Exploring 3D effects in runaway electron impacts in SPARC using HEAT

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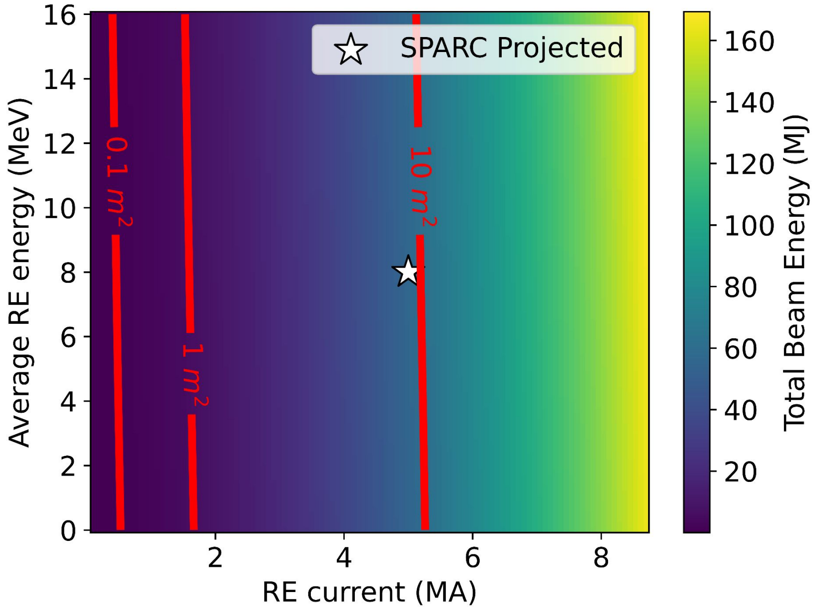
Introduction

Damage from RE impacts could be worse in SPARC than any previous machine

- Damage is largely related to energy density of strike
  - Depends on beam energy and wetted area
  - 3-5 MJ/m^2 melts tungsten
- Energy deposited includes kinetic and magnetic energy proportional to I^2_{RE}
- SPARC I_P = 8.7 MA
- RE beams could theoretically have 10s of MJ of energy

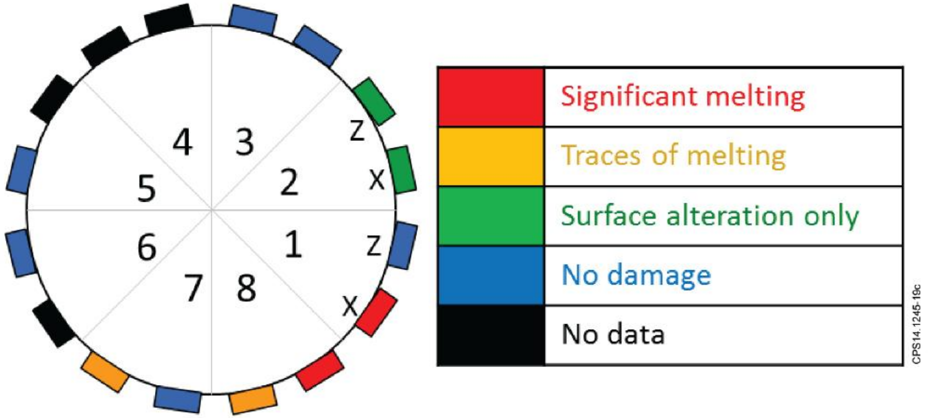


[Lehnen JNM 2009]

[Tinguely NF 2021]

RE impacts are fundamentally 3D events

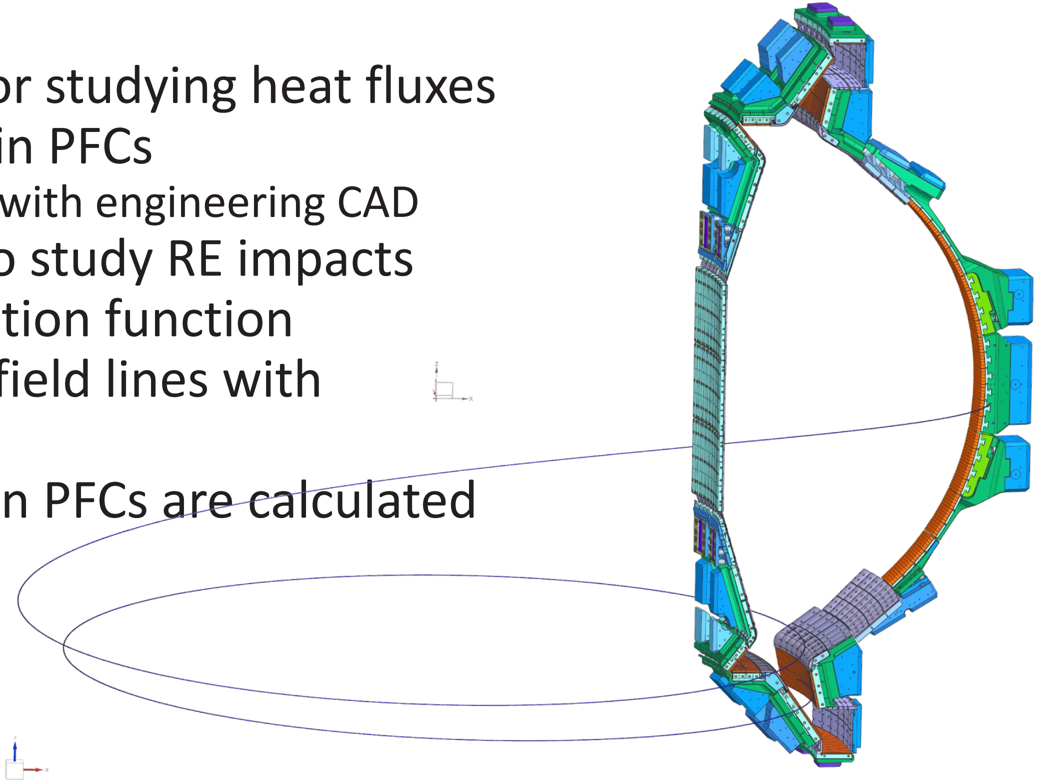
- Damage from REs tend to be toroidally asymmetric
  - Seen across many machines
- Likely due to
  - 3D MHD effects
  - Misaligned PFCs



JET RE toroidal damage profile [Reux NF 2015]

