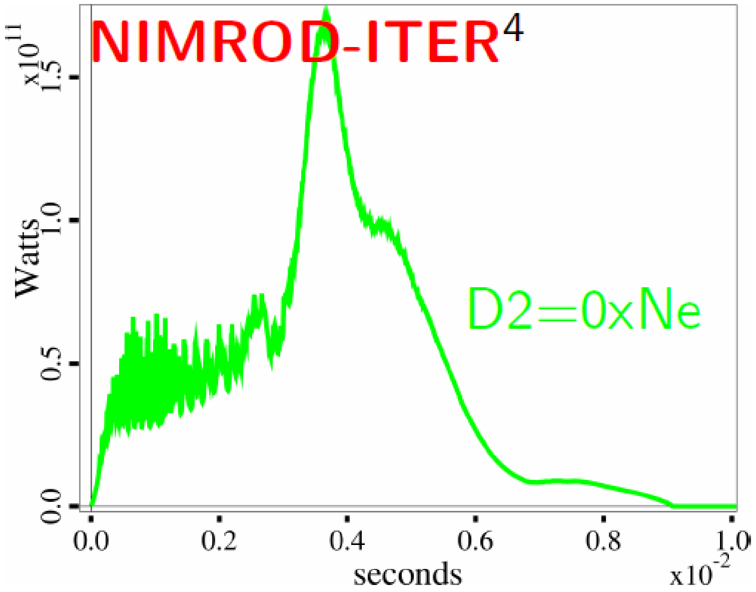
NIMROD status and plan for ITER simulation

