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IPP

Non-linear 3D hybrid kinetic-MHD studies of runaway electron beam termination events

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EUROfusion

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Disruptions and runaway electrons

- Disruptions remain one of the biggest problems in the design of large scale tokamak reactors.
  - Large EM forces on the vessel.
  - Substantial heat loads on the first wall.
  - **Generation of highly energetic runaway electrons (REs).**
- REs can strike the wall in a highly localized manner, leading to subsurface melting and posing a threat to the integrity of the cooling channels.
- Avalanche generation is <u>exponentially sensitive to pre-disruption plasma current</u>.

Illustration taken from: *M. Hoppe, PhD thesis (2021)*

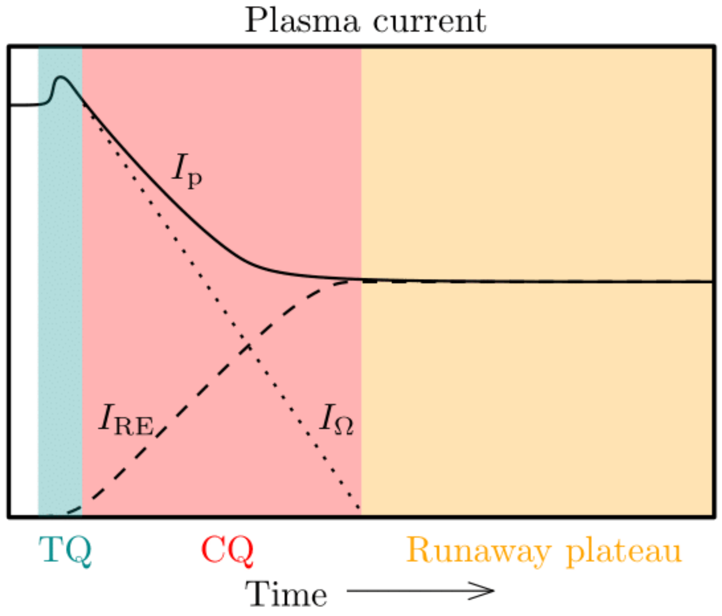


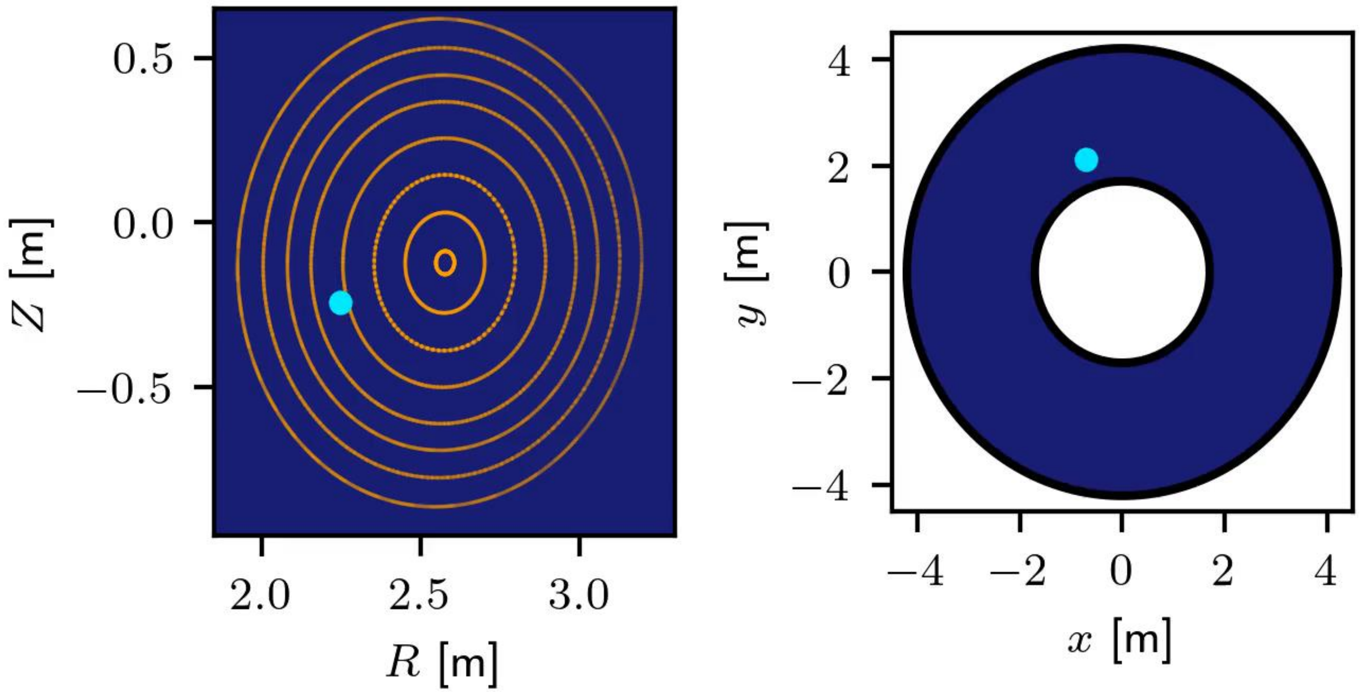
Image taken from: https://www.iter.org/newsline/-/2234

The challenge of self-consistent RE modeling

- Self-consistent disruption simulations require that the interplay between REs and bulk plasma is considered, as it can play a crucial role in:
  - Determining the magnitude of the electric field.
  - Affects force balance.
  - Heating the plasma through collisions.
  - Ionizing the plasma through collisions.
- RE transport occurs on a smaller time scale compared to e.g. growth of MHD instabilities and other transients during a disruption. **Self-consistent simulations of transport in 3D fields is difficult!**

Kinetic REs in JOREK

- REs simulated kinetically by pushing macroscopic marker particles in the JOREK fields.
- Downside: Markers evolved on small time scales, can be computationally expensive.
- Advantage: Phase space information retained and transport accurately captured.
- Both full-orbit and gyrokinetic models have been implemented.