The HEAT RE module has been developed to study these impacts

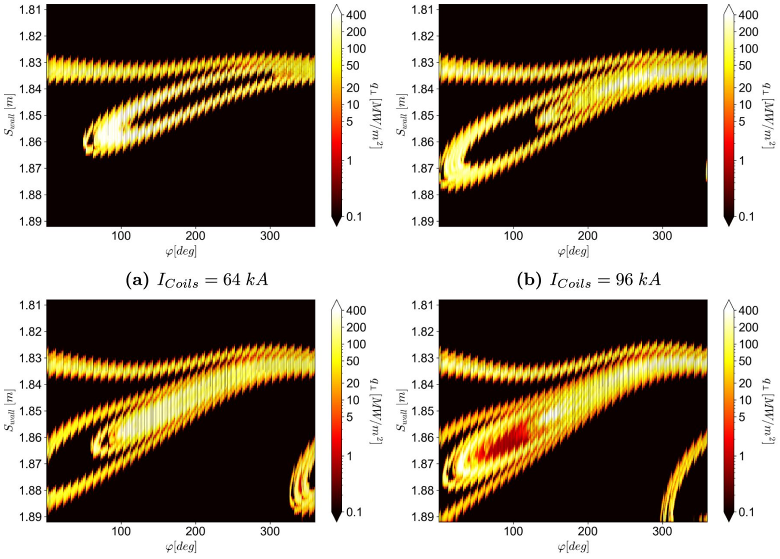
- HEAT is a simulation tool for studying heat fluxes and temperature changes in PFCs
  - Combines plasma physics with engineering CAD
- RE module builds on this to study RE impacts
- User inputs the RE distribution function
- REs are tracked, following field lines with corrections from drifts
- Intersections/heat fluxes on PFCs are calculated



[Looby FST 2022]

Goal of this work: predict SPARC impacts using 3D fields in the HEAT RE module

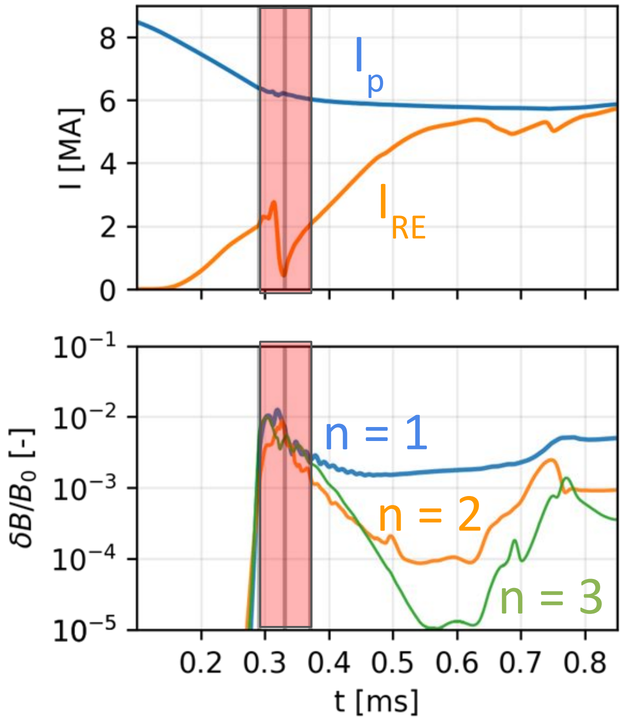
- HEAT has 3D field capabilities [Wingen NF 2025, Scotto d'Abusco NF 2025]
- This has been used to explore effect of error fields on PFC heat fluxes
- RE 3D fields can be a bit more complicated



(a) $I_{Coils} = 64\ kA$
(b) $I_{Coils} = 96\ kA$
(c) $I_{Coils} = 128\ kA$
(d) $I_{Coils} = 160\ kA$

3D field simulations

We started with a stochastic loss event simulated by M3D-C1

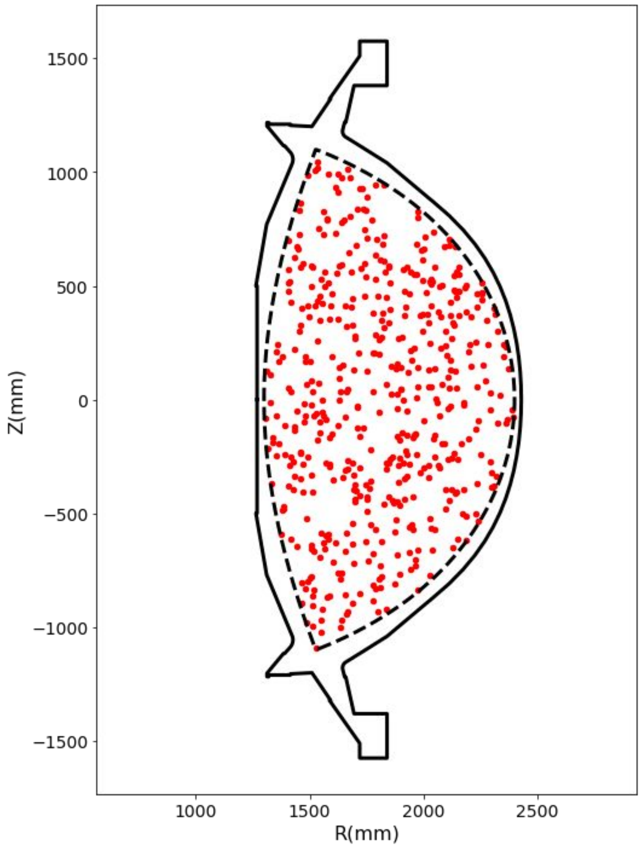


- M3D-C1 Nonlinear 3D simulation with neon injection and REs
- We are focusing on the loss period
  - ~2 MA of RE current is lost
- High MHD activity
  - Stochastic fields → difficult to model

[Jardin comp.sci.discov 2012, Datta NF 2026]

