Oak Ridge National Laboratory

RE tracer particle calculations using one-way couplings with KORC

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M3D-C1: Nate Ferraro[2], Steve Jardin[2], Brendan Lyons[3]
NIMROD: Brian Cornille[4], Carl Sovinec[4]
MARS-F: Yueqiang Liu[3]
AORSA: Don Spong[1]
DIII-D: Eric Hollmann[5], Carlos Paz-Soldan[6]

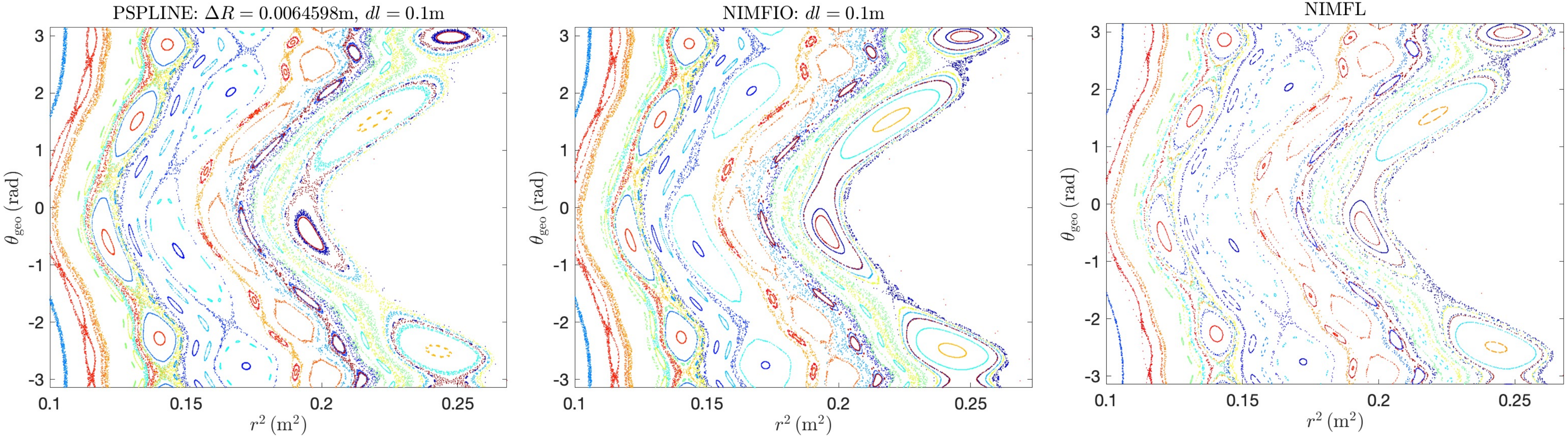
[1]ORNL, [2] PPPL, [3]GA, [4]UW-Madison, [5]UCSD , [6]Columbia

KORC is coupled to M3D-C1 and NIMROD using Fusion-IO

- **Work was part of DOE Theory Milestones for SCREAM SciDAC in FY21**
- **Interpolations used for RE distribution initialization, full orbit evolution, guiding center evolution, and Coulomb collision operator evaluation**
  - $\boldsymbol{B}, \boldsymbol{\nabla B}, \psi_p, \boldsymbol{E}, n_e, T_e, n_i, n_{\mathrm{imp}}$ presently interpolated for M3D-C1
    - Can use all the RE physics models in KORC
    - Built all functionality from initial development of Nate Ferraro and Mark Cianciosa
  - $\boldsymbol{B}, \boldsymbol{E}, n_e$ presently interpolated for NIMROD (NIMUW branch)
    - Can only use full orbit evolution
    - Functionality developed by Brian Cornille
- **Fields and field derivatives and plasma and impurity profiles interpolated from dumpfiles using input files**
  - Reinitialize interpolants for each dumpfile in order
- **Search routine that locates logical coordinate of physical location is significant driver of computational time**
  - Helped by holding onto "hint" of where a particle is located
  - Present routine is not vectorized

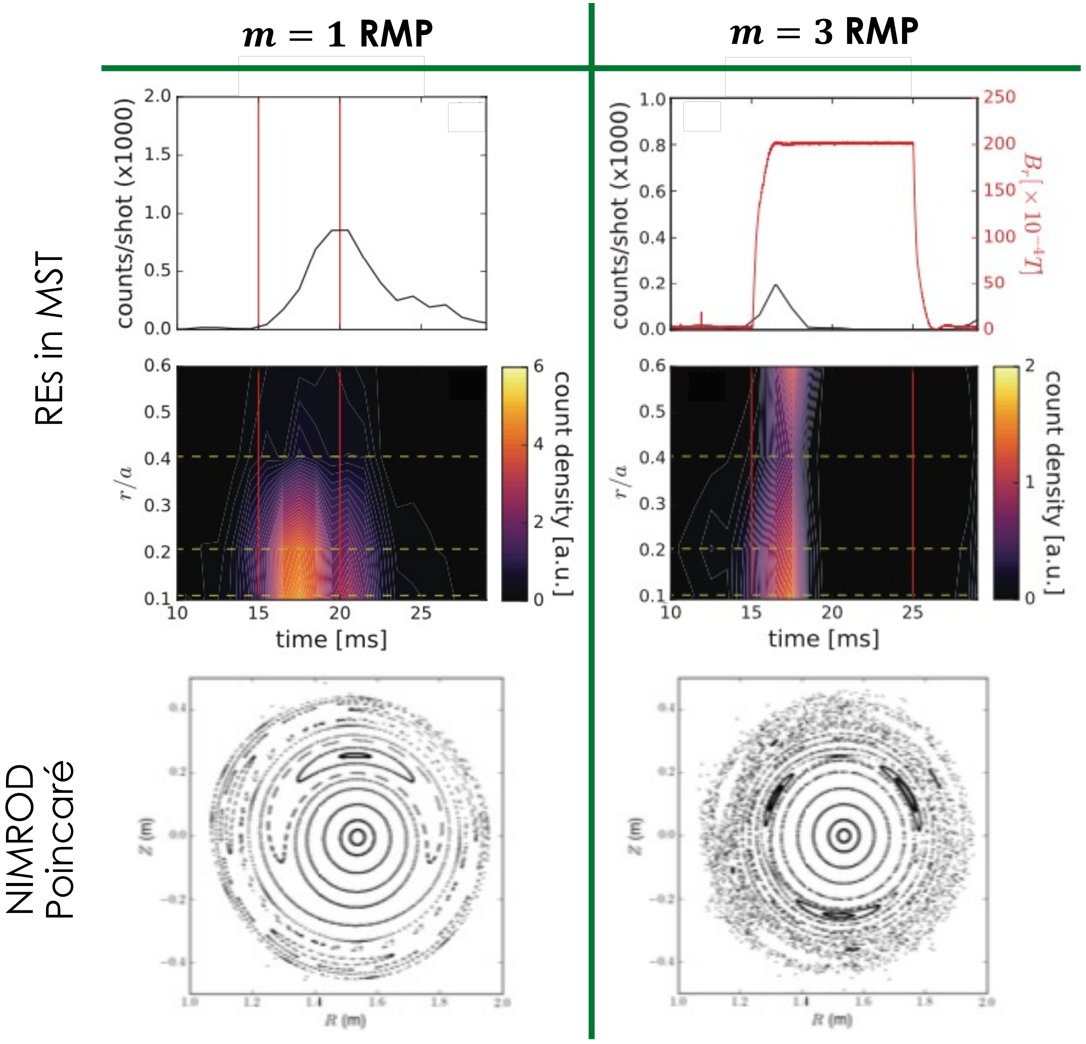
Interpolation with native resolution yields higher fidelity fields for particle tracking