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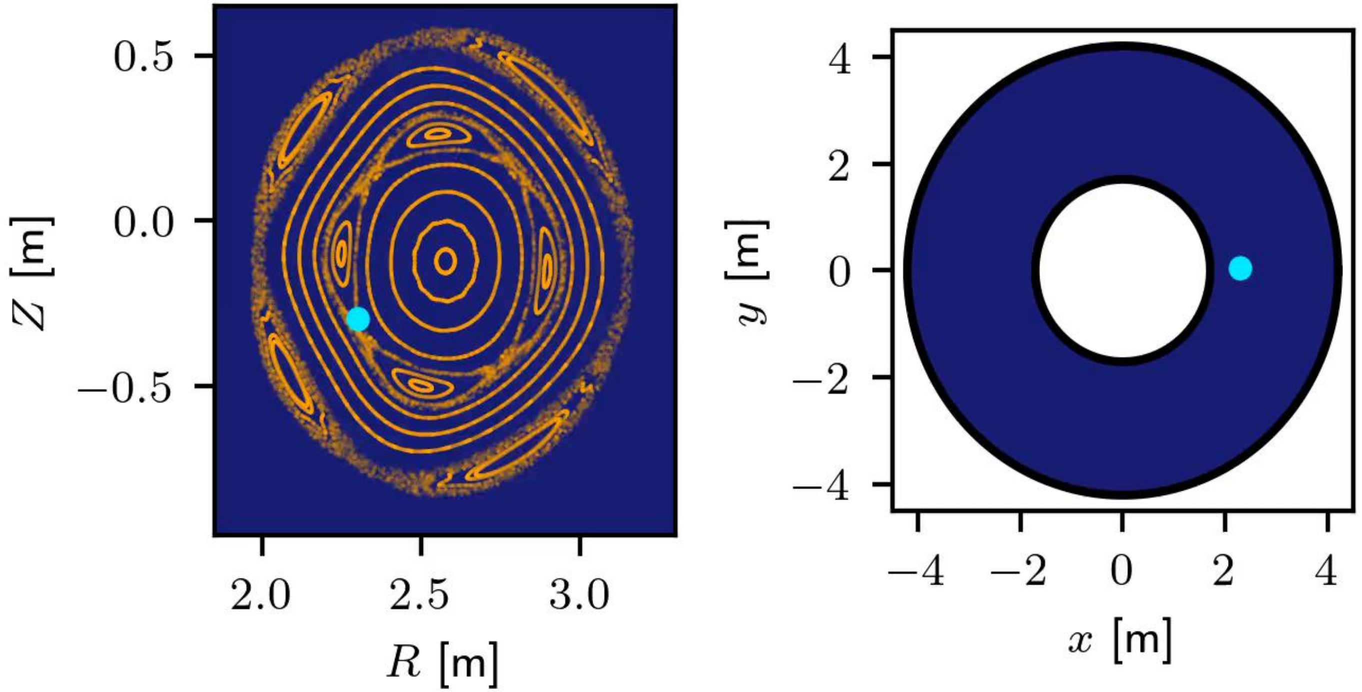
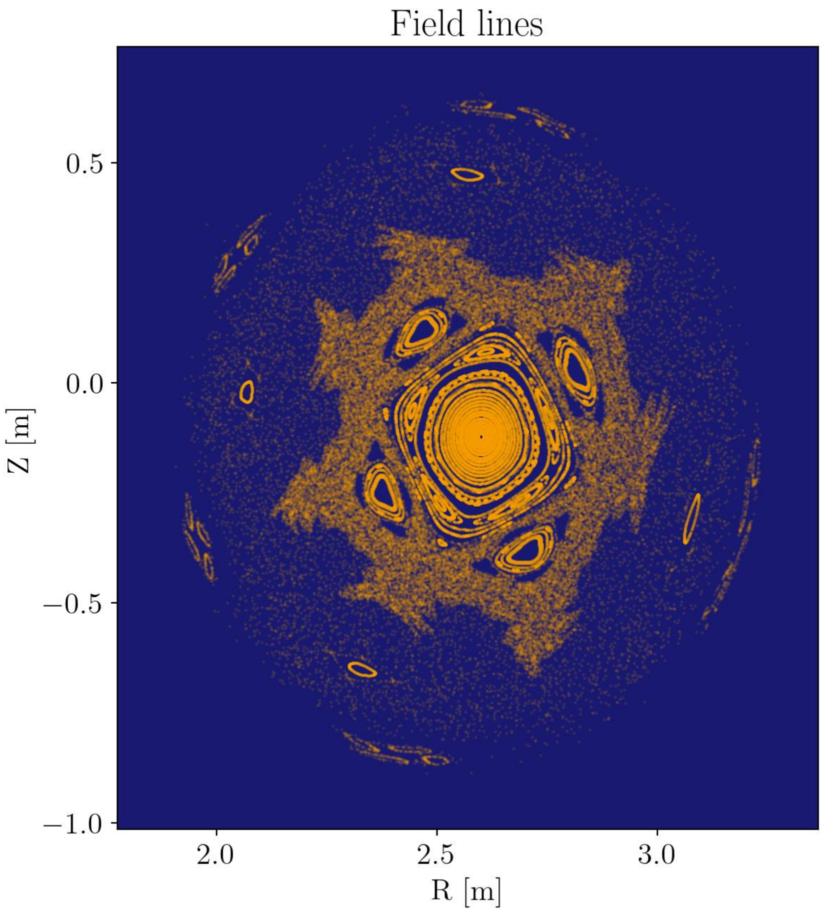
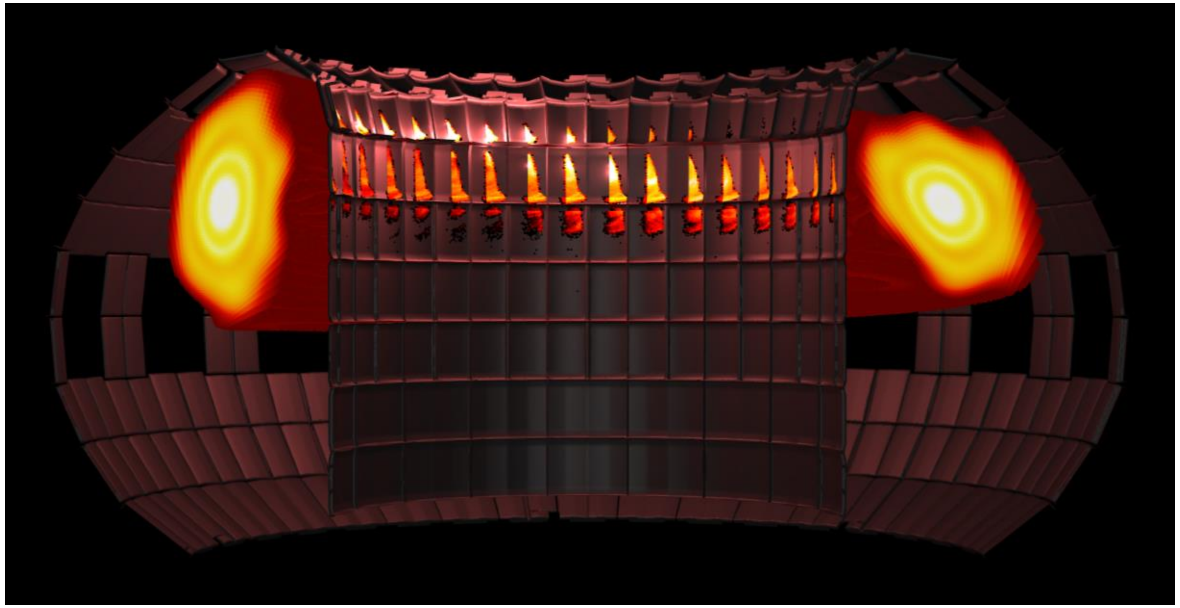