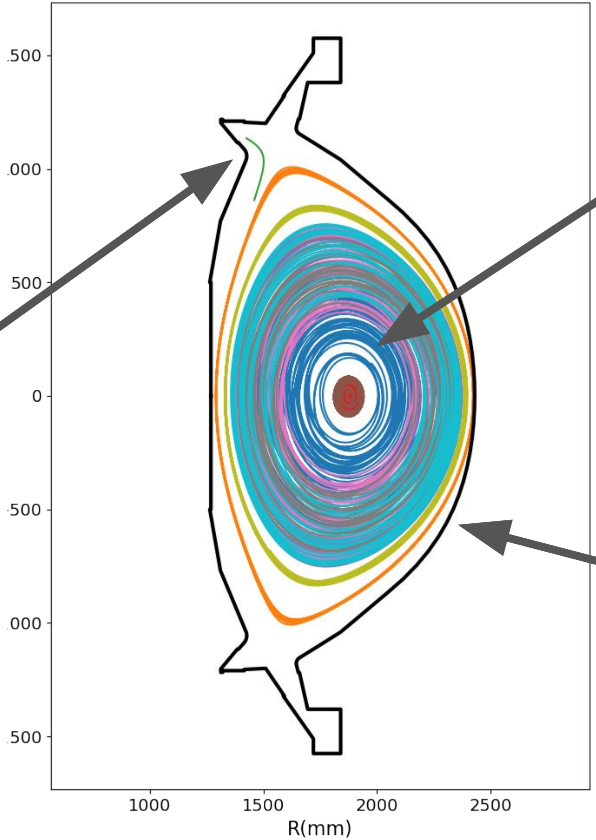
All simulations use the same particles

- 1 MeV (unless otherwise specified)
- No perpendicular velocity
- Particles are started within the LCFS of primary reference discharge
  - The starting point for M3D-C1 simulations
- Run for 2 µs



Preliminary simulations did not show many losses

Particles that are lost are lost to the divertor

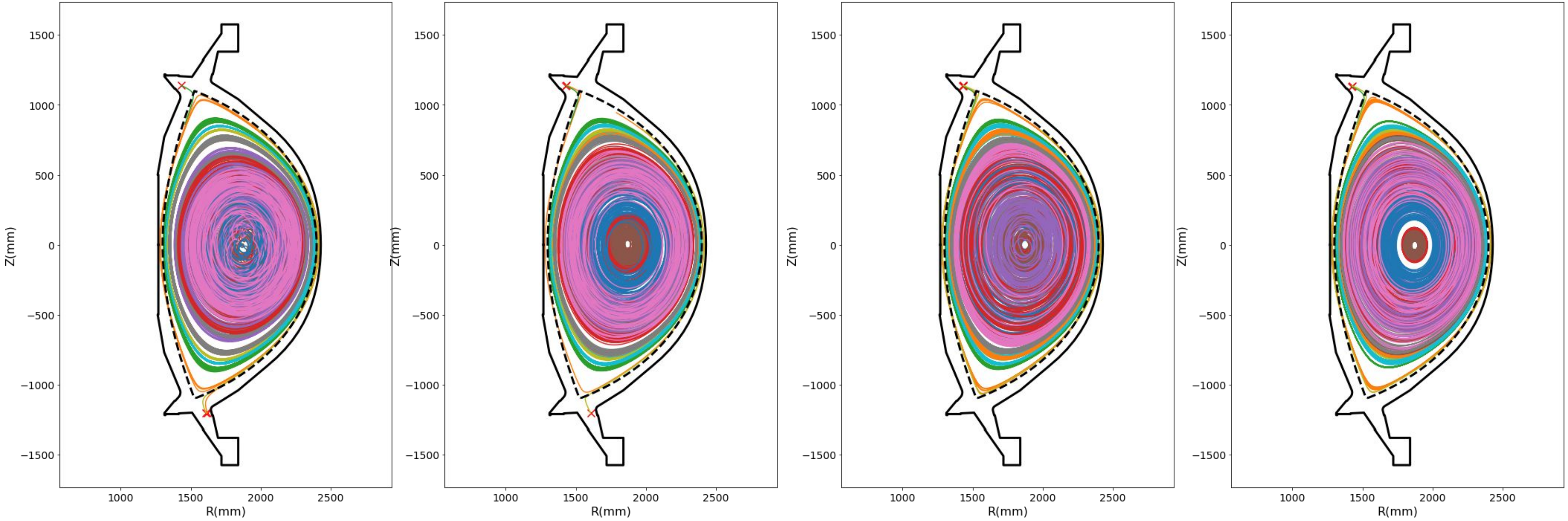


Fields in the center are stochastic

But there is a coherent flux surface at the edge which prevents loss

This is still true even when looking at the entire loss period

t = 0.318 ms | t = 0.324 ms | t = 0.331 ms | t = 0.337 ms

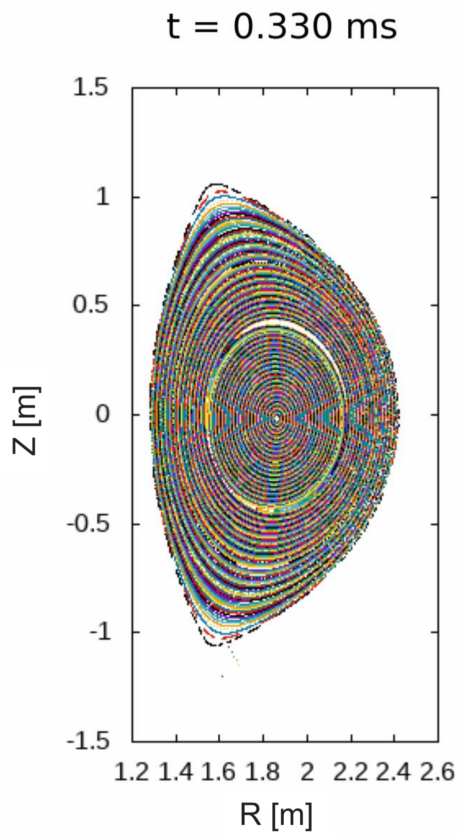


3.8% | 4% | 3.8% | 3.2%

So what are we missing?

