KORC Modeling of Runaway Electron Beam Impact on DIII-D DiMES

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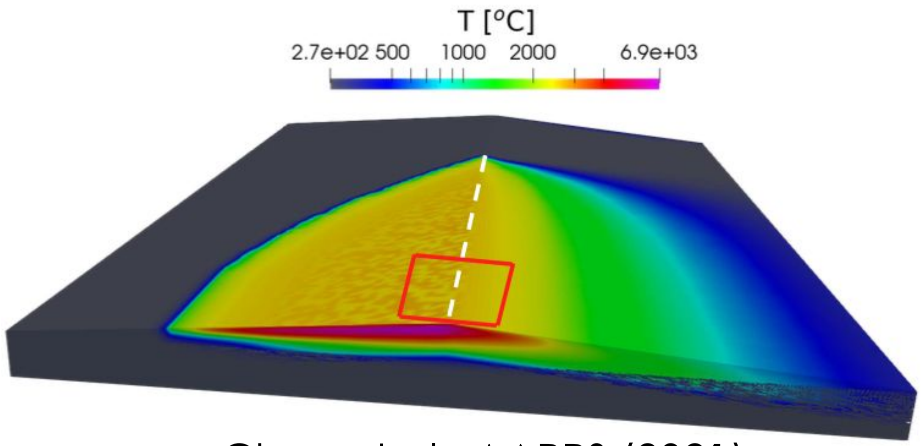
Motivation: Essential to predict wall damage due to post-disruption runaway electrons (REs)

- **Need to estimate material lifetime and design RE mitigation systems for ITER and future reactors**
- **Select between high-Z and low-Z secondary injection that leads to significantly different RE wall impacts**
  - Unstable MHD mode develops as flux surfaces scrape off during impact
  - Low-Z: one large strike, high kinetic energy, large wetted area
  - High-Z: many small strikes, low kinetic energy, small wetted area
- **Limited diagnostics to interpret RE wall strikes include infrared imaging (IR), HXR spectra, post-mortem analysis**
  - Leaves impacting RE energy and pitch angle distributions undetermined

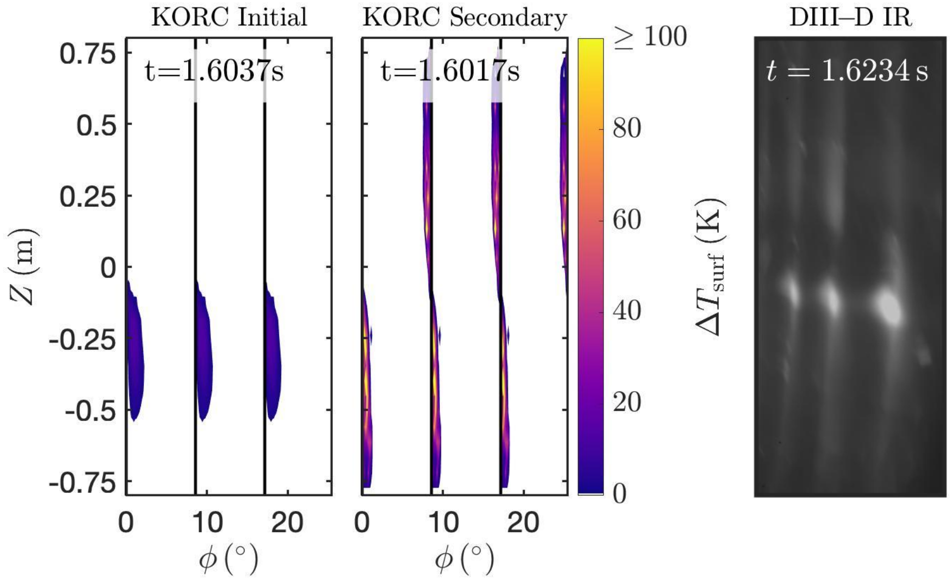
Background: Study enabled by recent modeling advances and ITPA DivSOL/MDC collaboration

- **High-fidelity models for volumetric energy deposition (GEANT4) and melt damage (MEMOS-U) used with analytic RE impacts**
  - Chen et al., AAPPS contribution MF2-I14 (2021)

- **High-fidelity model for RE impacts (KORC) used with a simple model for volumetric energy deposition and melt damage**
  - Beidler et al., *in preparation* (2023)
  - KORC: Kinetic Orbit Runaway electrons Code evolves particle-based RE distribution
    - Carbajal et al., *Phys. Plasmas* (2017)



Chen et al., AAPPS (2021)



Beidler et al., *in preparation* (2023), to be invited talk at APS-DPP

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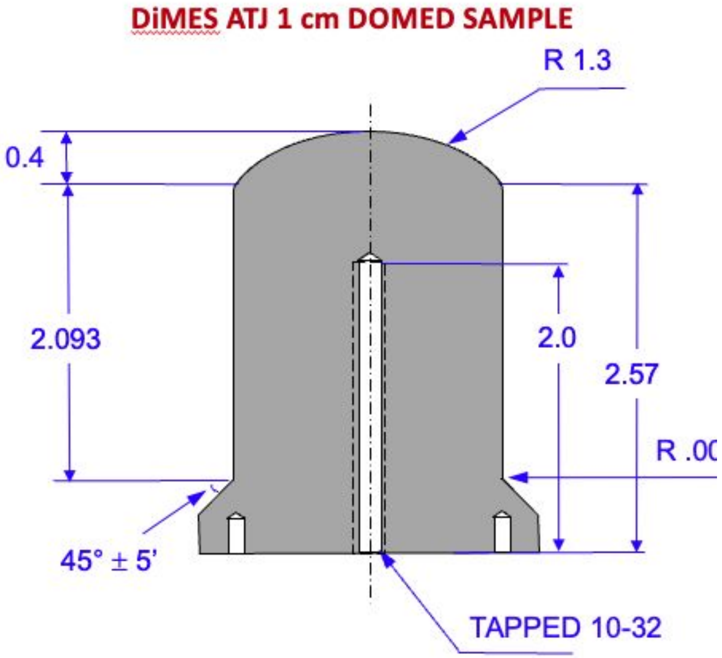
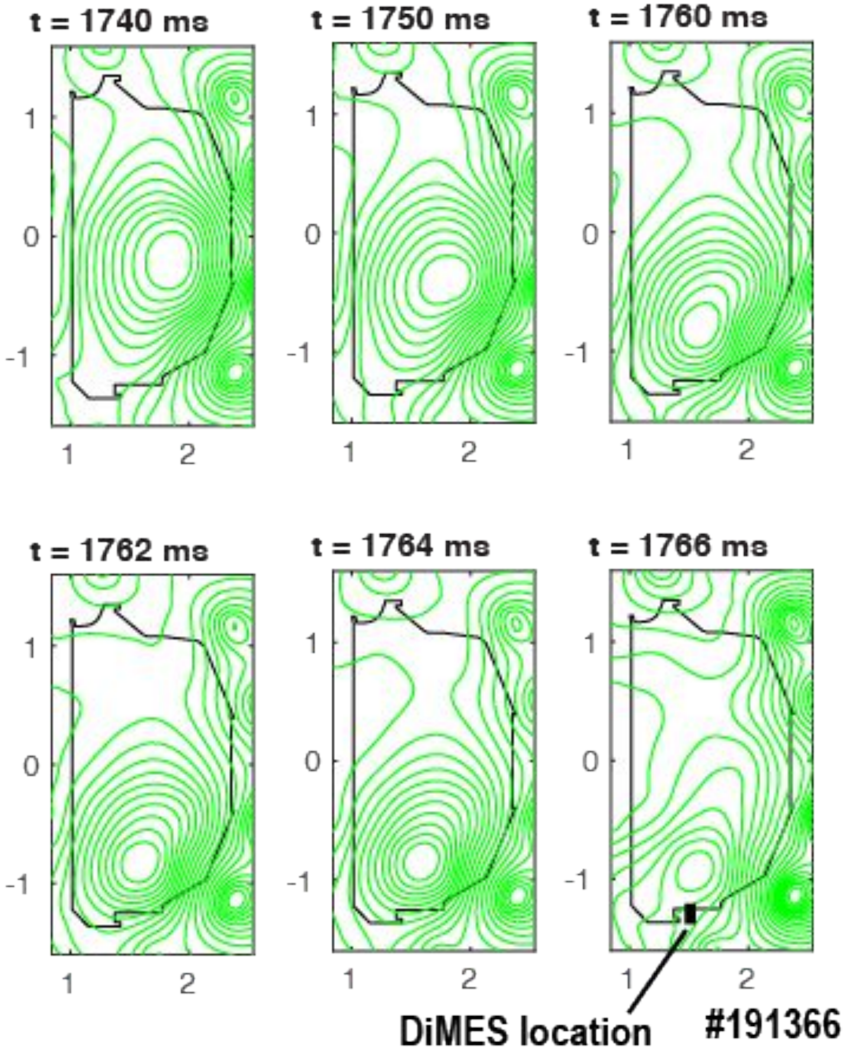
DIII-D experiment pushes RE beam down to impact DiMES