Kinetic REs in JOREK



Towards a more self-consistent treatment

- Kinetic model often used as a form of post-processing.
- Fluid RE model allows for more self-consistent treatment of MHD.
- Most accurate picture obtained when coupling kinetic RE model to the MHD.



Example from ITER simulation using RE fluid model.
Kinetic post-processing used to estimate heat loads.

This work: introduction of a full-f particle-in-cell scheme for coupling fully kinetic REs to the MHD

See also poster on Saturday by S-J. Liu (3045) for a drift kinetic version.

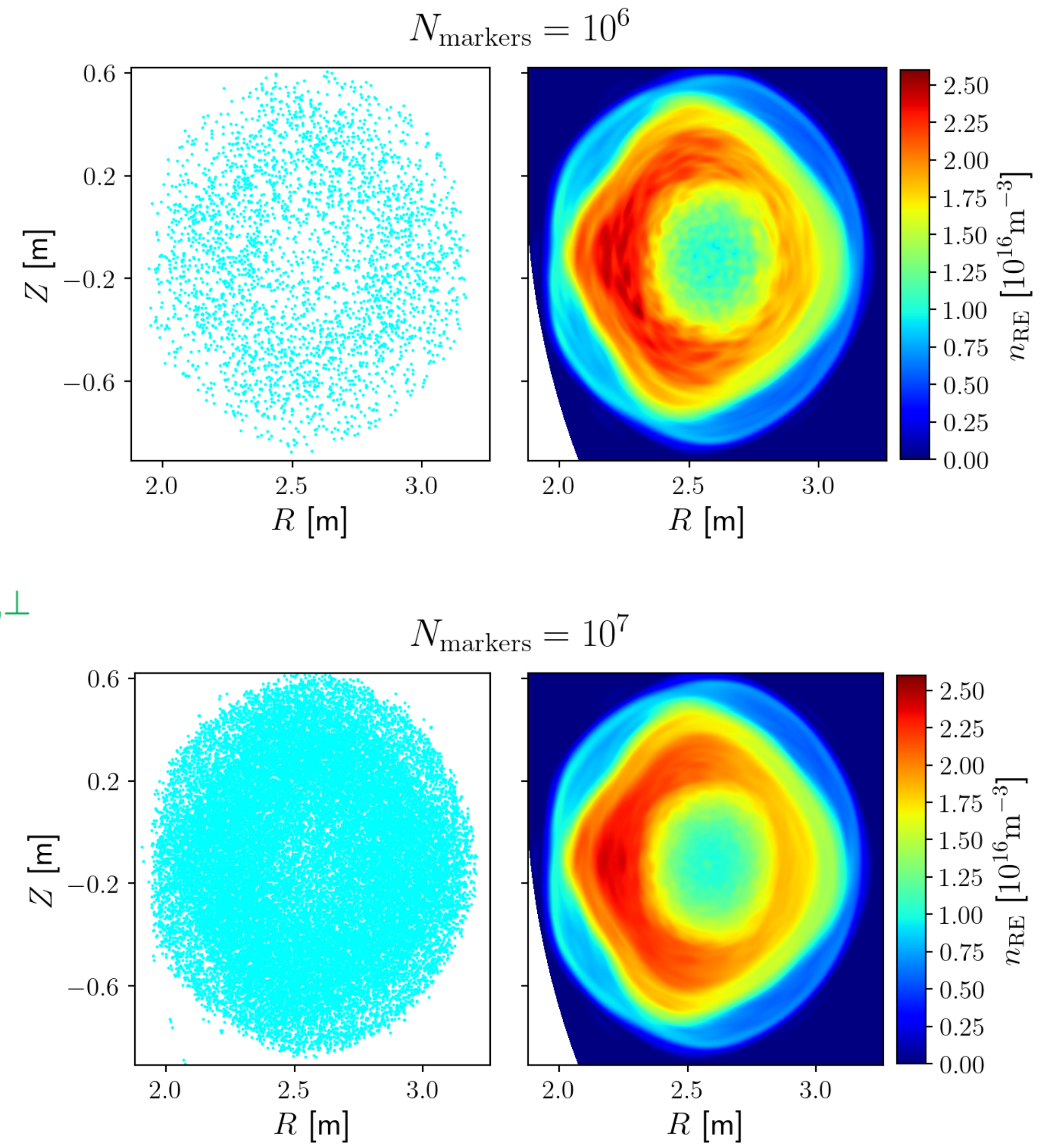
Coupled full-f relativistic kinetic RE model

- Full-f treatment sets constraints on number of markers used.
- Full orbit REs requires small time step, in the order of ~$10^{-13} – 10^{-11}$ s.
- For numerical efficiency we use the *pressure coupling scheme*:

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)=\boldsymbol{J}_{\mathrm{tot}}\times\boldsymbol{B}-\nabla p-(\mathcal{P}_{r,\parallel}-\mathcal{P}_{r,\perp})\boldsymbol{\kappa}-\nabla\mathcal{P}_{r,\perp}$$

$$\mathcal{P}_{r,\perp}\equiv\frac{1}{2}\int \mathrm{d}^3v\,\gamma m v_\perp^2 f_r,\quad \mathcal{P}_{r,\parallel}\equiv\int \mathrm{d}^3v\,\gamma m v_\parallel^2 f_r$$