- M3D-C1 uses advection
  - Fluid which hits the boundary is lost
- Potential causes:
  - Wrong particle energy
  - Lack of time resolution / missing the loss event in reconstructions
  - Conducting wall boundary

Poincáre Plots showing magnetic stochasticity (t = 0.35-0.47 ms)



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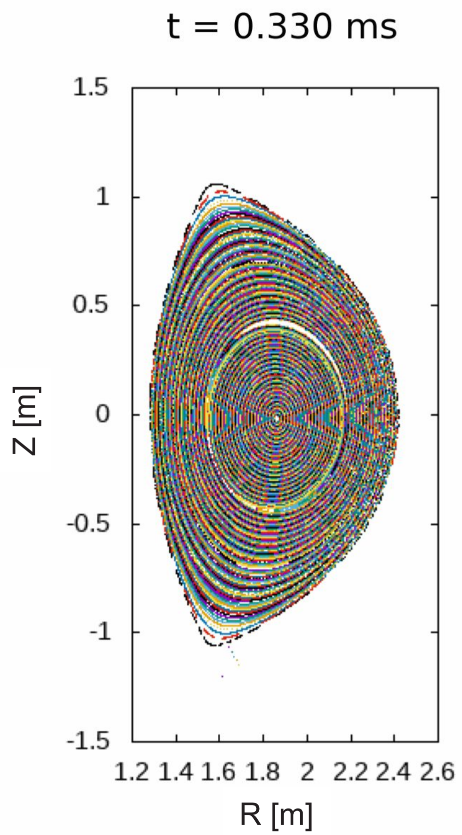
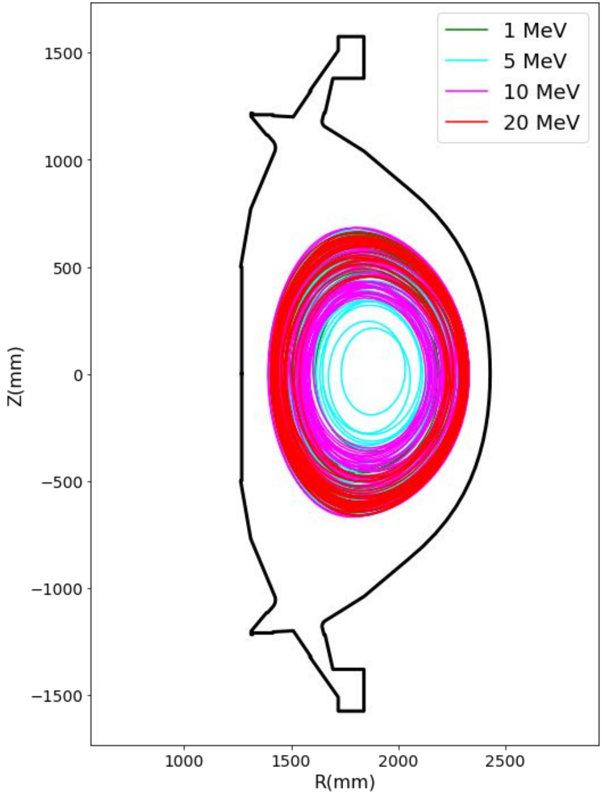


Do we get more losses with larger drifts?

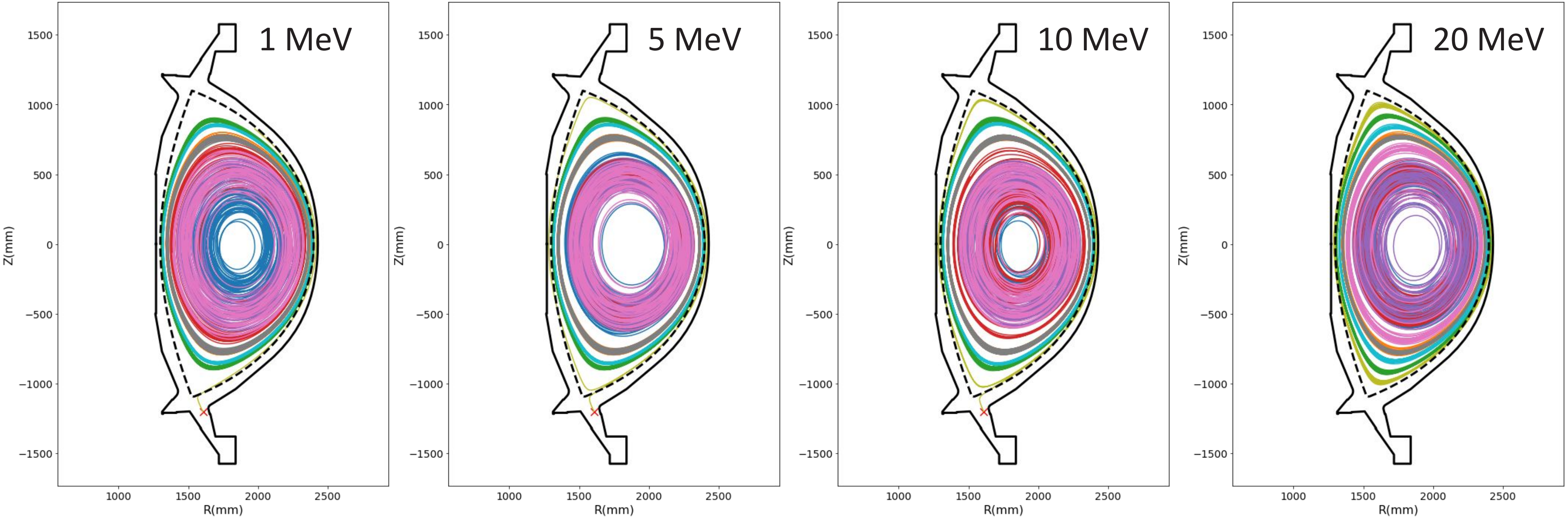


- Explore drift effects by scanning energies from 1 - 20 MeV

$$v_d = \frac{1}{\omega_c}(v_\parallel^2 + \frac{v_\perp^2}{2})\frac{R_C \times B}{R_c^2 B} \approx \frac{\gamma m_e}{eB_0R_0}(c^2)$$

- Trajectories do differ significantly
  - But how does this effect losses?