- **Form RE beam with Ar pellet injection**
- **Inject $200\ \mathrm{Torr-L}\ H_2$ to form a low-resistivity "purged" RE plateau**
- **Ramp current up to $500\ \mathrm{kA}$**
- **Elongate and kick down so beam drifts down into lower divertor**
- **Radially, impact is directly on DiMES**
  - Wong et al., *J. Nucl. Mat.* **258-263**, 433 (1998)
  - Graphite dome protruding 1cm



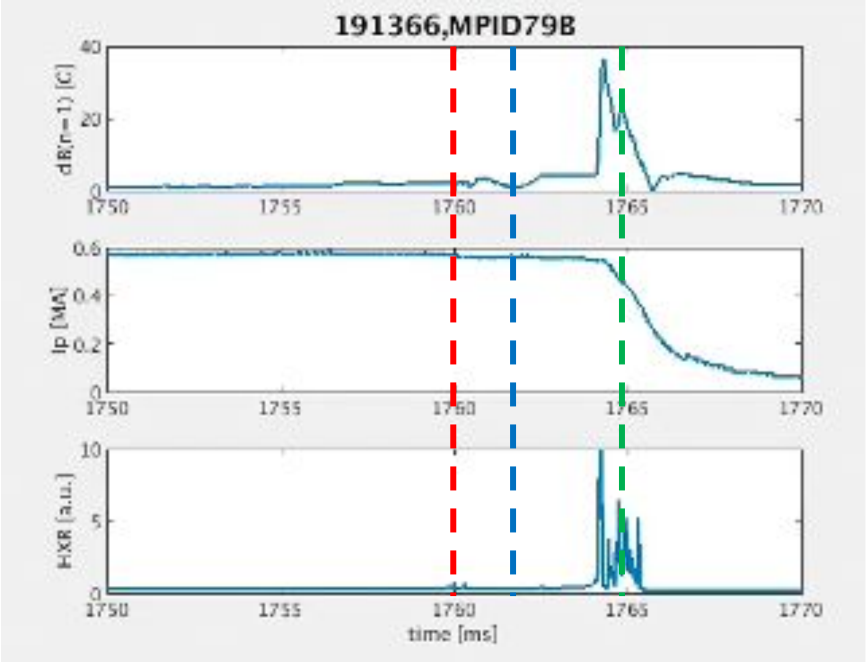
JFIT reconstructions

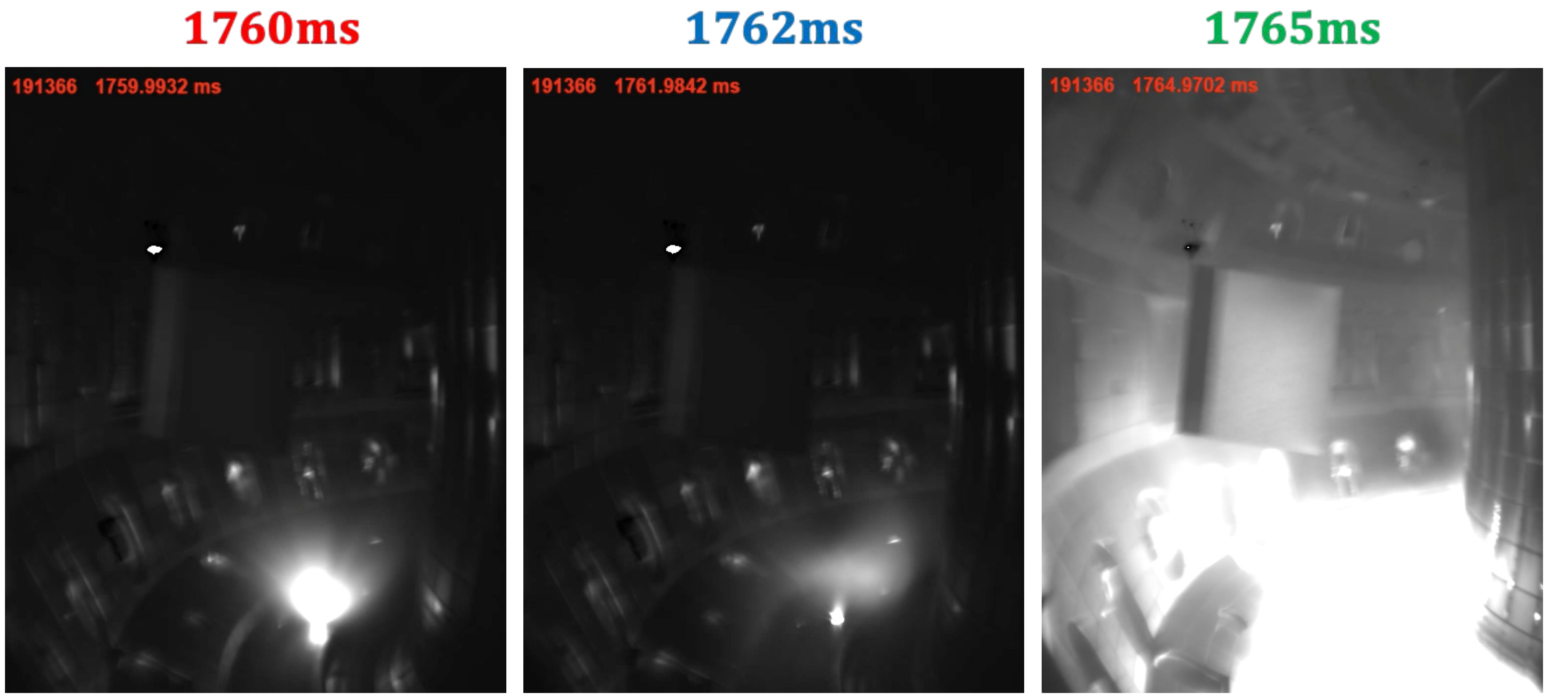


Infrared imaging movie of RE beam impact on DiMES

Complex phenomenology of multi-phase final loss not completely modeled

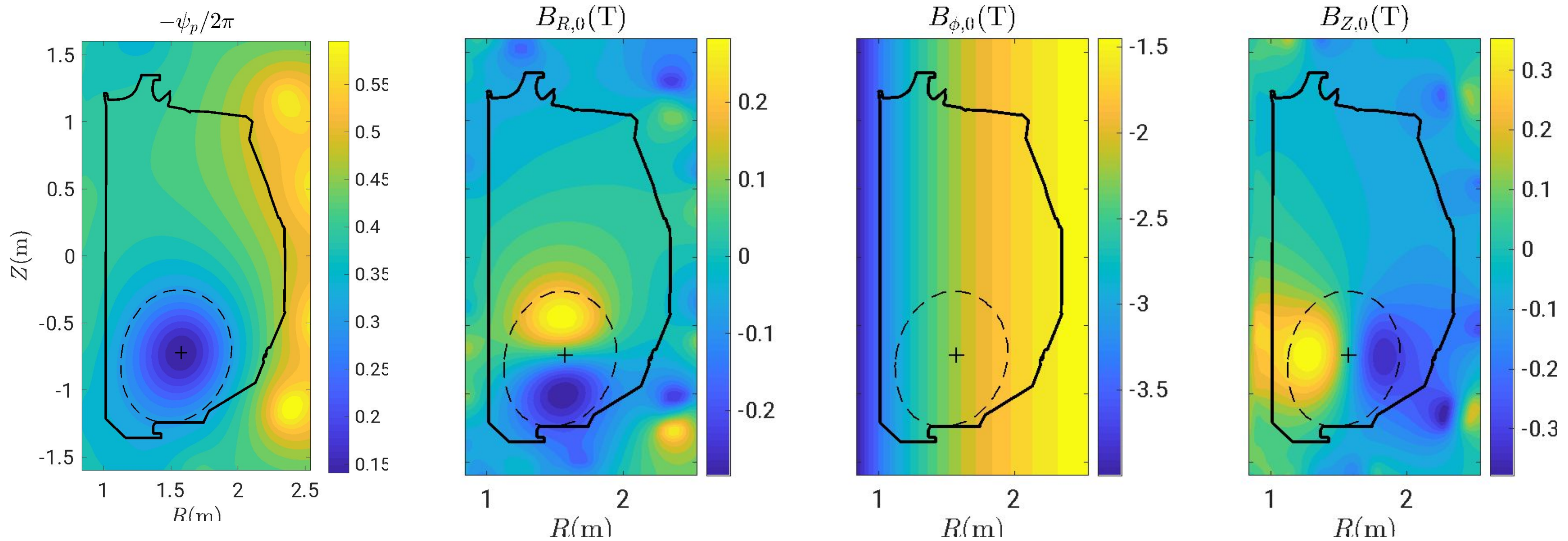
- **Two-stage final loss with MHD appearing in the second stage**