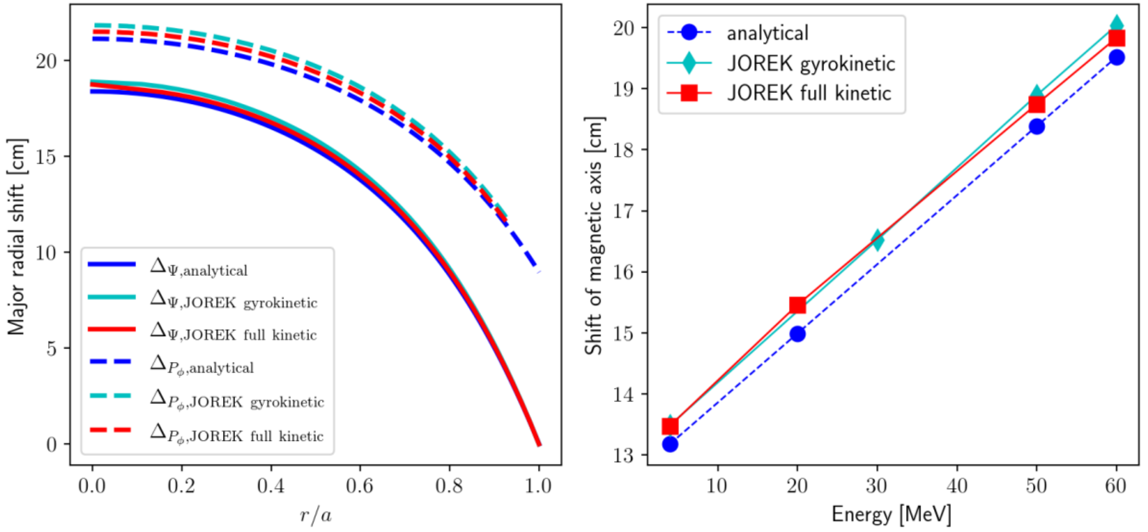
$$\boldsymbol{E}=-\boldsymbol{u}\times\boldsymbol{B}+\eta(\boldsymbol{J}_{\mathrm{tot}}-\boldsymbol{J}_r)-\frac{1}{\sigma_e}(\nabla p_e+\boldsymbol{S}_{\boldsymbol{u}_e})$$



Benchmarking

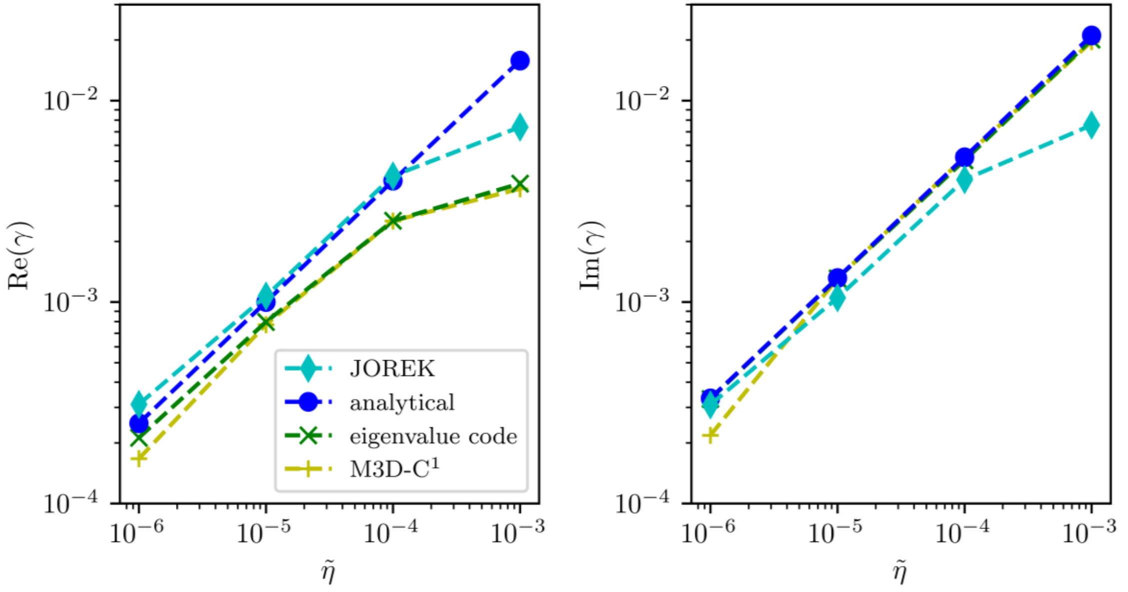
V. Bandaru et al, Physics of Plasmas 30.9 (2023)

- 2D verification by studying changes in radial force balance.
- At high energies, curvature drift leads to Shafranov like shift of flux surfaces.
- Both flux surfaces and drift orbits show good agreement with analytical predictions.



P. Helander et al, Physics of Plasmas 14.12 (2007)
C. Liu et al, Physics of Plasmas 27.9 (2020)

- 3D verification through linear tearing mode (TM) growth rate.
- Low energy limit.
- REs change the expected resistivity scaling and introduce mode rotation.
- See poster on Saturday by S-J. Liu (3045) for non-linear verification.