- **Poincare sections clearly show difference between PSPLINE, NIMFL, and NIMFIO interpolation for island chains**
  - Using $50\mathrm{G}\; m = 3$ RMP with MST equilibrium to be discussed
  - PSPLINE/NIMFIO interpolation at Poincaré section is different order than NIMFL algorithm



Resonant magnetic perturbations can deconfine REs in MST tokamak discharges

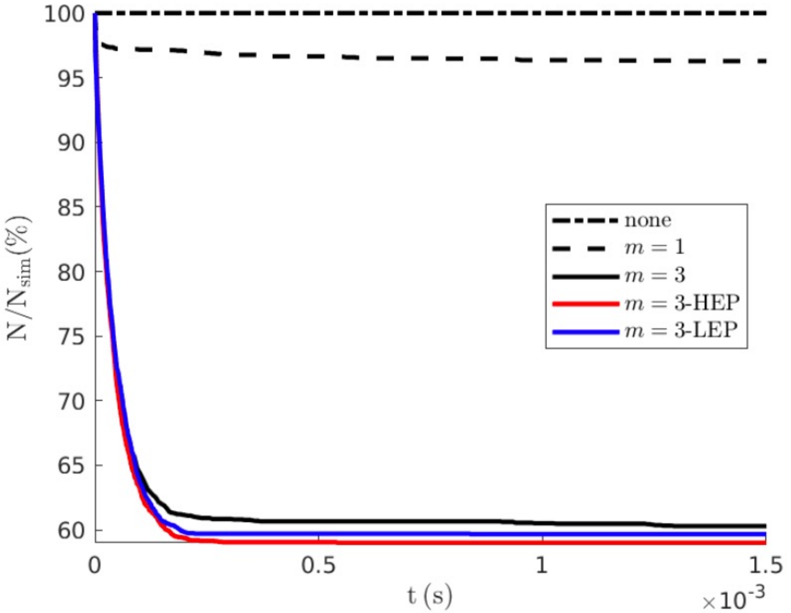
- **REs generated by electric field acceleration in low density operation**
  - Munaretto et al., *Nucl. Fusion* (2020)
  - Observed via bremsstrahlung X-rays with FXR and HXR array diagnostics
- **$m = 1, 2, 3$ modes are internally resonant**
  - $m = 3$ RMPs deconfine REs, $m = 1$ do not, $m = 2$ are ambiguous (not shown)
- **NIMROD simulations show sawtooth activity with stochastic edge**
  - Carl just discussed this is depth

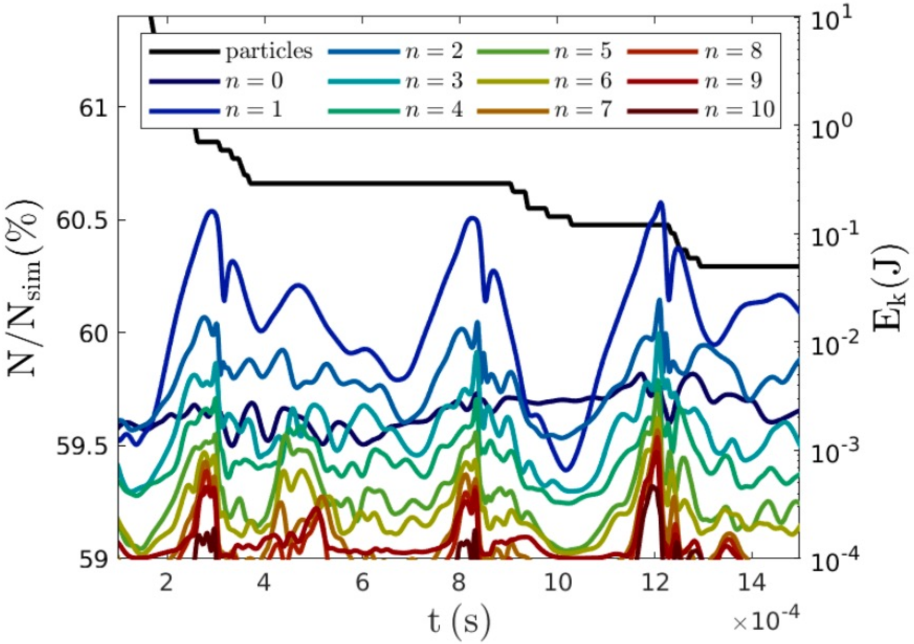


Munaretto et al., *Nucl. Fusion* (2020), Cornille et al., APS (2021)