  - Appears to have significant graphite sublimation into the remaining RE beam
- **This work uses EFIT reconstruction at 1762.75ms**





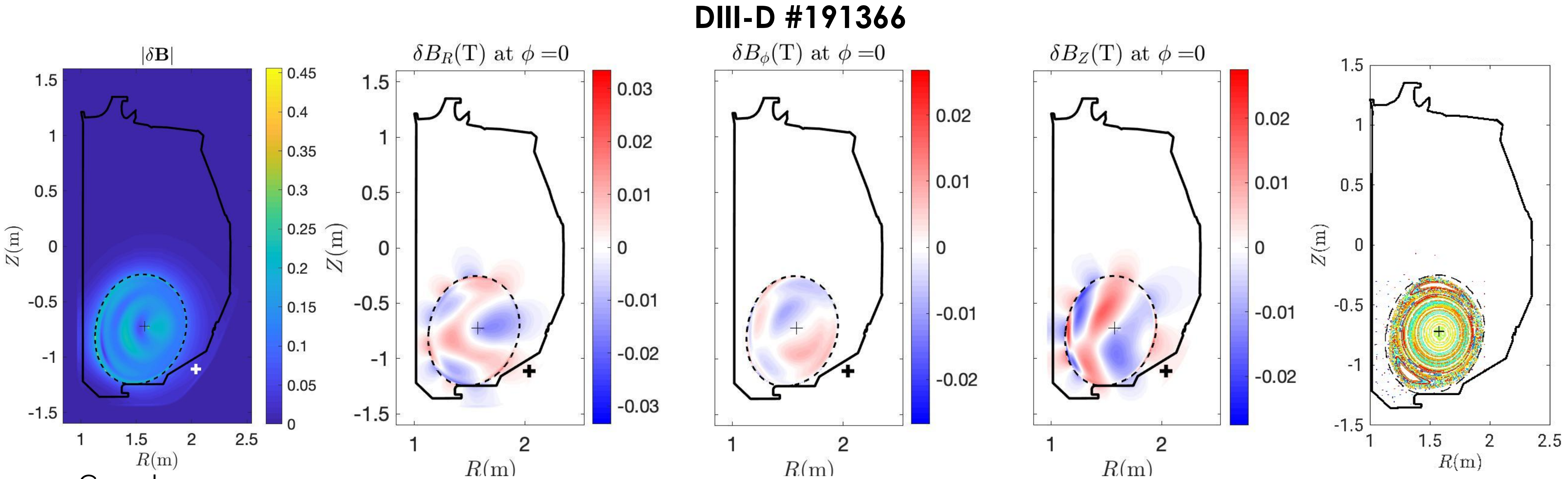
Modeling uses EFIT reconstruction of DIII-D 191366

DIII-D #191366 @ 1762.75ms



- **EFIT poloidal flux $\psi_{\mathrm{EFIT}} = -\frac{1}{2\pi}\psi_p$**
  - $\vec{B}_p = -\vec{\nabla}\psi_{\mathrm{EFIT}}\times\vec{\nabla}\phi = \frac{1}{R}\hat{\phi}\times\vec{\nabla}\psi_{\mathrm{EFIT}}$
- **Toroidal field in $-\hat{\phi}$ direction with current oppositely aligned**
  - RE pitch angle $\eta \equiv \mathrm{acos}(\hat{p}\cdot\hat{b}) < 90°$

MARS-F 3D perturbation fields scaled to $n = 1$ experimental signals on DIII-D final loss events