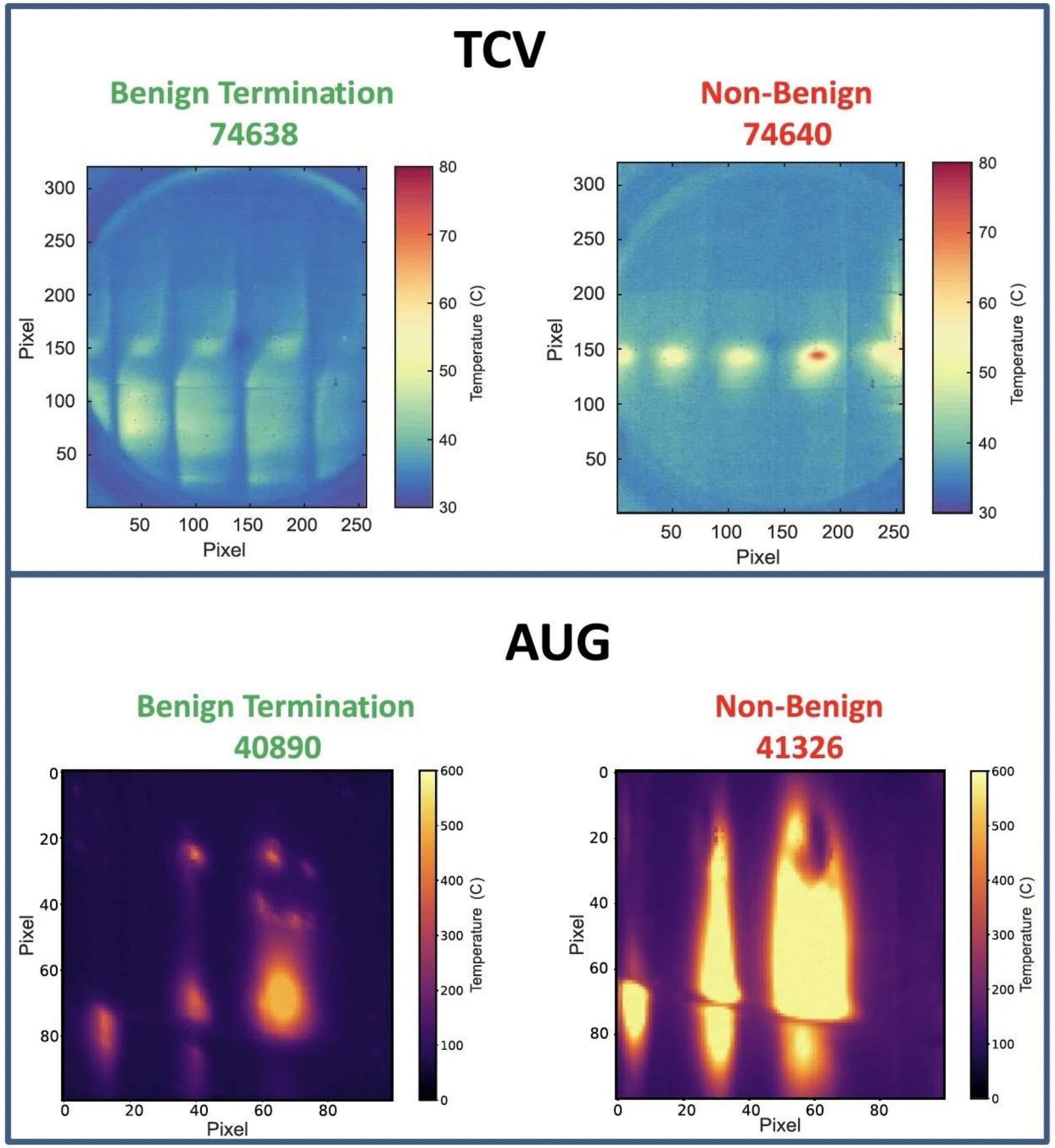
Benign termination of runaway electron beams

The concept of benign termination

Overview was given in poster by U. Sheikh (2818)

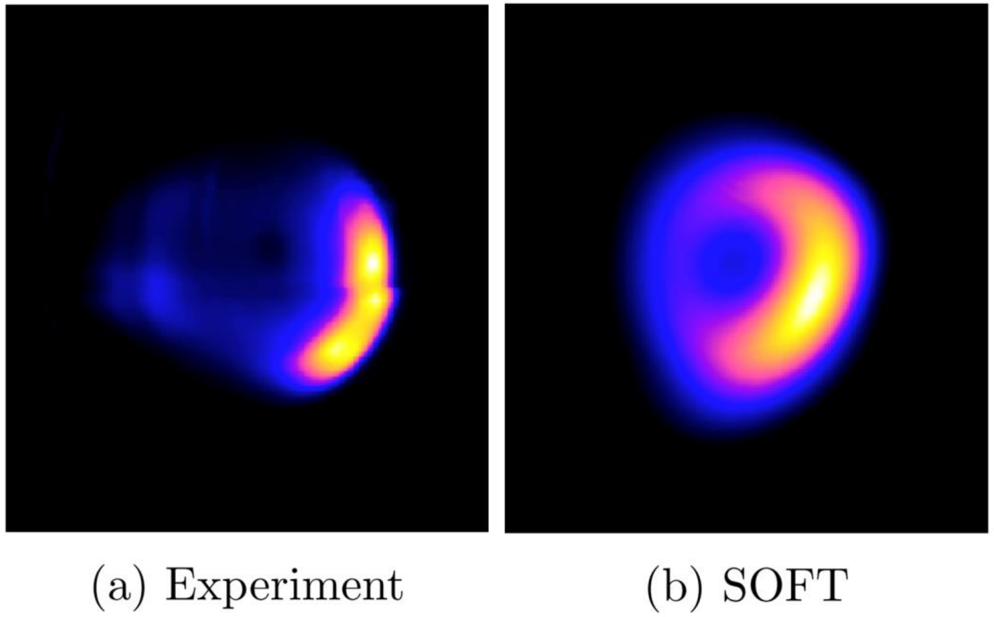
- During RE beam phase: 2nd injection of large amounts of low-Z material recombines the plasma.
- q_{edge} is reduced either through plasma compression or current ramp up → large MHD activity results rapid loss of REs.
- This can reduce heat loads on the wall since:
  - REs are spread over a larger surface area.
  - Lower conversion from magnetic to kinetic energy during the termination.
- Successfully reproduced on DIII-D, JET, TCV, AUG and WEST.
- Current modeling efforts aim to understand the dynamics of the cold companion plasma and the triggering of such a large instability.

Illustrations taken from: *U. Sheikh et al, Plasma Phys. Control. Fusion 66 035003 (2024)*