SLS2 Consulting

NIMROD D2 Fraction Validation and ITER



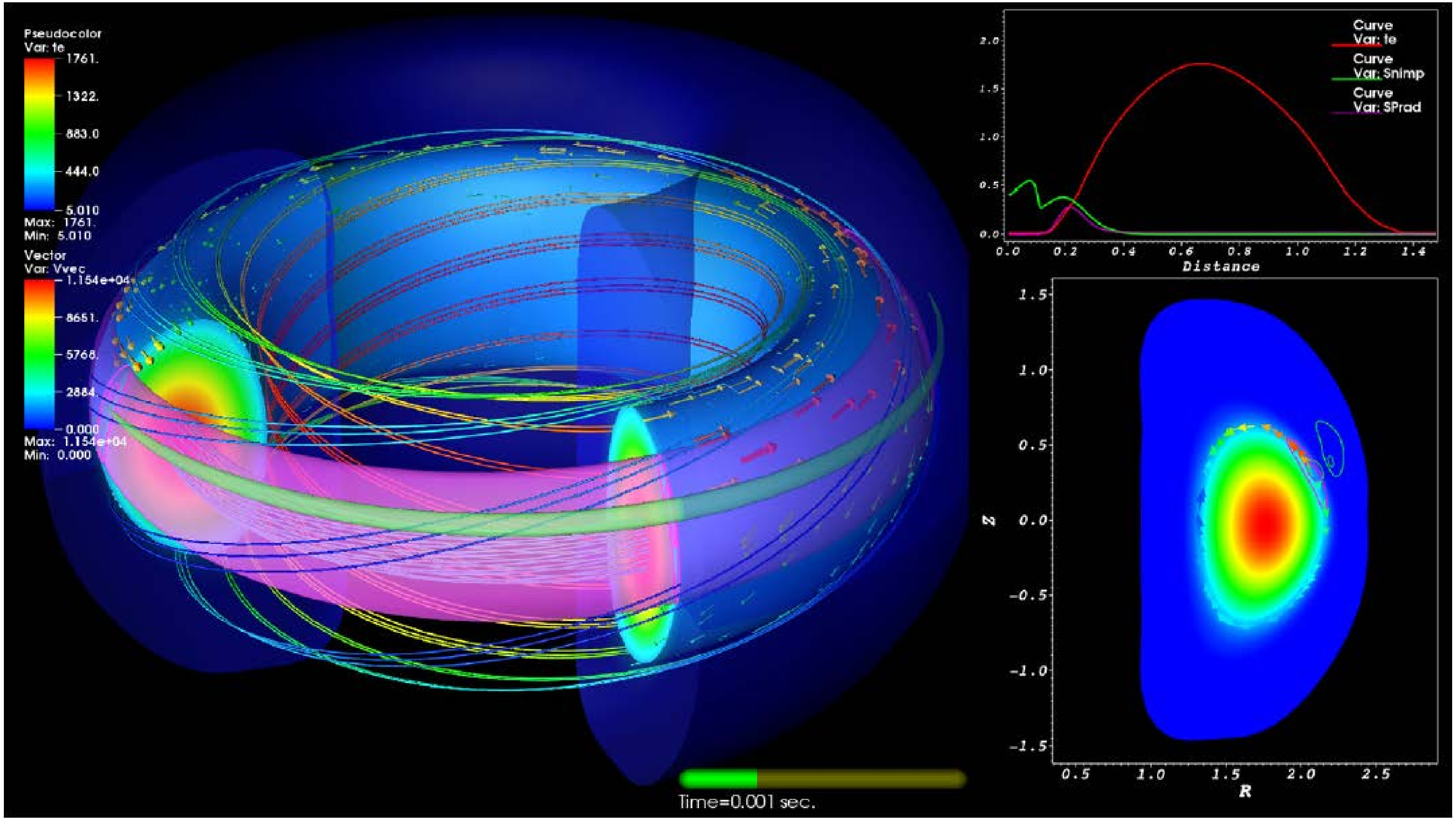




- single upper injector, v=200ms/, dϕ=0.10, visc=250m/s^2, D2=[0x,10x,100x]Ne
    - τ_{TQ}=[1.27,1.57,1.35]ms, radiation fraction [58,50,14]%
- very good agreement with DIII-D experiment (Shiraki PoP 2016)
- ITER pure Ne SPI shows many similar features as DIII-D
    - anticipate DIII-D results to extrapolate to ITER
    - higher fidelity ITER-SPI simulations in progress

[3]Shiraki PoP 2016
[4]C. C. Kim PoP 2019

NIMROD ITER simulation



3D visualization of mixed deuterium/ neon SPI thermal quench simulation showing parallel transport driven by ablating fragment "cradles" quenching plasma core for benign thermal quench.

C. C. Kim et al., Phys. Plasmas 26, 042510 (2019)

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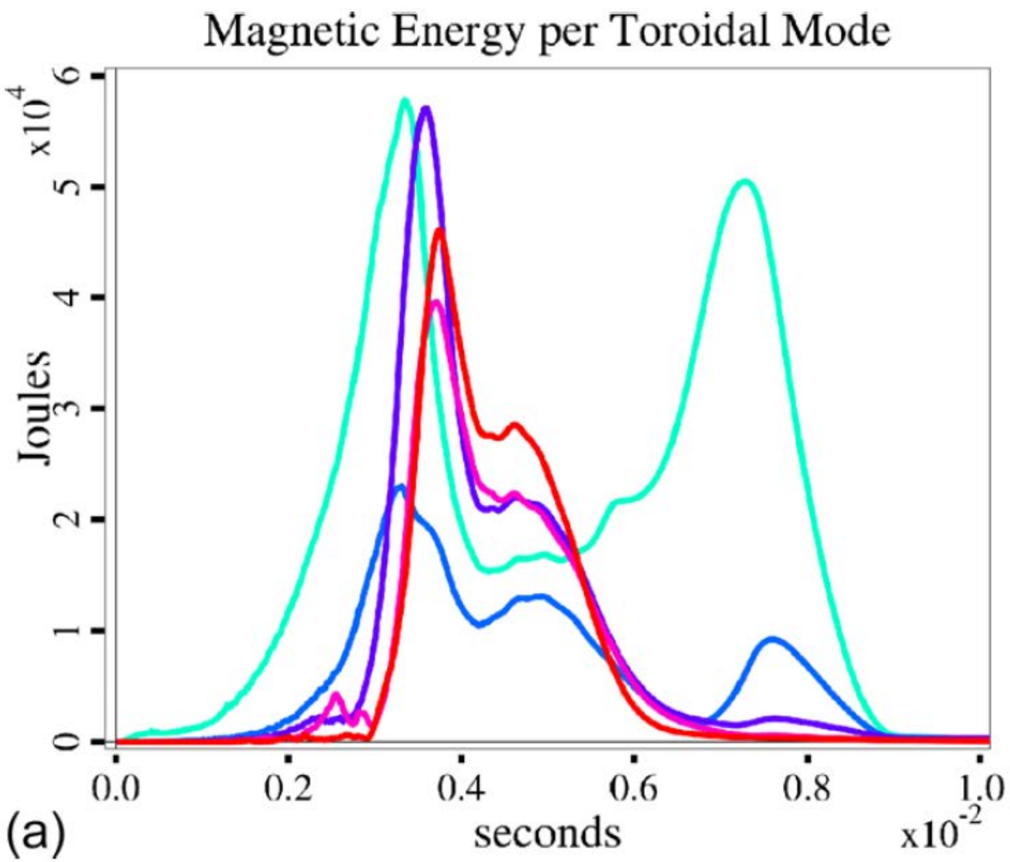
MHD response during ITER simulation with pure neon SPI

The magnetic energy spectrum for the ITER simulation shows **broad spectrum activity associated with the radiation spike** around t = 4.0ms. In particular, large amplitude odd modes n = [1 (light blue), 3 (dark blue), 5 (red)] indicate a kink instability terminates the thermal quench. Closer examination of the magnetic energy spectrum reveals many interesting features that will be deferred for future studies with higher fidelity simulations. This work focuses on the gross features of the SPI simulations and validation.