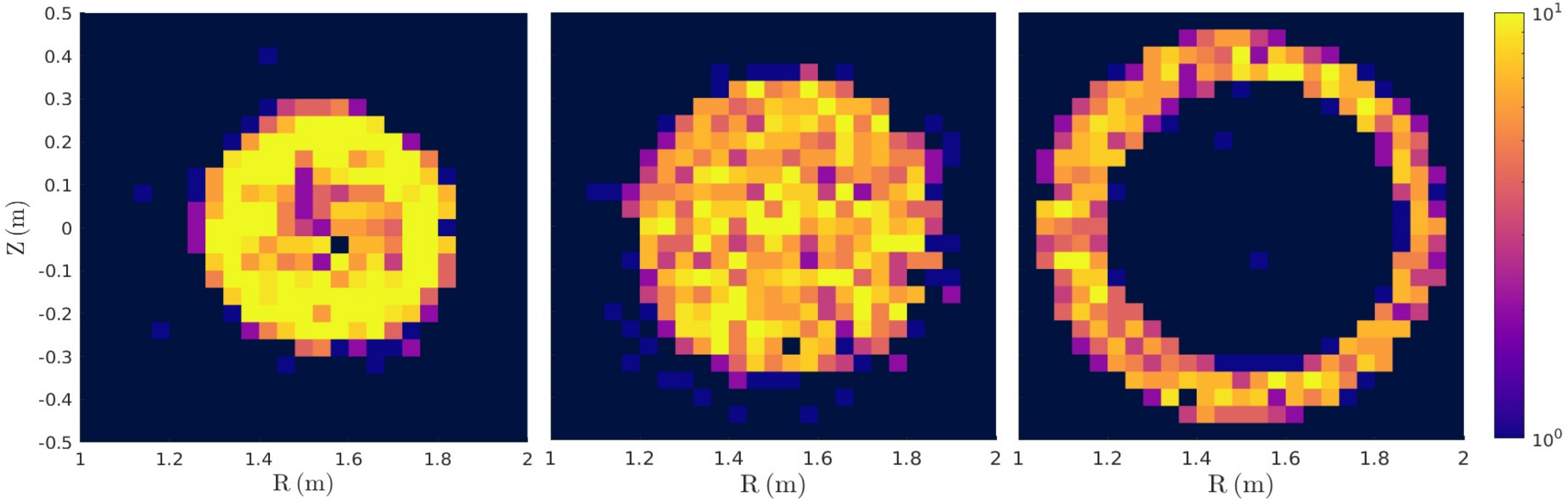
KORC calculations with time-dependent NIMROD $m = 3$ RMPs yield significant but not complete deconfinement

- **Initial RE beams are monoenergic $E = 10\mathbf{keV}$, monopitch $\eta = 170°$, and uniformly distributed**
- **Rapid deconfinement of REs initialized in stochastic edge for $m = 3$ RMP case**
  - Few additional losses at each reconnection event





Majority of deconfined REs lost from edge, core REs redistributed by reconnection events