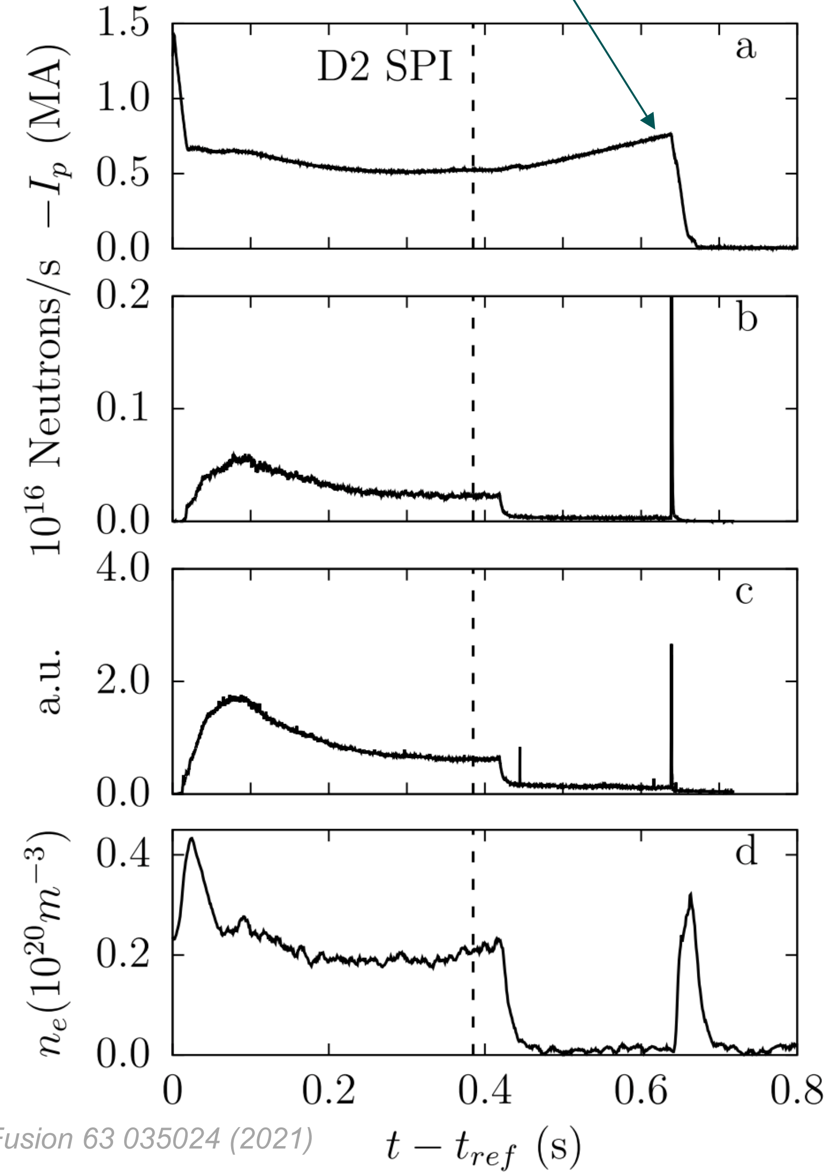


Simulation setup

- First application of coupled model concerns JET shot: **#95135**.
- Simulation starting point a few ms before termination.
- Runaway population initialized based on:
    - Plasma current
    - Observed synchrotron radiation → hollow current profile
    - MHD activity (given different q-profiles)



We are here!



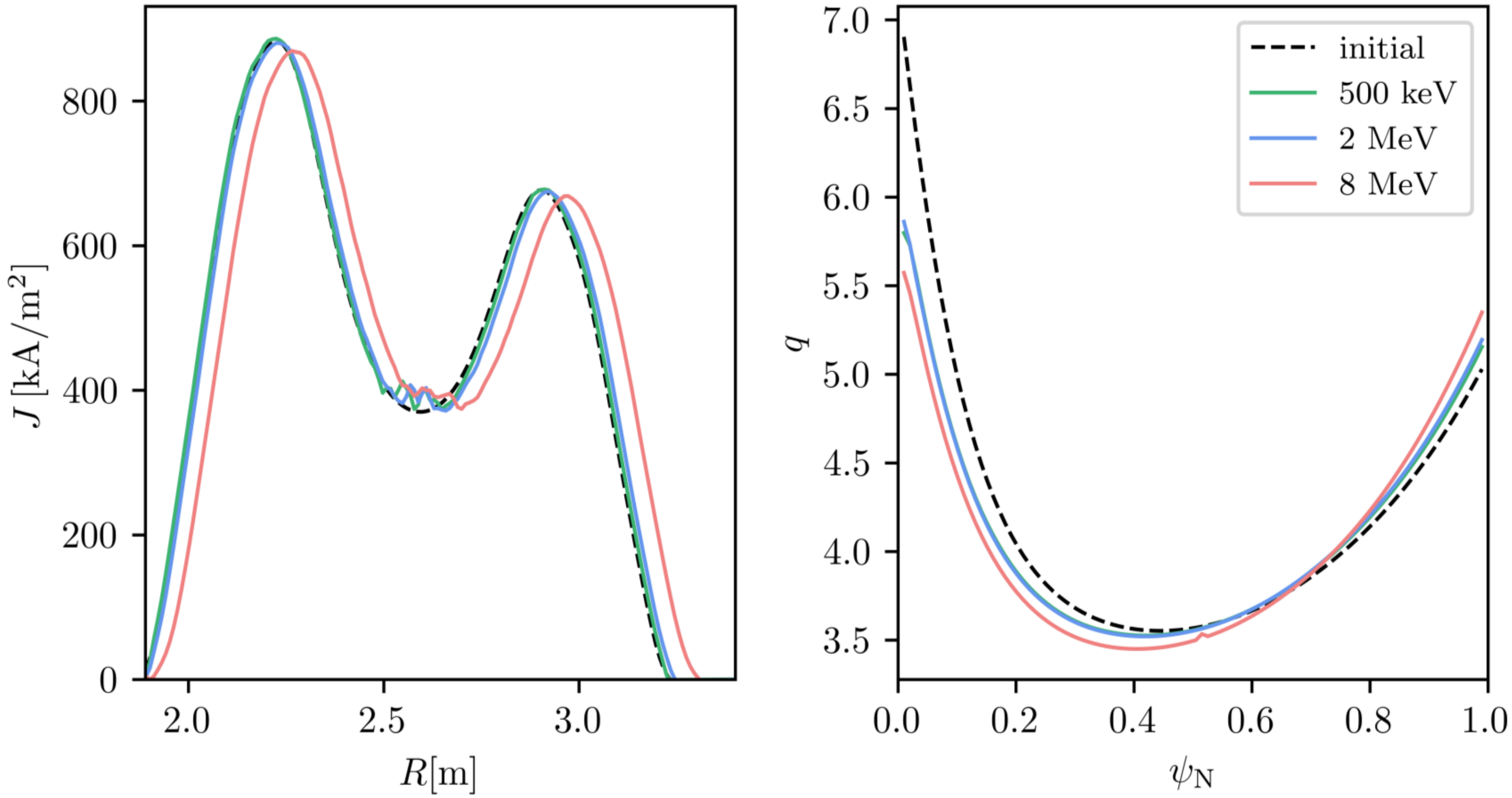
Illustrations taken from: *V. Bandaru et al, Plasma Phys. Control. Fusion 63 035024 (2021)*

Growth of DTM instability

- REEs initialized with pitch 0.99 and energies:

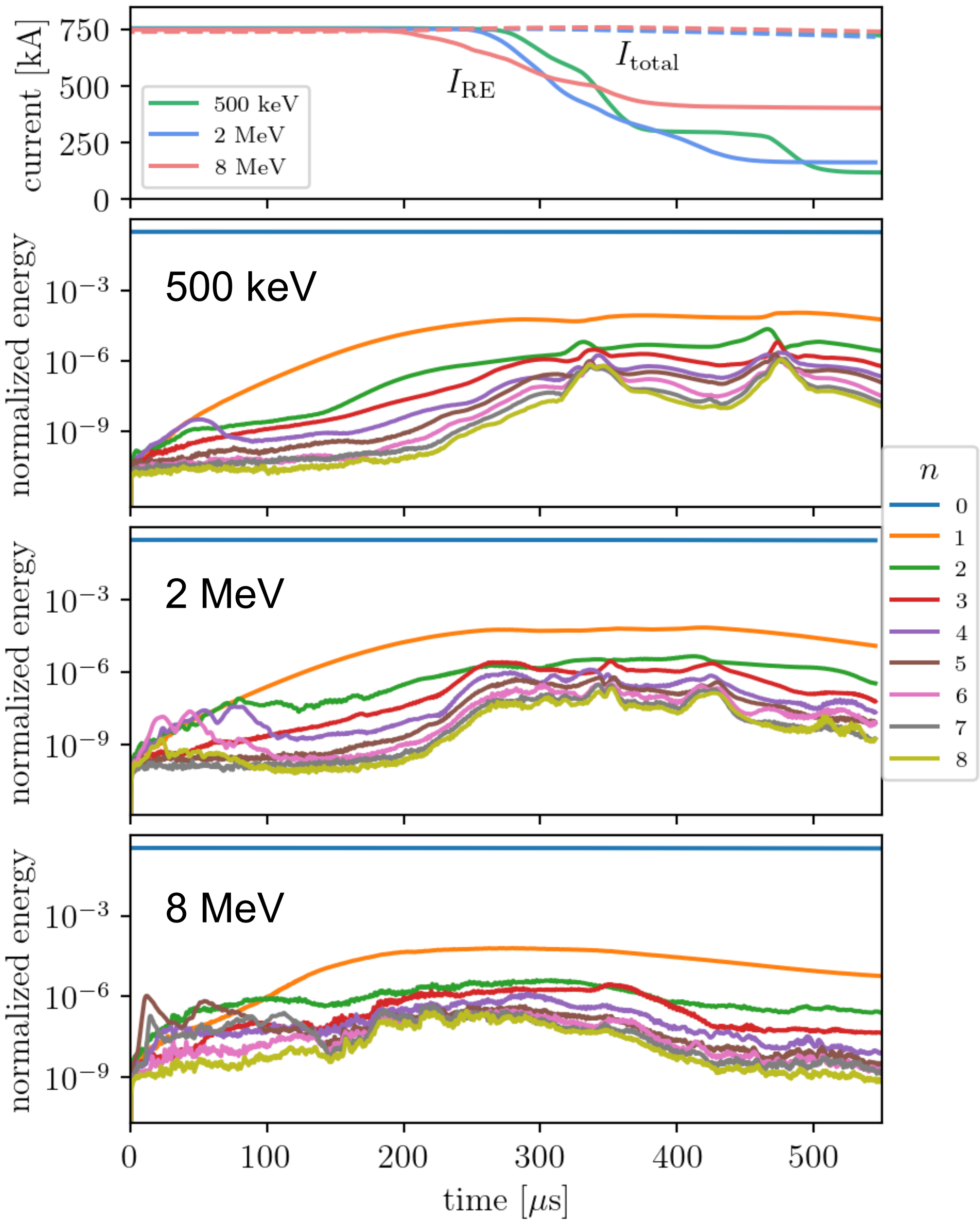
500 keV, 2 MeV, 8 MeV.

- Changes in equilibrium profiles.