Complex norm of MARS-F fields

Experimentally-scaled MARS-F fields at $\phi = 0$

Poincaré section at $\phi = 0$

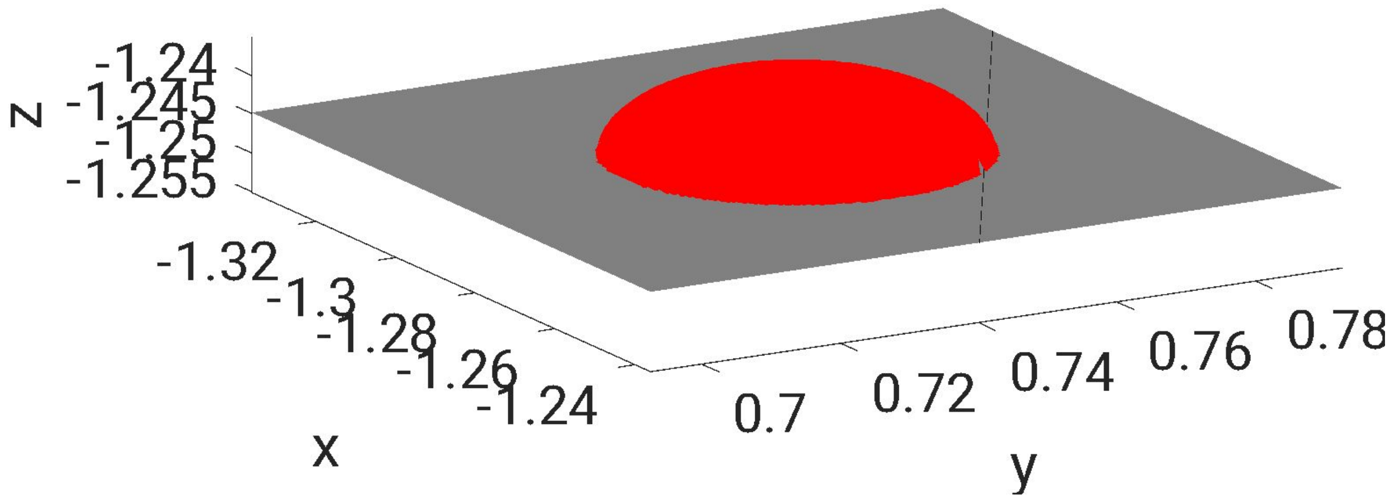
- **Toroidal array of magnetic pickup coils fit to $n = 1$ yields 36.4 G**
  - Located at plus in lower-right of plots
- **Scale $n = 1$ MARS-F perturbation field to experimental fit and shift toroidal phase**
  - Results in 3D $\delta B/B \sim 1\%$
  - Stochastic edge seen in Poincaré plot

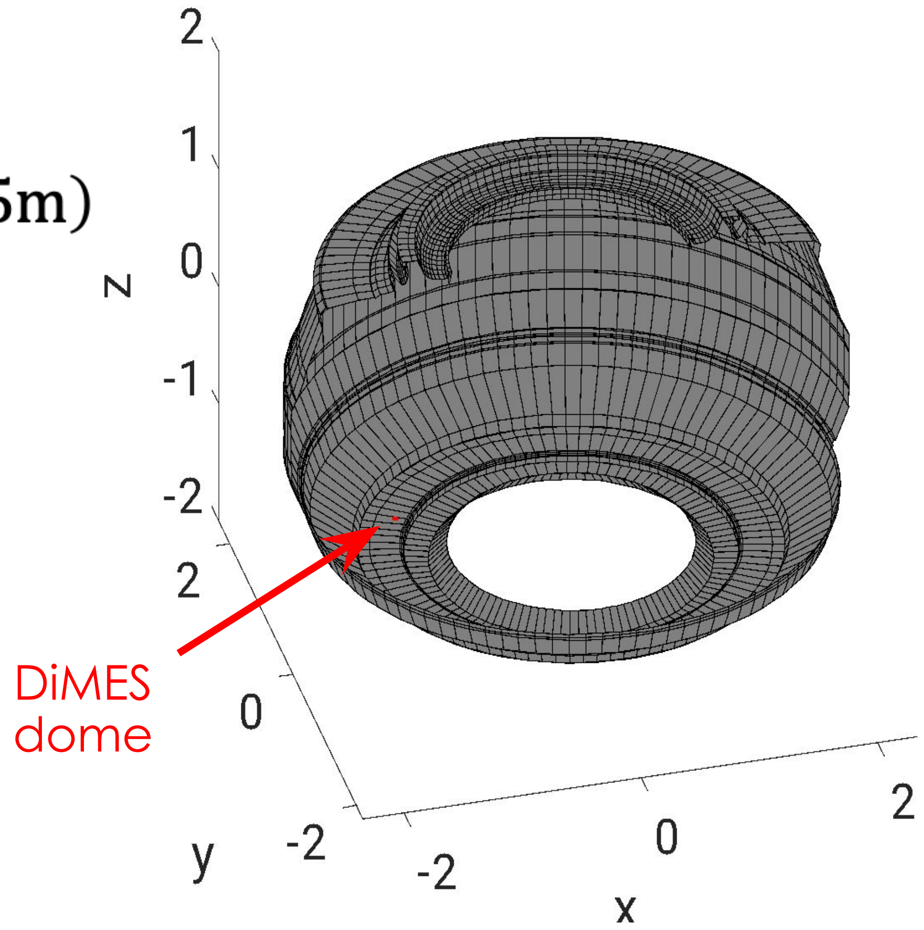
Graphite dome in DiMES is modeled as semi-spheroid

- **Semi-spheroid surface given by**

$$r_D^2 = (x - x_D)^2 + (y - y_D)^2 + \left(\frac{z - z_D}{h_D / r_D}\right)^2$$

  - Center at $(R_D, \phi_D, z_D) = (1.485\mathrm{m}, 150°, -1.245\mathrm{m})$
  - Dimensions $(r_D, h_D) = (0.025, 0.01)\ \mathrm{m}$





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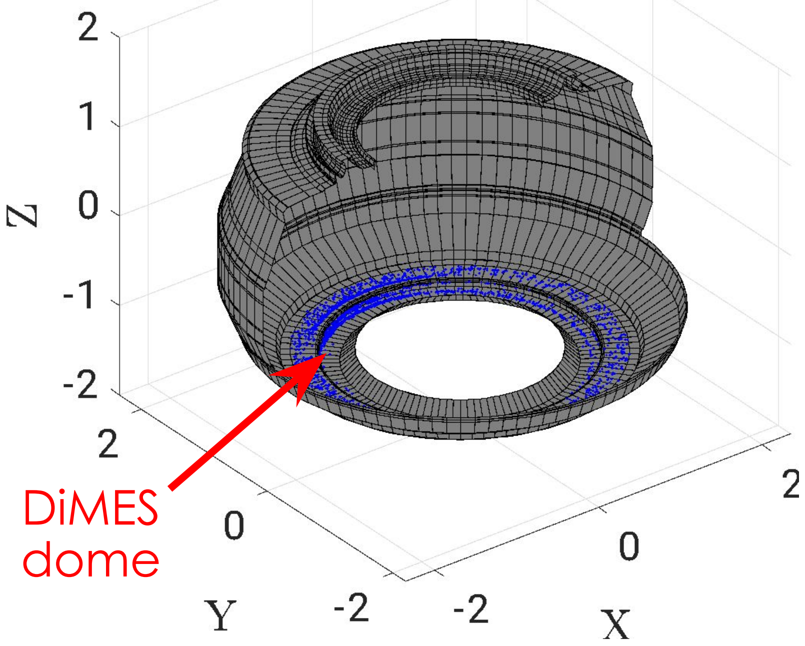
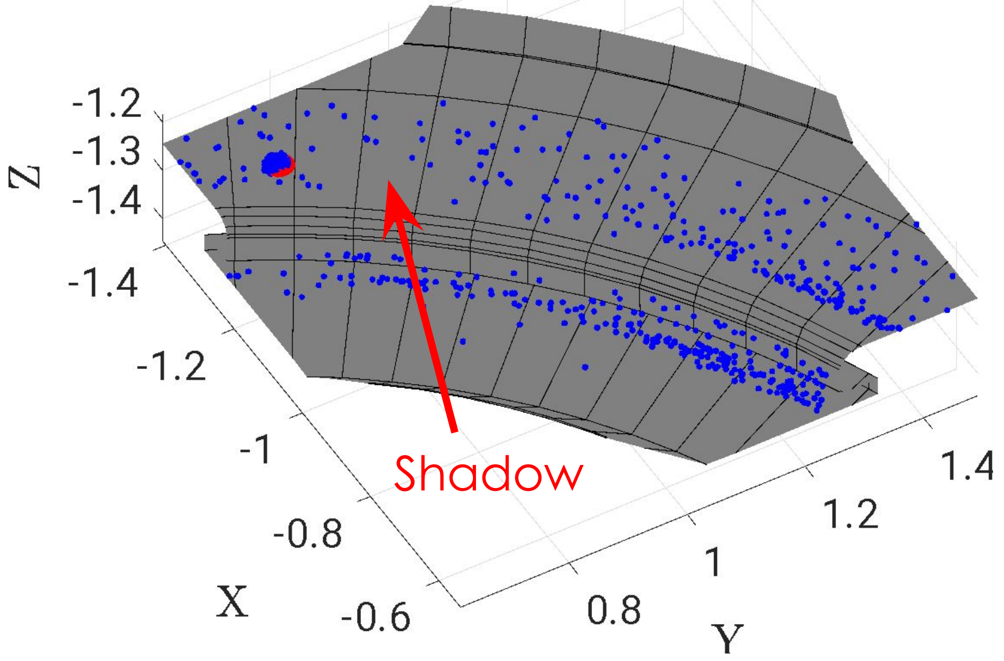
Significant number of REs are deposited onto DiMES dome, but many REs deconfined elsewhere