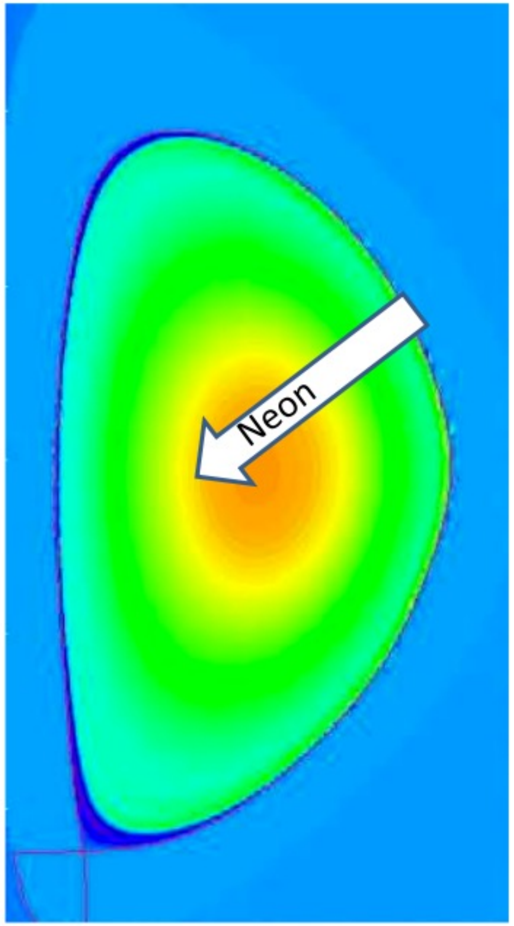
Final location of confined REs

Initial location of confined REs

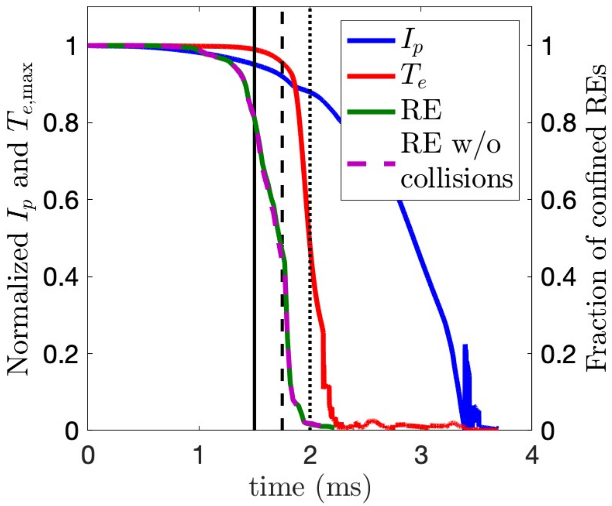
Initial location of deconfined REs

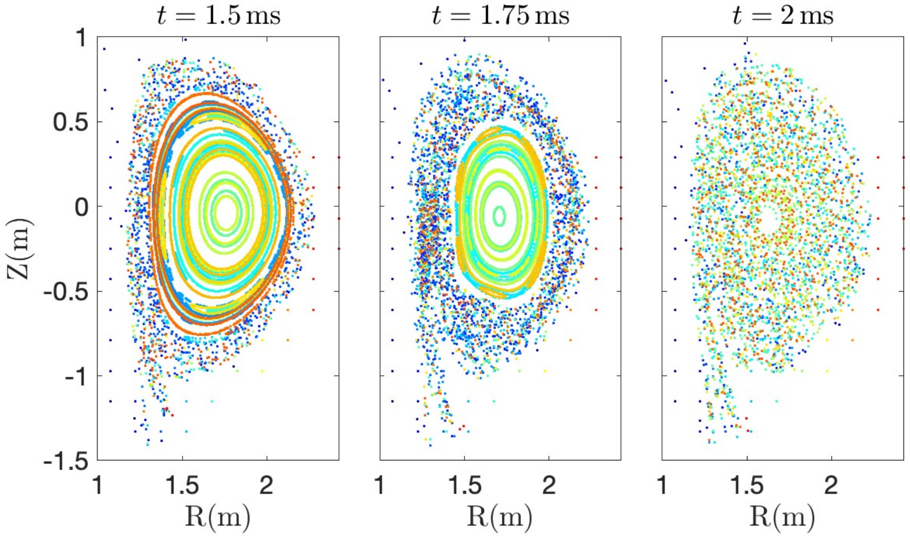
- **Discrepancy with full deconfinement observed in experiment**
  - Possible effect of RMP rise time and sidebands
  - Location of RE generation not captured by HXR
    - New results using multi-energy soft x-ray detector (L. F. Delgado-Aparicio, PPPL) more accurately capture RE generation and early transport

KORC is modeling RE transport in stochastic magnetic fields from 3D extended-MHD simulations



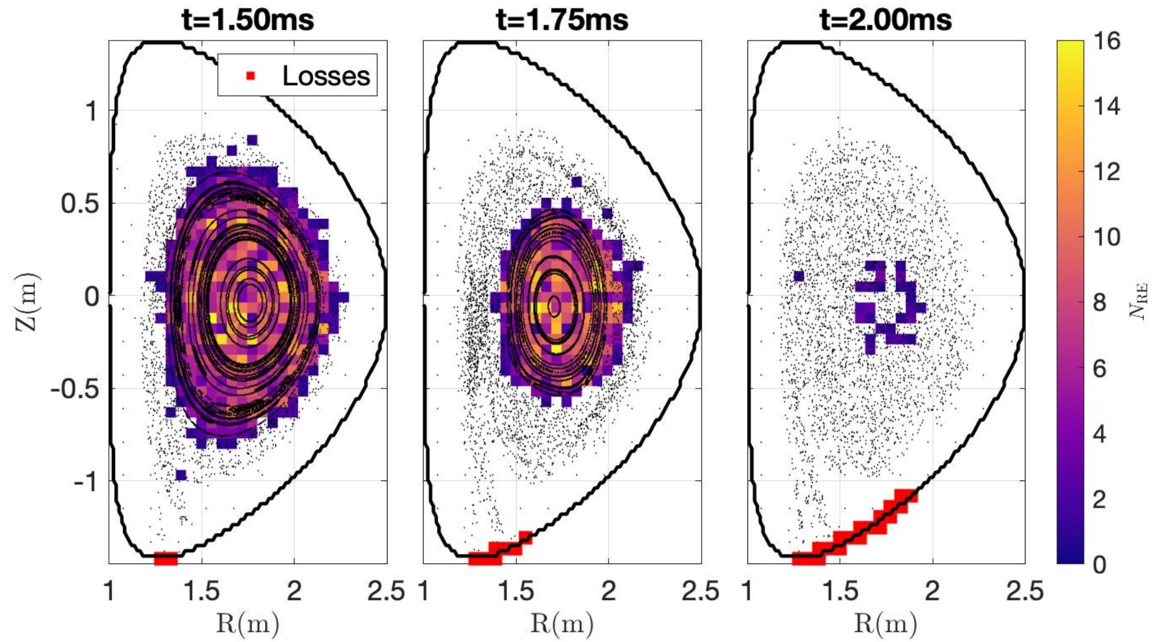
- **M3D-C[1] simulation of Ne pellet into DIII-D #160606**
  - Experiment doesn't result in a post-disruption RE beam
- **KORC guiding center orbits with electric field acceleration, Coulomb collisions, RE radiation**
  - Initial RE beams are monoenergic $E = 10\mathrm{MeV}$, monopitch $\eta = 10°$, and uniformly distributed within LCFS
- **All REs are deconfined during the TQ on a faster time scale than the thermal energy loss**