High energy particles are lost at lower rates



4% | 4.6% | 3.4% | 3%

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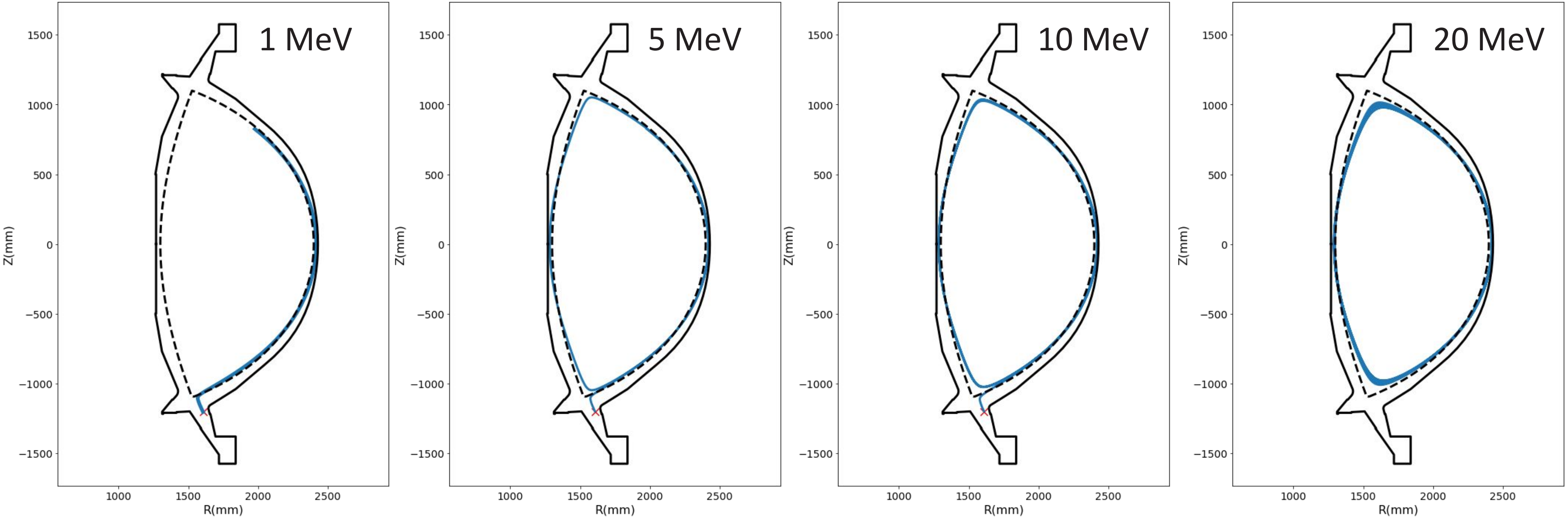

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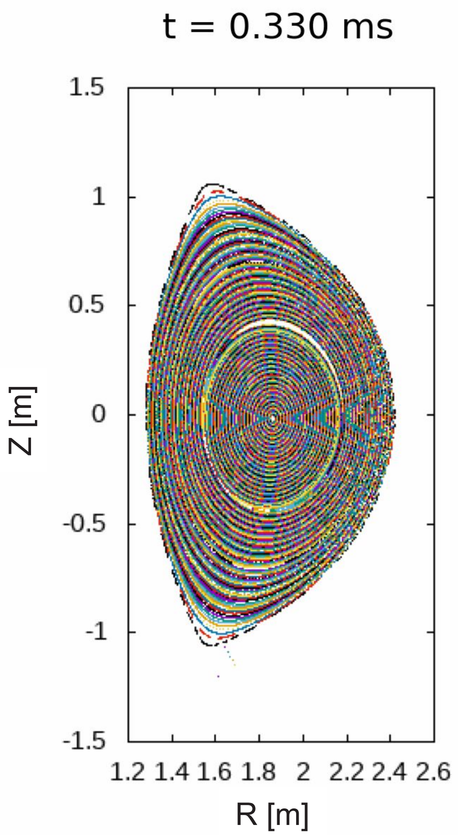
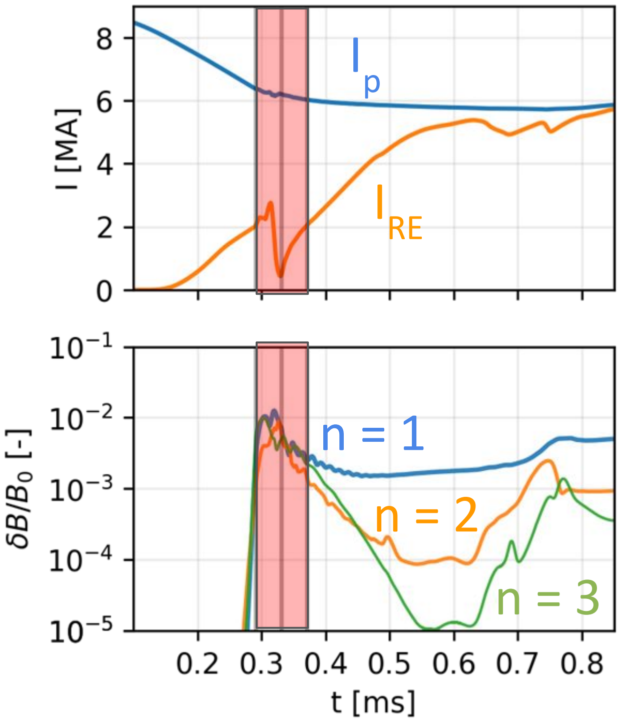
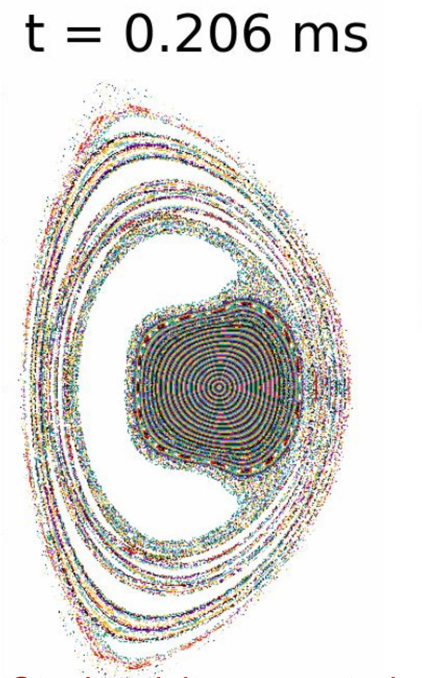


Loss event is very fast in this simulation, perhaps not captured in magnetic geometry

- Scalar values are recorded on much shorter timescale than magnetic geometries
- Loss is very fast in this simulation
- The magnetic geometry at the loss time may not be saved