- **Full orbit trajectories without collisions or electric field acceleration**
  - No sheath dynamics included
- **Initial RE beam is uniform within LCFS, monoenergetic with $\mathcal{K} = 10\mathrm{MeV}$, and monopitch with $\eta = 10°$**
  - Let unconfined REs exit calculation with equilibrium fields before continuing calculation with perturbation fields

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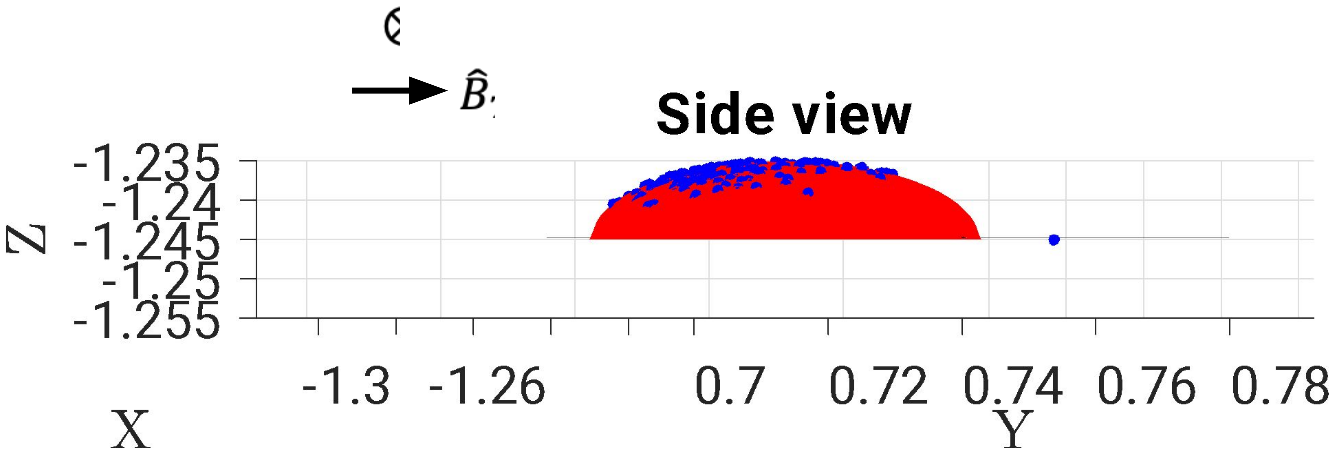
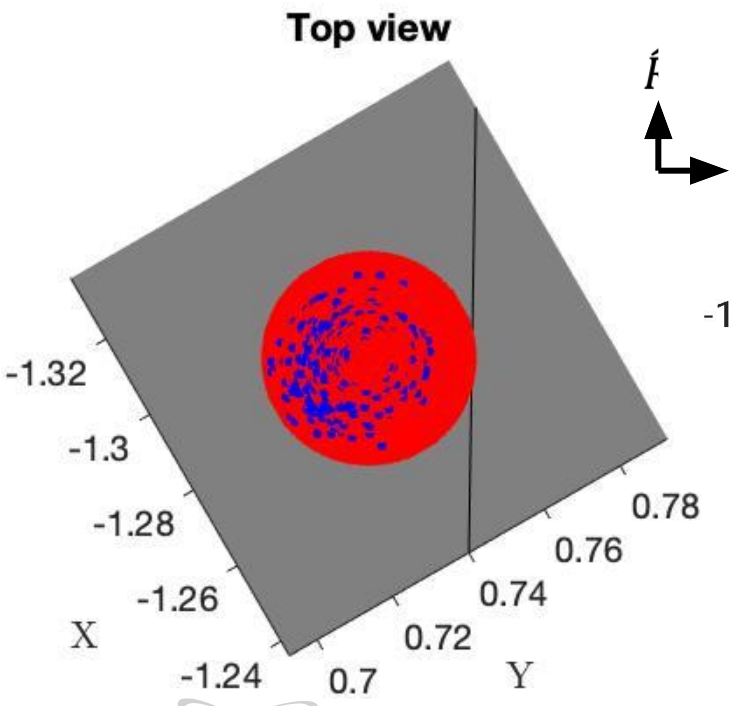
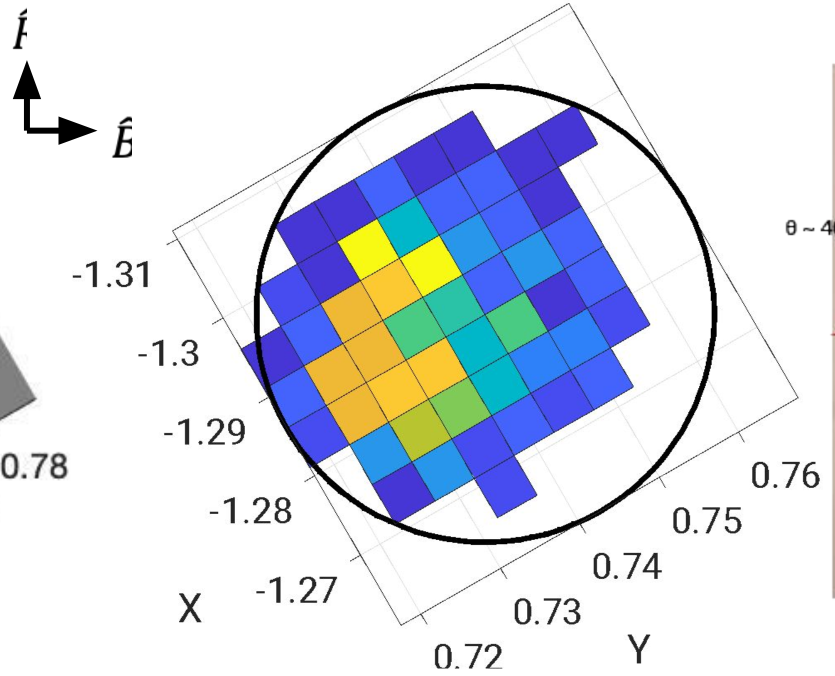
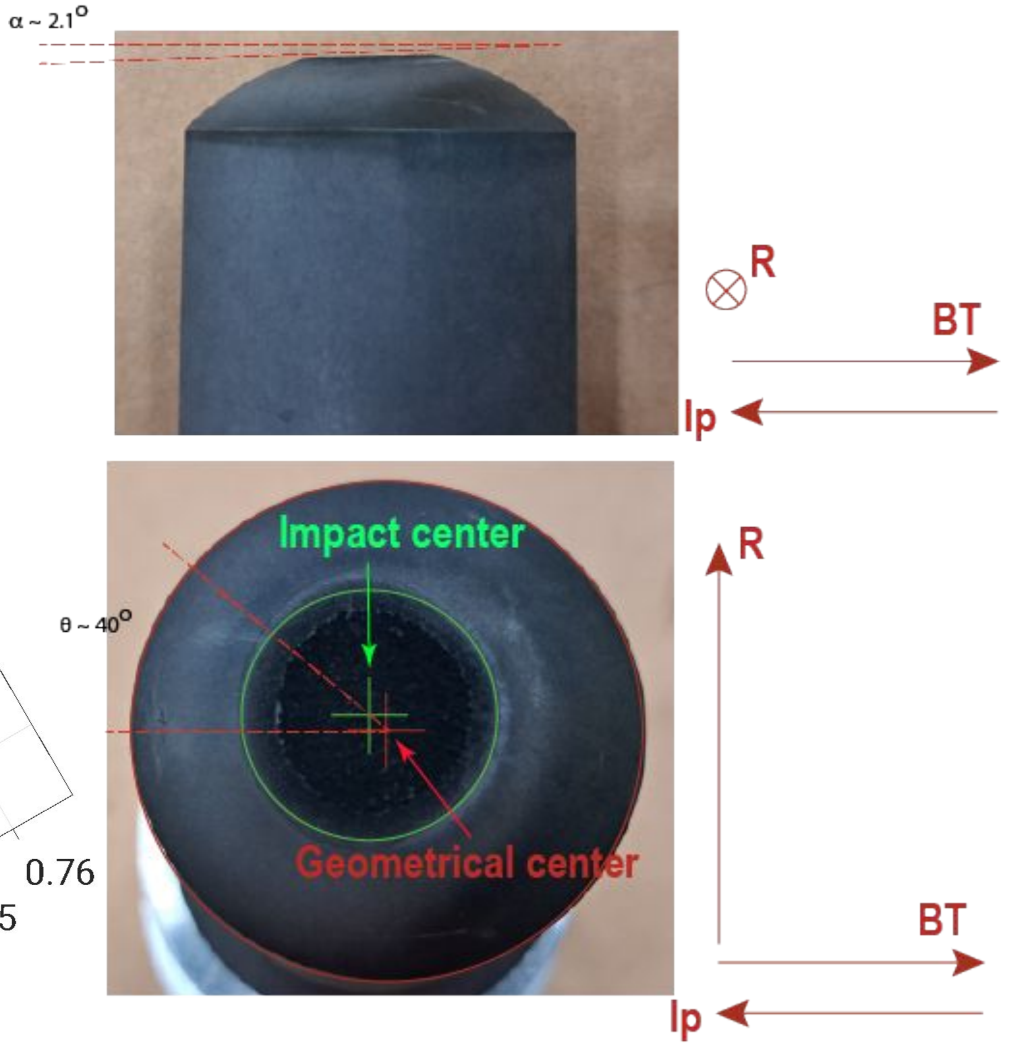
Preliminary analysis exhibits some qualitative agreement