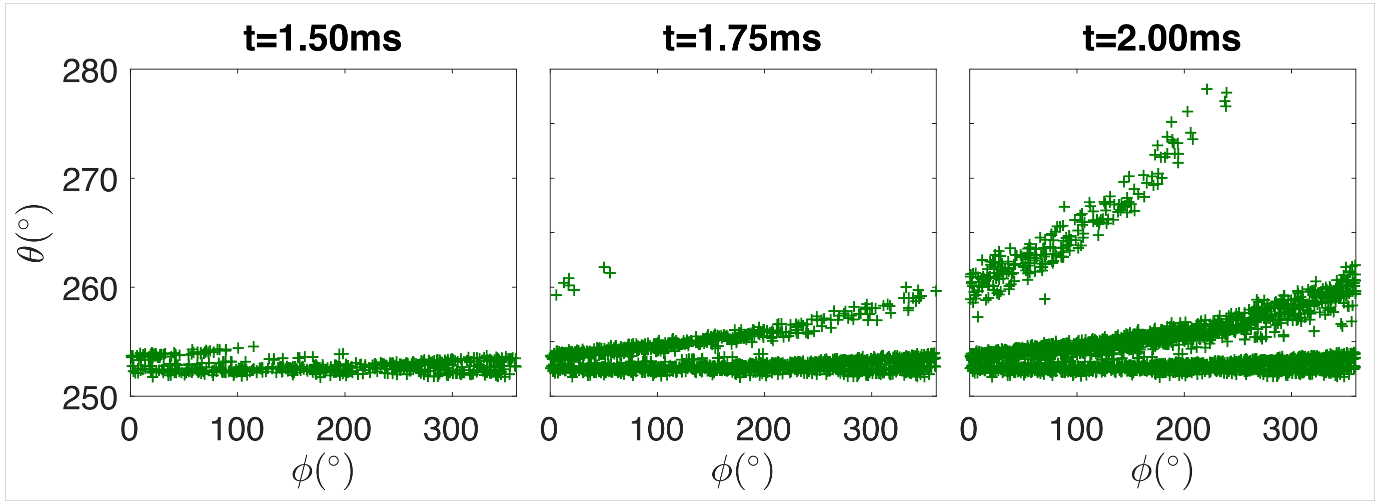




REs are increasingly deconfined as MHD mode and stochasticity grows

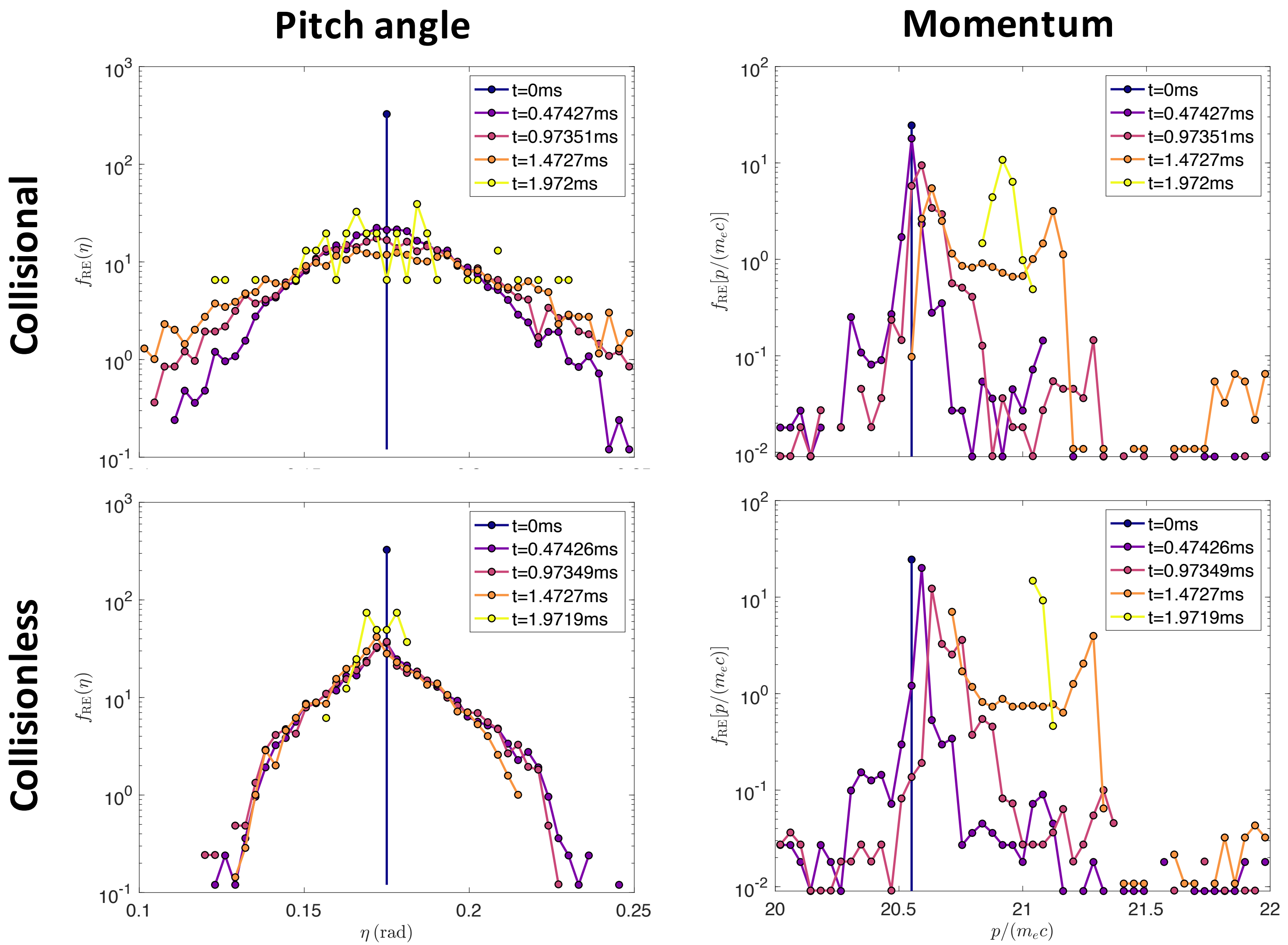
- Collisionless and collisional KORC simulations yield qualitatively similar results
- Wetted area spirals out as MHD mode becomes more nonaxisymmetric





Collisions have a small, but finite effect on the RE distribution evolution

- **Collisional time scales are much longer than deconfinement (~1ms)**
  - Pitch angle scattering $\tau_D = 140\text{ms}$
  - Slowing down $\tau_S = 55\text{ms}$
- **Pitch angle scattering is more than phase mixing in collisionless case**
- **Electric field acceleration is counteracted slightly by slowing down**