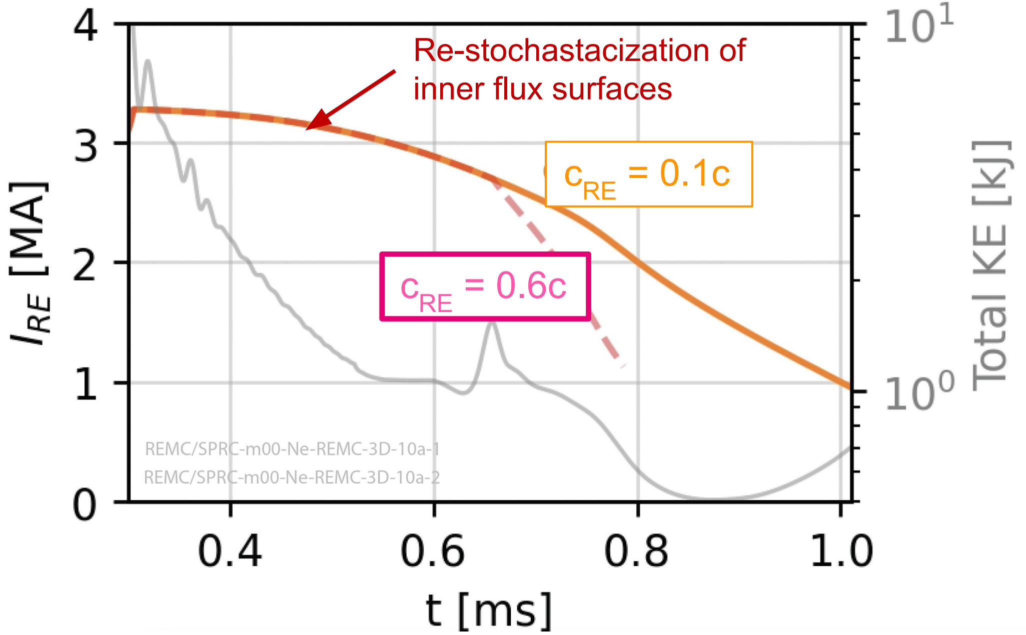


Luckily we have simulations with slower losses



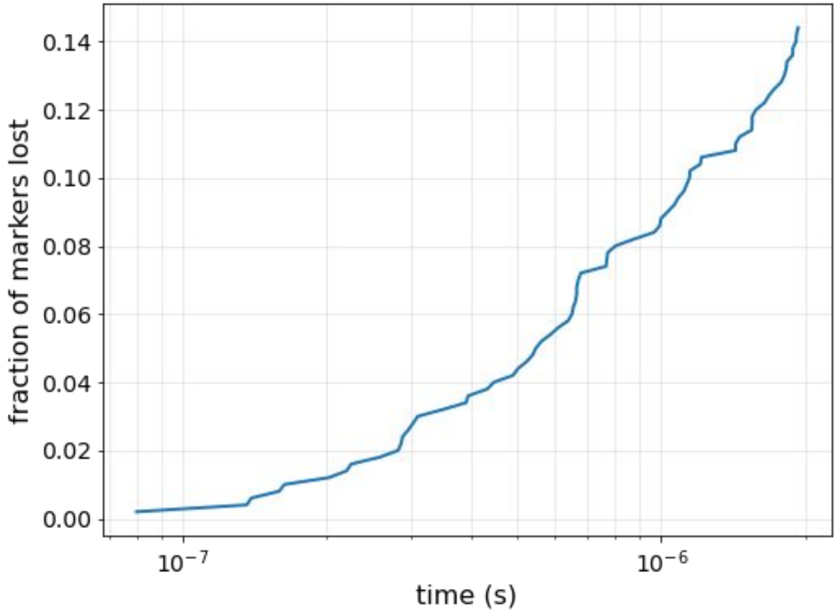
Stochasticity generated by the SPARC REMC

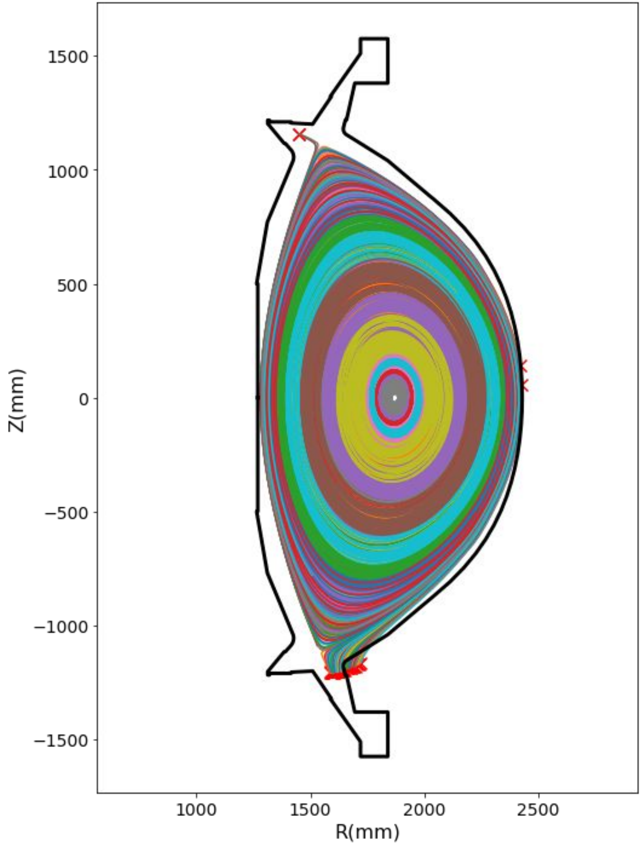
RE Losses calculated by the RE fluid model in M3D-C1 for different parallel velocity



Datta REM 2026

We get a lot more losses in this simulation!