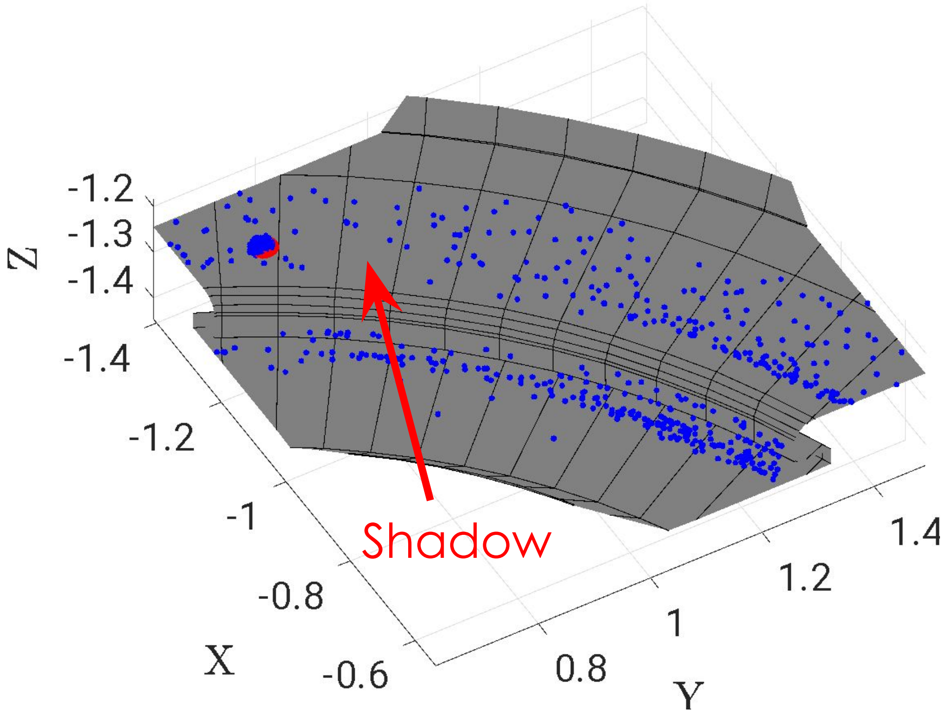


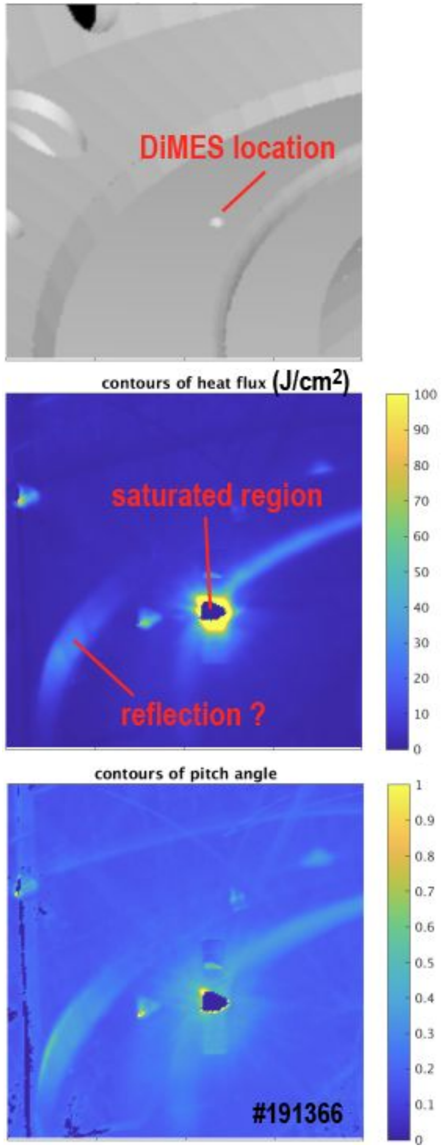




Preliminary analysis exhibits some qualitative disagreement

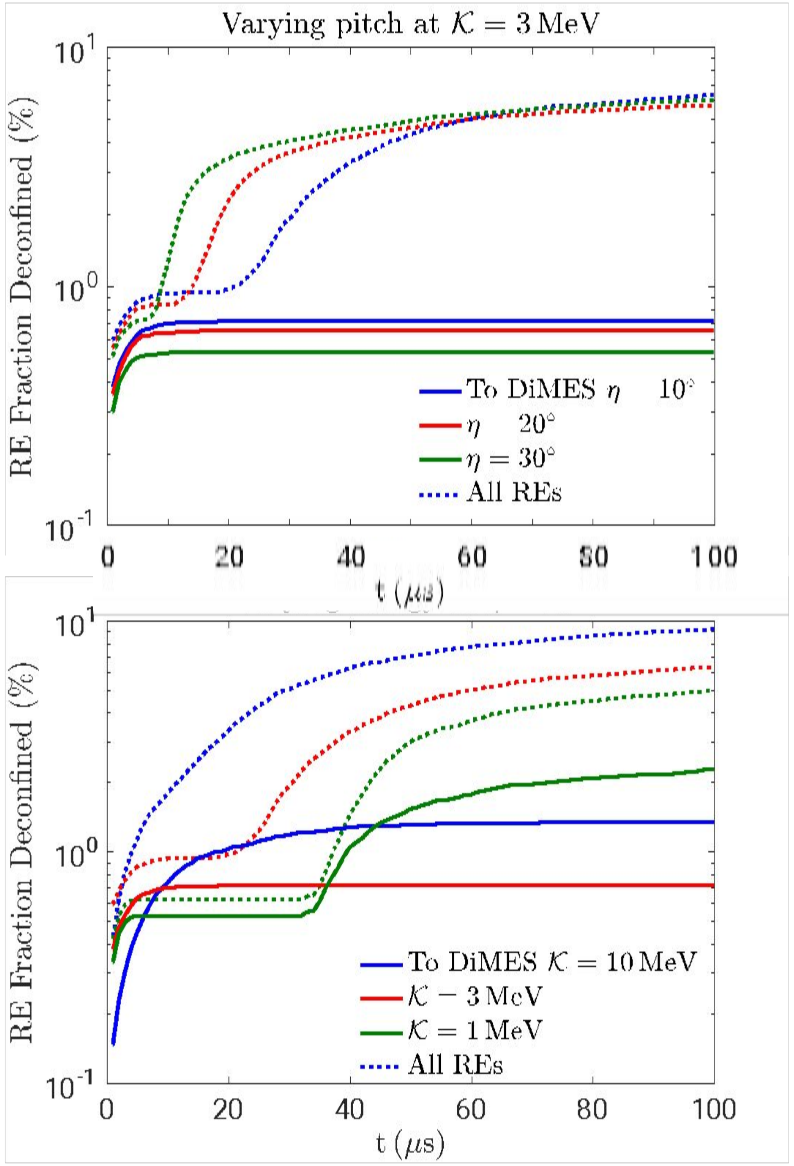
- **Modeling yields a shadow behind DiMES that is less prominent in experimental IR**
  - IR from long after large MHD event
- **Modeling yields RE deconfinement into lower divertor region that isn't observed in experimental IR**



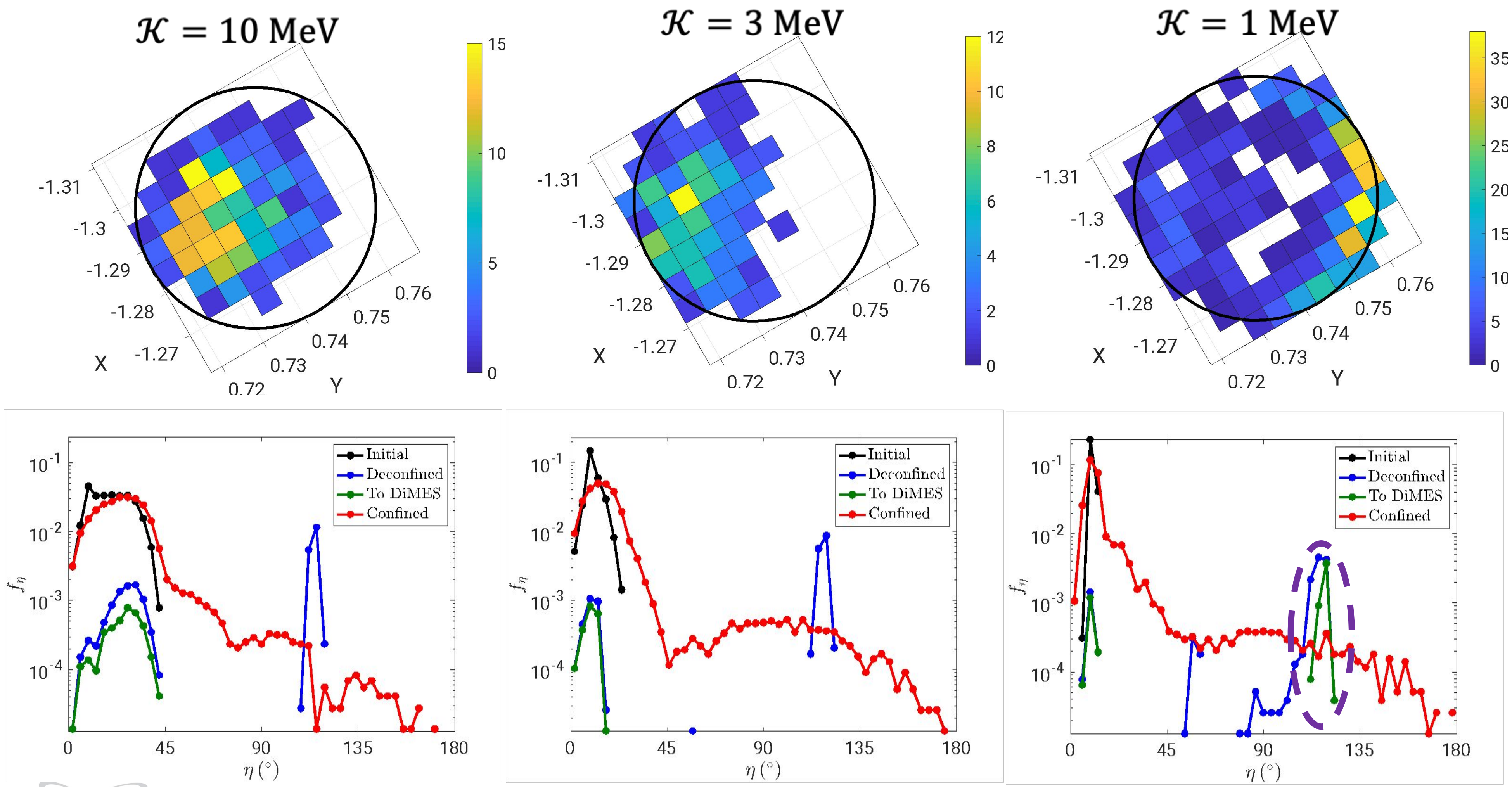


More REs strike DiMES at lower pitch angle, scaling with energy is more complicated

- **Simulations of varying pitch angle show more REs strike DiMES at lower pitch angles**
  - Total deconfined REs independent of pitch angle
- **Simulations varying energy show REs strike DiMES (dotted traces) in a two-stage process at lower energy**
  - Same trend for total deconfined REs (solid traces)



Calculations show pitch scattered lower energy REs impact shadowed side of DiMES in second stage loss