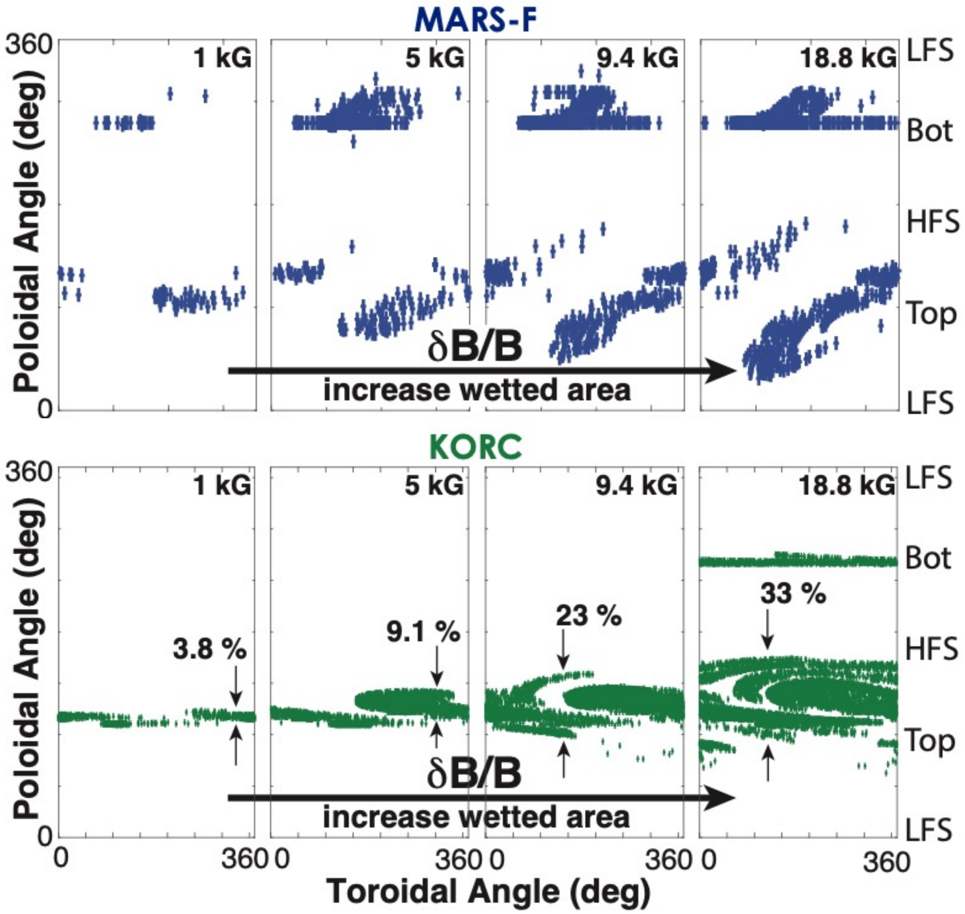


KORC coupling with M3D-C1 and NIMROD future work

- **Early Career Award project with postdoc Omar Lopez**
  - "Hybrid Kinetic-Fluid Modeling of Tokamak Disruption Mitigation"
- **Having KORC coupled in memory with NIMROD will enable more efficient/accurate tracer RE calculations**
  - Extending Val Izzo's work by including collisional effects
- **Look at power deposition and PFC heating from Liu et al. *PPCF* (2021) of RE mitigation with low-Z impurities**
- **Study localization of Dreicer and avalanche RE growth in simulations of disruption mitigation with different impurities**

KORC coupling with MARS-F studies deconfinement due to perturbations from unstable MHD modes

- **Began using KORC to model deconfinement losses due to unstable MHD modes in low-Z RE mitigation**
  - FO KORC compared to GC MARS-F
- **Presently engaged in ITPA DivSol/MDC collaboration: "Characterization of power deposition to PFCs by runaway electrons"**
  - Comparison of high-Z vs low-Z RE final loss events

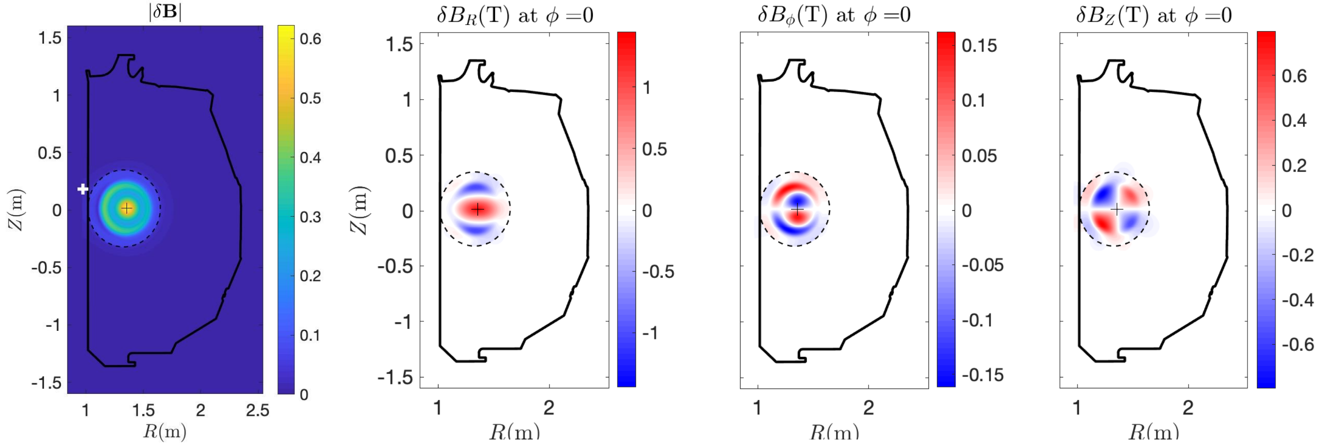


Strike patterns for MARS-F calculated resistive external kink mode in DINA-ITER simulations

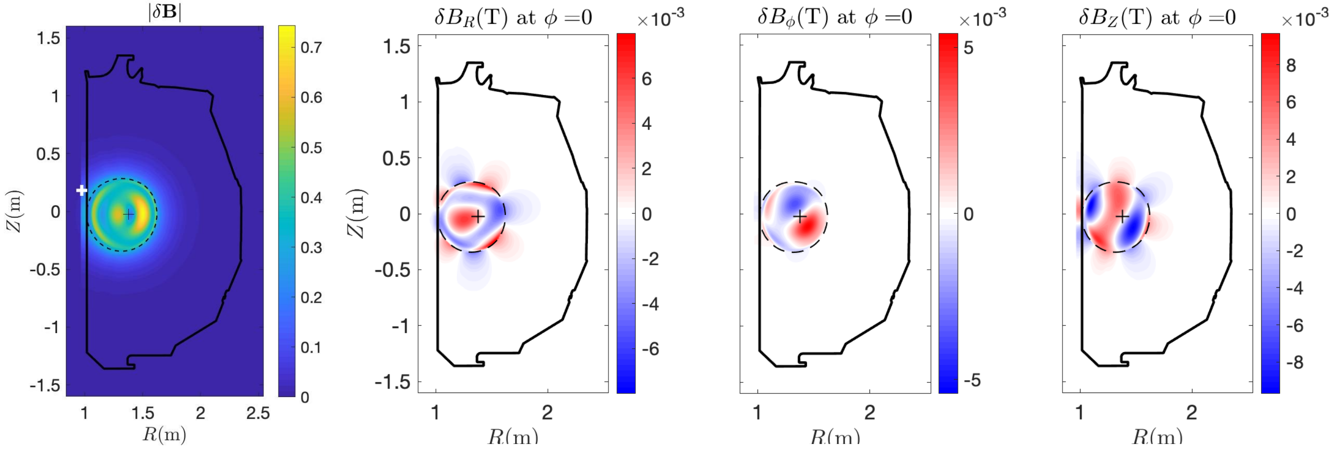
MARS-F 3D perturbation fields scaled to n=1 experimental signals on DIII-D final loss events