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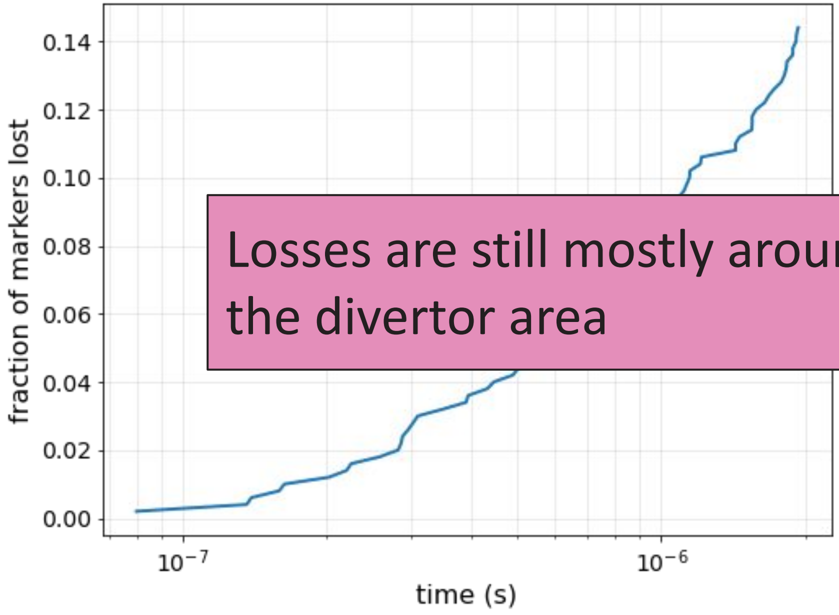
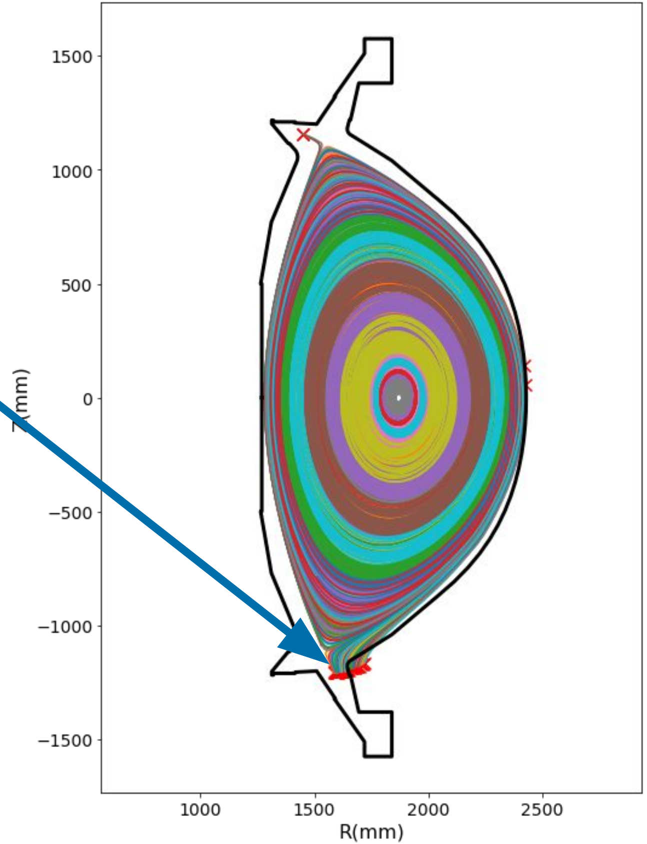
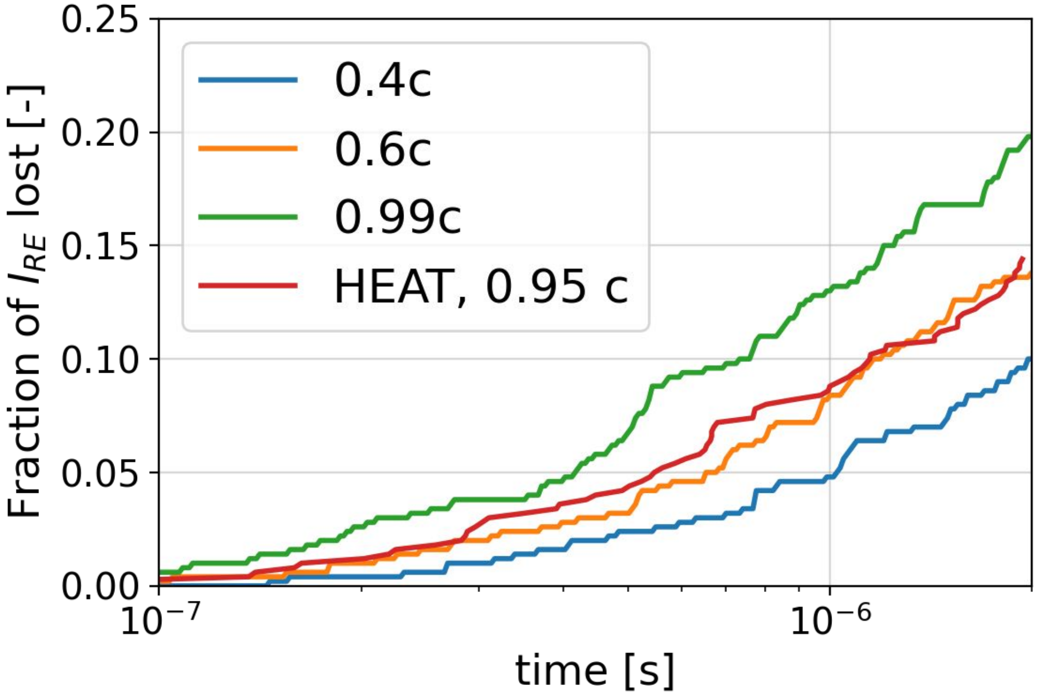


Losses are still mostly around the divertor area



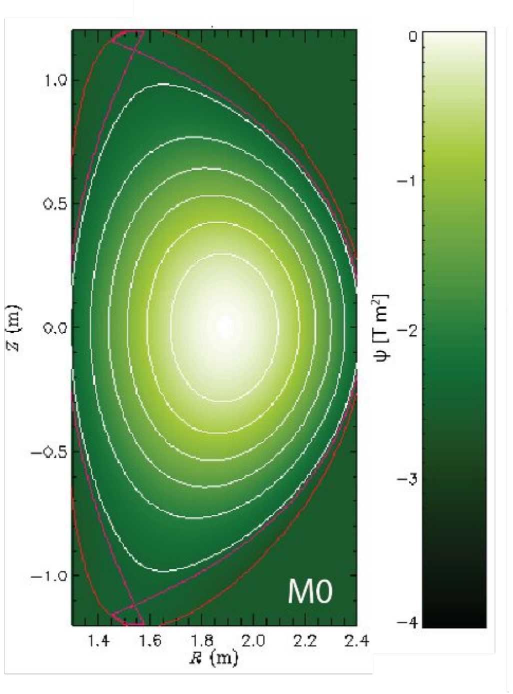
Quick aside: We're working on comparing this result against ASCOT