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Summary & Outlook

- JOREK simulation of both mono- and dual-SPI into ITER L-mode plasmas have been carried out with the two temperature model.
- The MHD destabilization mechanism is in accordance with previous understanding. **The MHD behavior correlates with the injection configuration in terms of symmetry.**
- Short time difference between injectors cause remarkable changes in the dominant MHD response.
- **The toroidal radiation peaking factors remain mitigated even with asymmetry dual-SPI.**
- D2 SPI simulation found possibility of strongly dilute the plasma before incurring the TQ, providing a scheme for suppression of hot-tail generation

Summary & Outlook

- JOREK **non-equilibrium description** of impurity charge state distribution is underway. Continue to look into multiple injection scenarios. Working on treating the **hot-tail electron contribution** to the ablation rate properly as well as a **non-local ablation law**.
- M3D-C1 provides opportunity **to truly resolve the ablation cloud toroidally**, as well as **realistic wall coupling** and **accurate description of the impurity radiation**. Future development of **self-consistent runaway modelling** is promising. Will explore a variety of configurations.
- NIMROD has conducted preliminary **ITER H-mode pure neon simulation** with **non-equilibrium** impurity charge state treatment after the D2 fraction validation, and more high fidelity ITER simulations are underway. **Broad spectrum MHD activity as well as strong kink motion** are found to play significant role in the quenching process (similar observation in JOREK).

Backup Slides

NIMROD's Impurity Modified Single Fluid Resistive MHD Equations

- $\dfrac{\partial n_\alpha}{\partial t} + \nabla \cdot (n_\alpha \mathbf{V}) = \boxed{S_\alpha} + \nabla \cdot D \nabla n_\alpha$
  - $\alpha =$ ions(i) and impurities(Z) (*including neutral ions and impurities*)
  - S_α source and sink due to ionization and recombination
  - electron(e) density from quasi-neutrality
- $\rho \left(\dfrac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p$
  - $\rho = m_i n_i + m_e n_e + \boxed{\sum_Z m_Z n_Z}$ $\quad p = n_t T \quad n_t = n_i + n_e + \boxed{\sum_Z n_Z}$
- $\dfrac{n_t}{\Gamma - 1} \left(\dfrac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = -p \nabla \cdot \mathbf{V} - \nabla \cdot \mathbf{q} + \boxed{Q}$
  - single temperature, $T = T_i = T_e = T_z$, assumes instant thermalization
  - heat flux $\mathbf{q}$ parameterized by constant $\chi_\parallel$ and $\chi_\perp$
  - Q includes Ohmic heating and loss due to ionization, recombination and radiation
- $\dfrac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \qquad \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \qquad \mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J}$
  - temperature dependent Spitzer resistivity $\eta(T)$ with high T cutoff

Particle Based SPI Model Provides Discrete Moving Source of Neutrals

1. **does not** resolve SPI fragment, assumes point particle of radius r_f with velocity $\vec{\mathbf{v}}_f$
   - **fragment time-of-flight: $\tau^{tof} = L_{axis}/|\vec{\mathbf{v}}_f|$ is key time scale**
2. **does** resolve ablated cloud
   - Gaussian circle in poloidal plane and vonMises toroidal direction ϕ
     - $S(\phi|\mu,\kappa) = \dfrac{e^{\kappa\cos(\phi-\mu)}}{2\pi I_0(\kappa)}$, centered at μ, $\kappa = 1/(2\pi \times d\phi)^2 \sim 1/\sigma^2$
   - ablated cloud computed from mass ablation function $G(n_e, T_e, r_f, X)$ *(P.Parks)*
3. after deposition, KPRAD[5] based ionization/radiation subroutines takes over
   - same as NIMROD Massive Gas Injection[6]
4. particle based SPI model is flexible and easy to modify
   - easy to apply forces to fragments and add additional injectors

Flexible particle based source model applicable to many applications:

e.g. shell pellet, pellet fueling, ELM pacing, molecular beam, Li droplets

[5] D. G. Whyte, *GA Report* **A22639** 1997

[6] V. A. Izzo, *NF* **46** 2006