- **Toroidal array of B_Z magnetic pickup coils fit to n=1**
  - Located at white plus in left column plots
  - 636.3 G for low-Z
  - 28.76 G for high-Z
- **Complex norm of MARS-F B_Z perturbation field is $|\delta B_Z| = \sqrt{B_Z B_Z^*}$**
  - Scale complex norm to experimental fit
- **Maximum physical field $\delta \vec{B}_p$ is larger than $\vec{B}_{p,0}$ for low-Z injection**

DIII-D #184602: low-Z injection



DIII-D #185604: high-Z injection

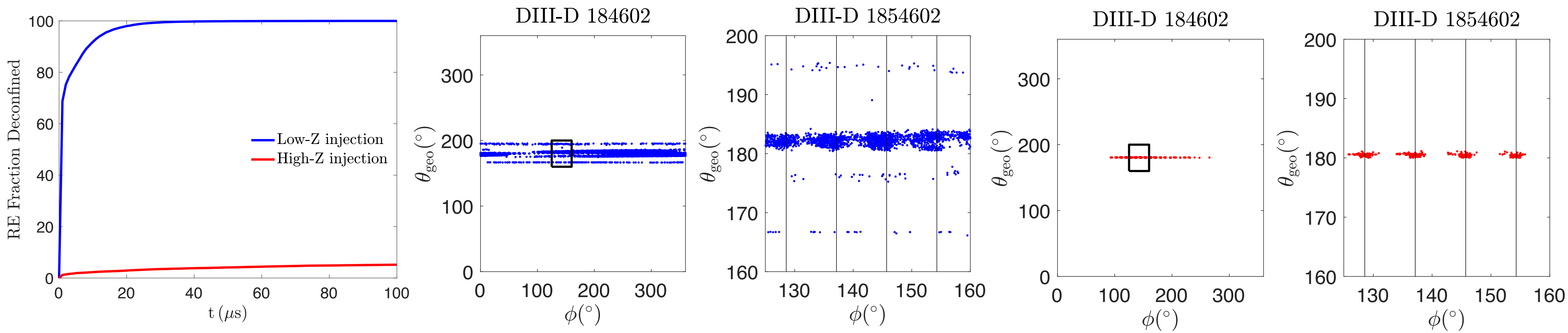


Complex norm of MARS-F fields

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

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

- **Initial RE beam is monoenergic $E = 10\text{MeV}$, monopitch $\eta = 170°$, and uniformly distributed within LCFS**
- **Two stage KORC simulations with MARS-F 3D fields**
  - Evolve orbits for $100\mu s$ in equilibrium fields where unconfined REs exit the simulation domain and phase mixing occurs
  - Reinitialize simulation including $\delta\vec{B}$ fields and evolve for $100\mu s$
- **REs are deconfined on DIII-D center post**
  - Inner wall limiter modeled as 42-sided polygon with circumradius of $R_c = 1.016\text{m}$
  - All REs lost for low-Z injection over a larger wetted area compared to high-Z injection

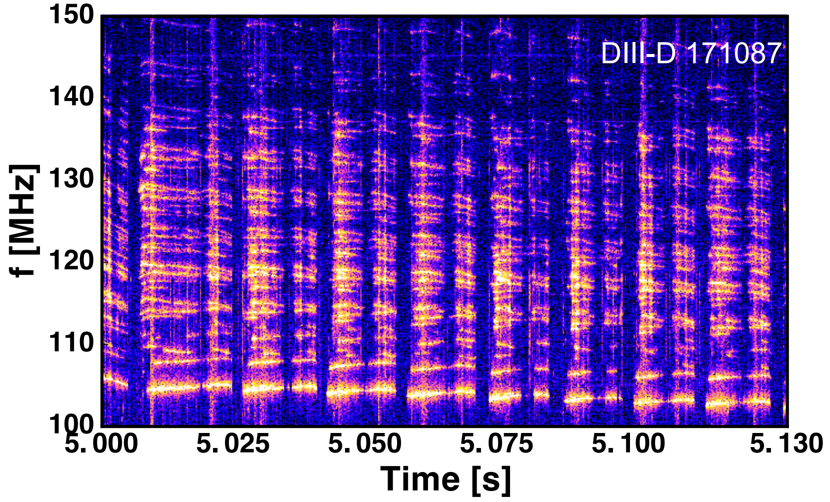


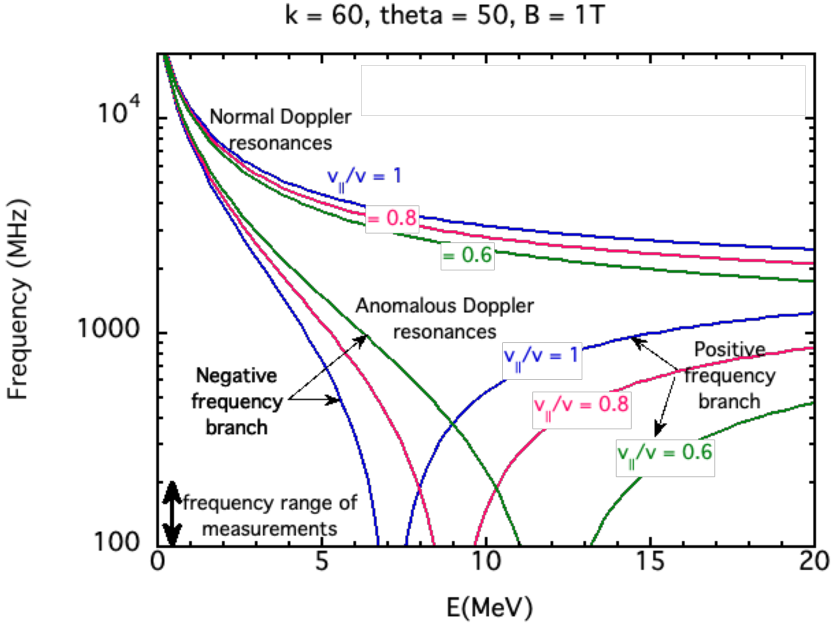
KORC coupling with MARS-F future work

- **Ongoing ITPA collaboration to understand energy deposition during final loss events**
  - Passing KORC data to ITER organization to run through GEANT4/MEMOS-U analysis of energy deposition/heating
  - Similar analysis for JET pulses and DINA-ITER simulations
- **Enable interpolation using MARS-F field representation (toroidal/poloidal Fourier, radial finite difference with packed mesh)**
  - Full orbit vs guiding center model comparisons
  - Deconfinement for different unstable MHD modes