We do not have a 1:1 velocity comparison yet

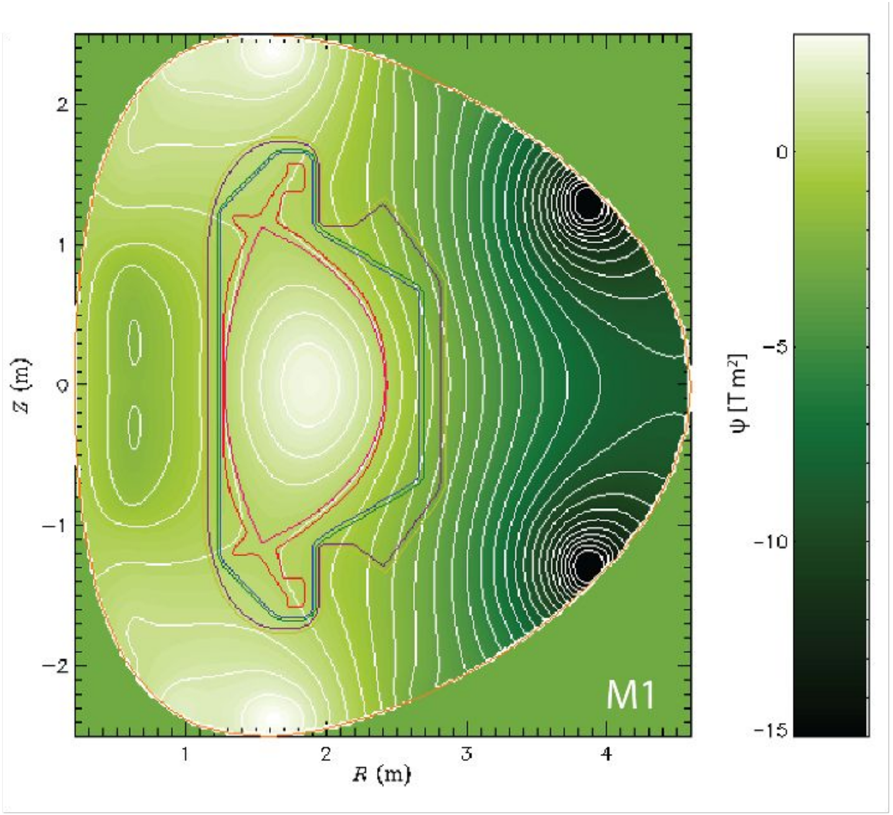
The conducting boundary may be inhibiting losses in other areas

- M3D-C1 uses an ideal conducting boundary
- For these simulations, this boundary is a simplified wall
- Conducting surface lies very close to plasma lcfs
    - Inhibits losses at midplane
    - Losses that do happen are near the diverter



Luckily we do have M3D-C1 simulations with a resistive wall

- These simulations take much longer to run, not many of them
- Applying HEAT to these simulations is an area of future work



Conclusions

- 3D fields are essential for studying RE loss events
- We now have the capability to study this with M3D-C1 and HEAT
- Only certain M3D-C1 simulations can provide interesting loss results
- Still working on optimizing workflow!

TEXTOR[Forster NF 2011], WEST [Diez NF 2021], JET[Matthews Phys.Scr. 2016]

Backup slides

Remaining questions and future work

- What physics are we missing?
- Will the larger simulation boundary be enough to get interesting losses?
- How do

Runaway electrons (REs) have caused damage in previous tokamaks

- REs have been observed in many previous tokamaks
  - MeVs of energy, MA of current
  - Naturally occuring
  - Induced with massive gas injection
- Melting/damage seen in JET, C-Mod, EAST, WEST, etc.
- Caused magnet quench in Tore-Supra

[Tinguely REM 2017]

WEST [Diez NF 2021], JET[Matthews Phys.Scr. 2016, Reux NF 2015] Tore Supra[Torre IEEE TAS 1029], EAST [Zhu NF 2023]

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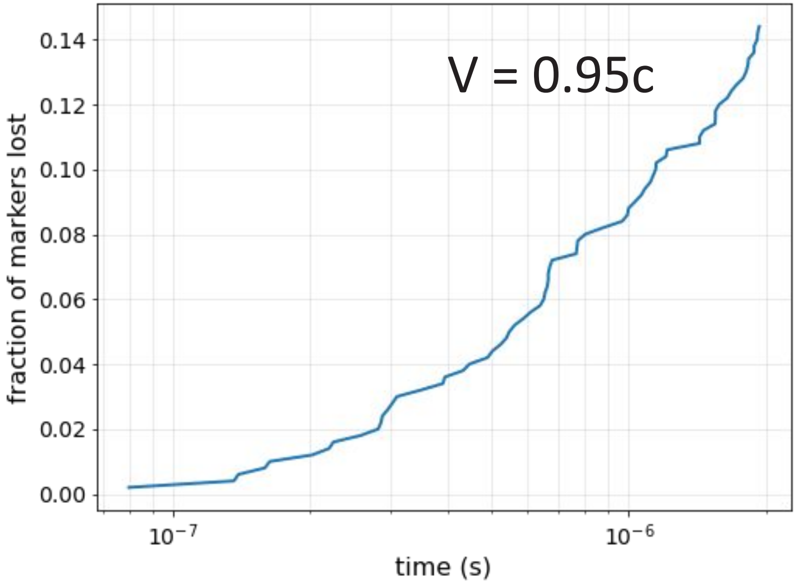

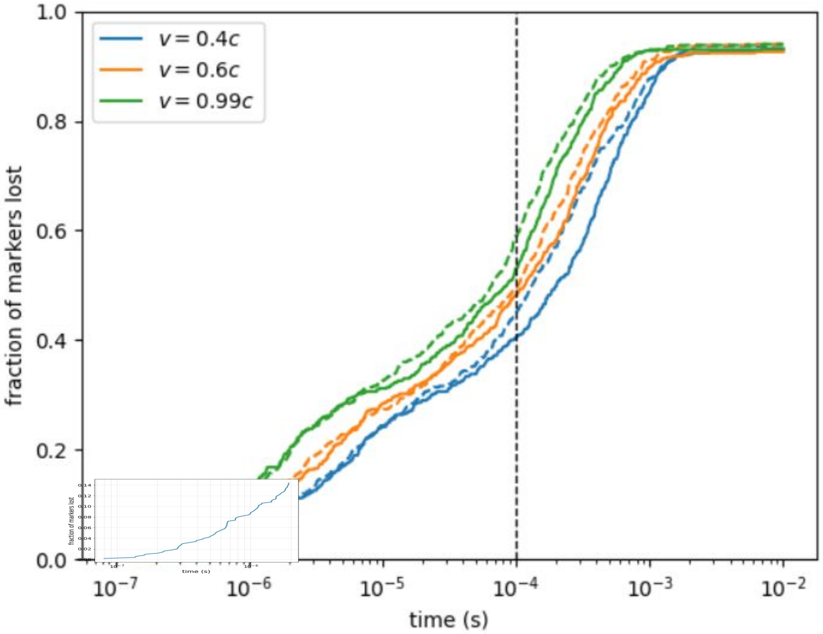

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