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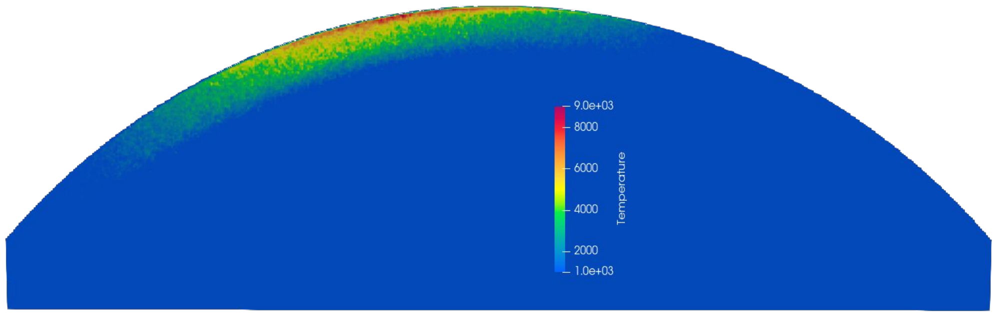
Conclusions

- **Analytic wall capability in KORC can model a graphite dome sample in DiMES**
- **Preliminary KORC simulations of RE impact on graphite dome in DiMES show qualitative agreement**
- **Collisionless pitch angle scattering in stochastic magnetic fields leads to delayed RE deconfinement for lower energy REs**

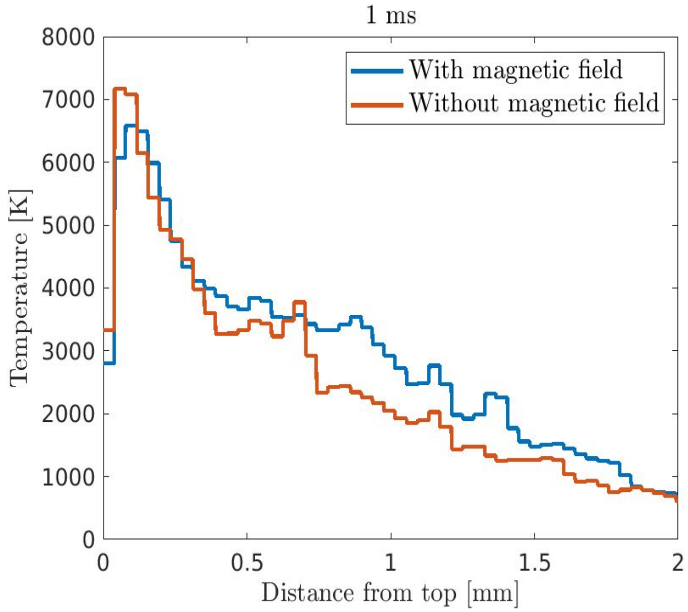
Future Work

- **Rerun calculations with a GPU-enabled version of KORC**
- **Prepare DiMES-impacting RE distributions for use in GEANT4/MEMENTO workflow**
- **Run tracer particles in time-evolving extended-MHD simulations of RE wall impact**

Rizzi et al., DivSOL ITPA (2023)



9000-1000 K colormap



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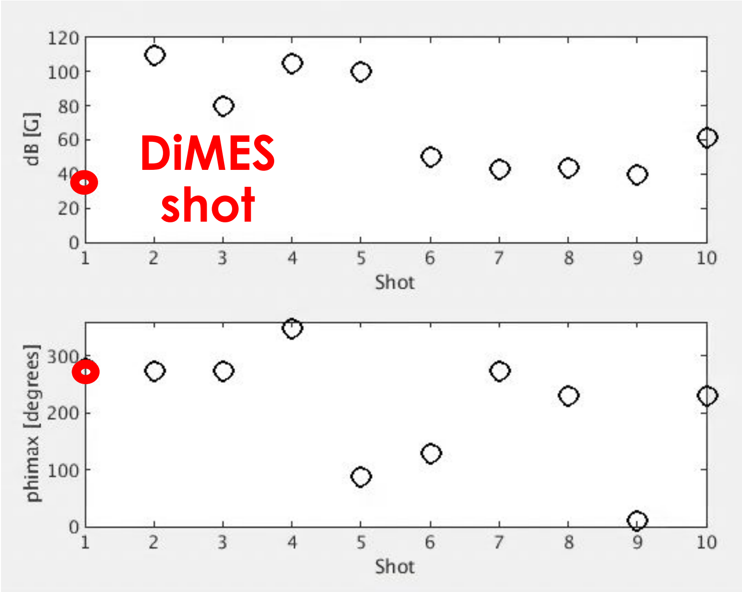
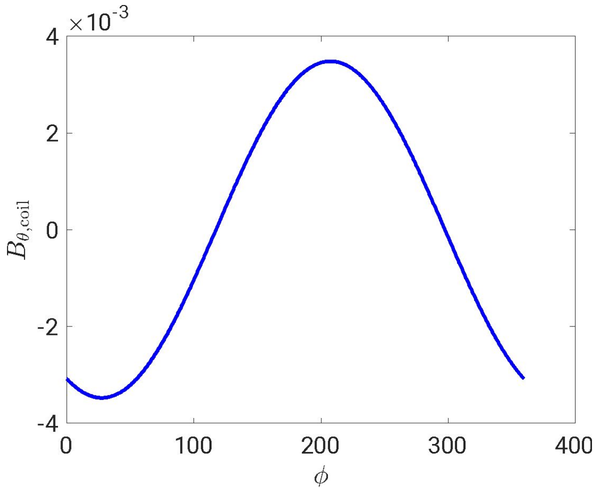
Extra Slides

Toroidal phase of MARS-F 3D mode is adjusted to match $n = 1$ signal from DIII-D toroidal magnetic coil array

- **Maximum $n = 1$ signal at coil array at toroidal angle $\phi_{\max(\mathrm{DIII-D\ dB})} \sim 280°$**
- **Maximum absolute value of MARS-F computed B_θ at coil array at toroidal angle $\phi_{\max(\mathrm{MARS\ dB})} \sim 27°(207°)$**
- **Use phase shift of $253°(73°)$**



MARS-F computed B_θ at coil array



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KORC full orbit simulations with MARS-F 3D fields show qualitative agreement with experimental results

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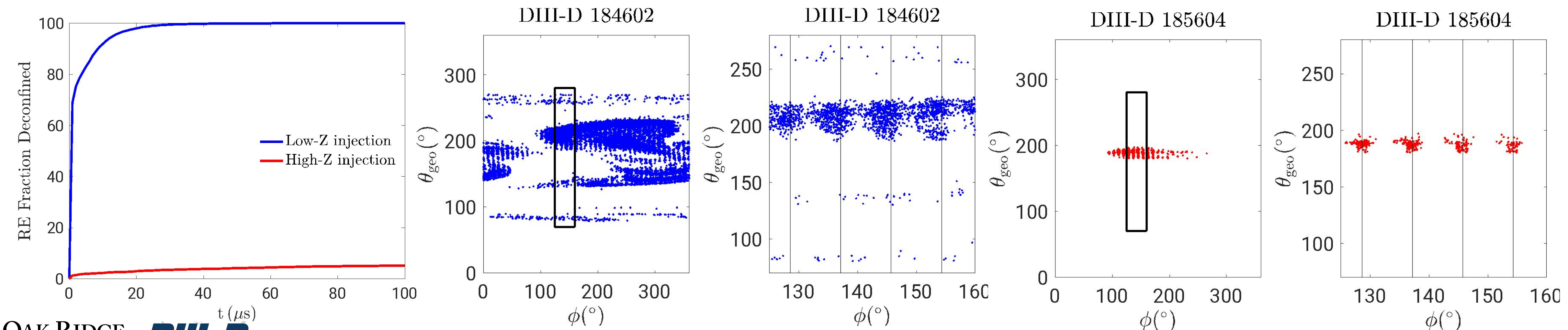

Low-Z discharge with large MHD mode leads to deconfined REs with increased energy deposition length scale which could result in deeper PFC damage

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