Experiments indicate that REs interact with whistler waves

- **DIII-D Frontier science program**
- **Toroidally separated magnetic pick-up loops measure fluctuating $\widetilde{B}_\phi$**
  - In the $\sim 100\mathrm{MHz}$ range
  - Multiple frequency bands
  - Correlated with hard x-rays, non-thermal ECE, visible synchrotron
- **Wave-particle resonance of REs with whistler wave**
  - $\omega - k_\parallel v_\parallel - k_\perp v_d - l\Omega_{ce,0}\gamma = 0$
  - $l = -1$ corresponds to anomalous Doppler resonances in experimental range of frequencies
  - Many resonances for different RE energy/pitch and wave frequency/mode





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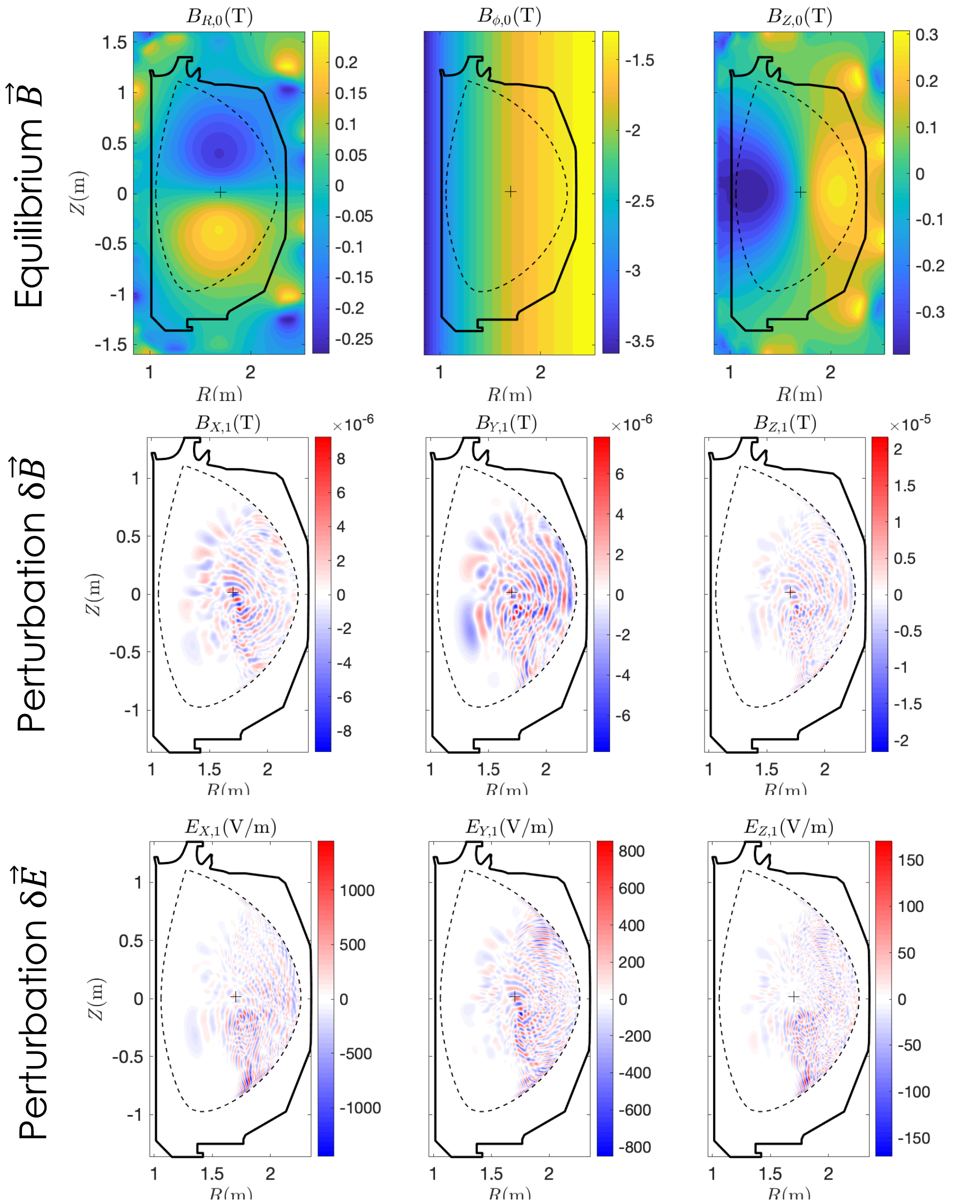
KORC coupling with AORSA studies interaction of REs with whistler waves

- **AORSA yields full solutions to inhomogeneous wave equation**
  - MHD equations reduced to 3D eigenmode problem with external antenna currents
  - Calculates complex magnetic and electric fields
  - Wave amplitudes are not matched to experiment, need to scale
- **Modeling DIII-D #171089 at 5450ms**
  - EFIT axisymmetric magnetic reconstruction
    - No DC toroidal electric field
  - 200MHz, $n = 35$ AORSA calculations drive whistler wave with modeled antenna
    - Globally varying $k_{\parallel}$
  - $$\delta\vec{B}(\phi,t) = \mathrm{Re}\{\delta\vec{B}_{\mathrm{AORSA}}\}\cos(\omega t + n\phi) + \mathrm{Im}\{\delta\vec{B}_{\mathrm{AORSA}}\}\sin(\omega t + n\phi)$$
    - Plots for $\phi = t = 0$



Preliminary results indicate significant resonant energy evolution and pitch angle scattering

- **Initial RE beam is monoenergic $E = 15\text{MeV}°$ and uniformly distributed within LCFS**
  - Using estimate of $k_{\parallel} = 38.5\text{m}^{-1}$ yields resonant energy
  - Scale AORSA fields by $10^4 \rightarrow \delta B/B_0 \sim 10\%$
  - Look at monopitch $\eta = 170°, 10°$
- **Full orbit KORC calculations exhibit complex dynamics of pitch angle scattering and resonant interaction of REs with globally varying whistler wave eigenmode**