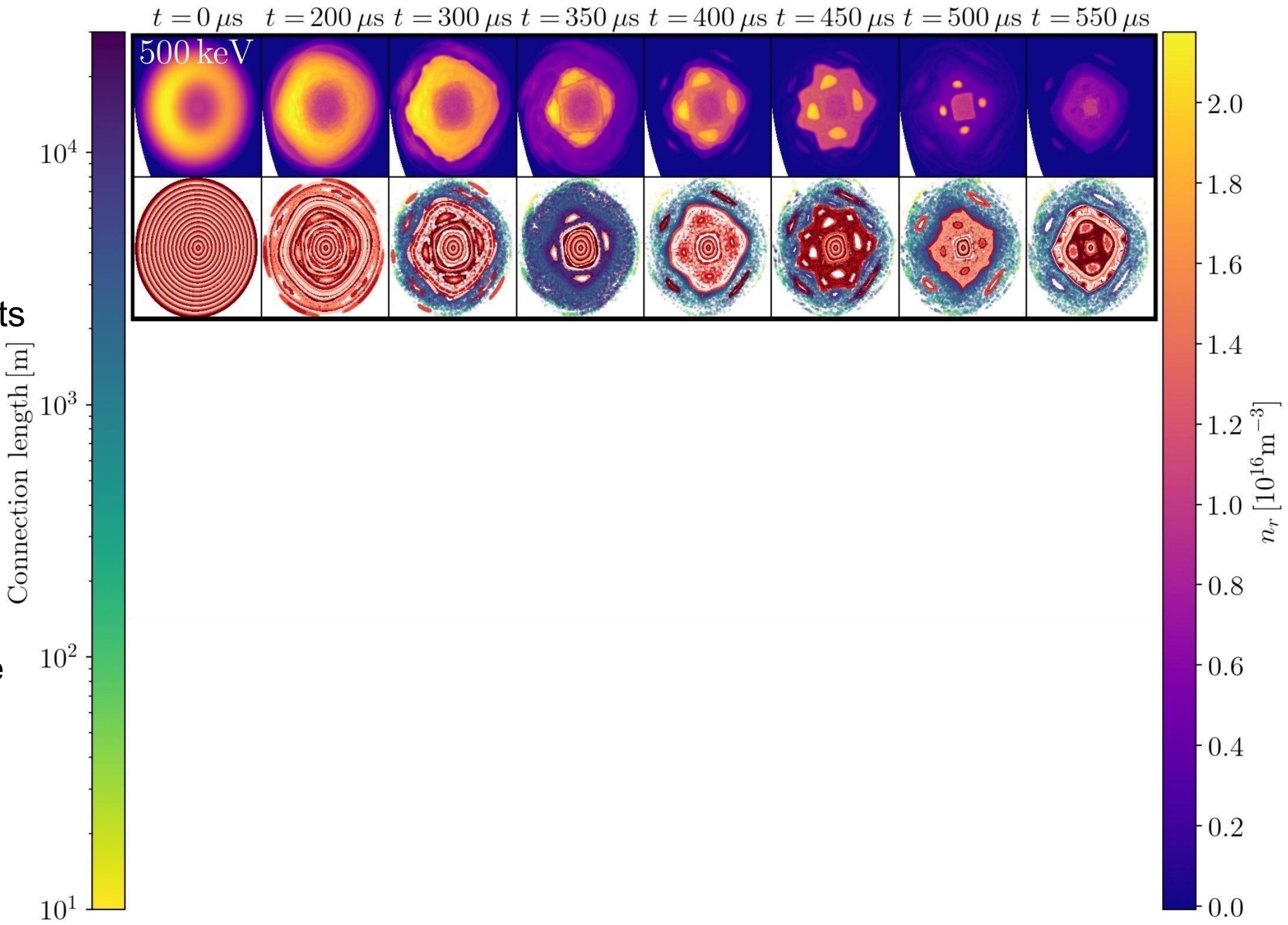
Growth of DTM instability

- REs initialized with pitch 0.99 and energies: 500 keV, 2 MeV, 8 MeV.
- Changes in equilibrium profiles.
- Switching to 3D, rapid growth of (4,1) double TM observed in all cases.
- RE become deconfined after ~200μs for 8 MeV scenario. 2 MeV and 500 keV follow shortly thereafter.
- Losses in 8 MeV case are slower and more steady. Final RE current is ~400 kA, compared to ~160 kA and ~120 kA for 2 MeV and 500 keV cases.



Termination event

- After 200μs:
  plasma clearly deformed by the two m=4 island chains.
- 500 keV:
  Majority of particles lost in short burts around 350μs and 475μs.
- 2 MeV:
  Similar end result, though more like one continuous loss event.
- 8 MeV:
  Very short stochastic phase, degree of stochasticity much lower.



Towards more realistic phase space distributions

- In simulations we have seen indications that the phase space distribution of REs may have a notable effect on the details of the termination.
- Having a continuum of energies/drift orbits may hinder the formation of a thin current layer.
- There are analytical distributions assuming avalanche dominated regime.

- <u>However</u> termination occurs 100s of ms after avalanching has stopped.
- In threshold E-field, REs are expected to gather around some attractor region:
  - Low energy REs are lost to bulk through collisions.
  - High energy REs are limited by synchrotron losses.
  - Details depend on companion plasma.

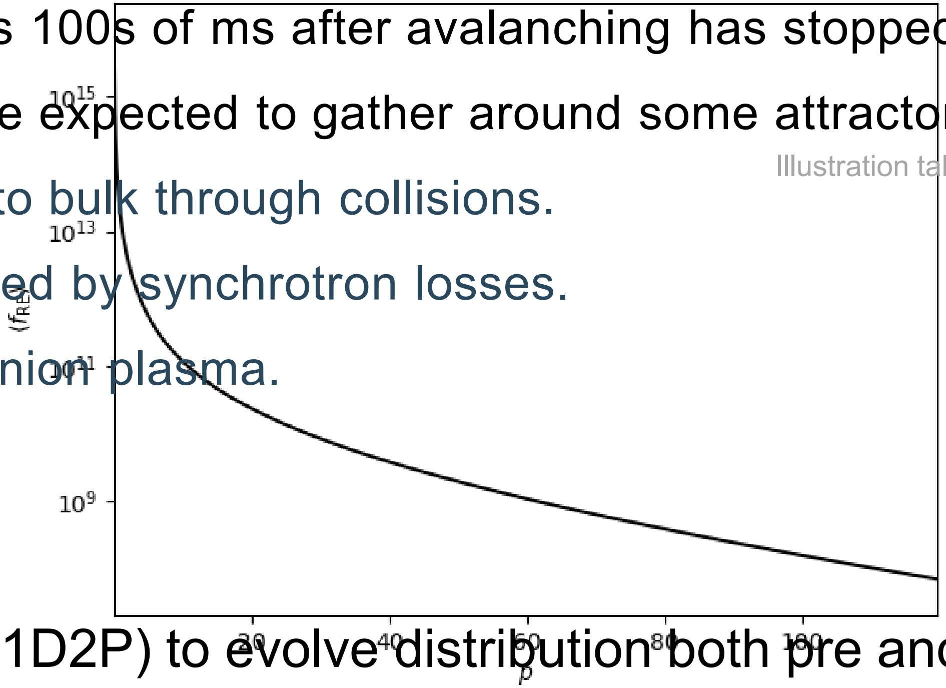
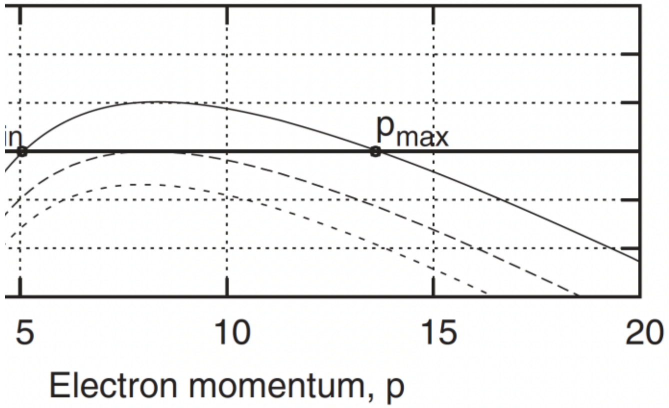


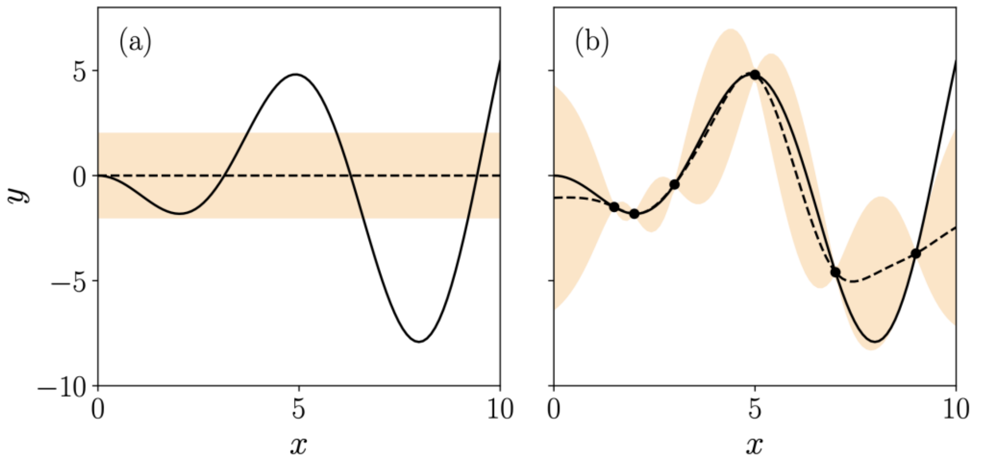
Illustration taken from: *P. Aleynikov et al, PRL 114 155001 (2015)*

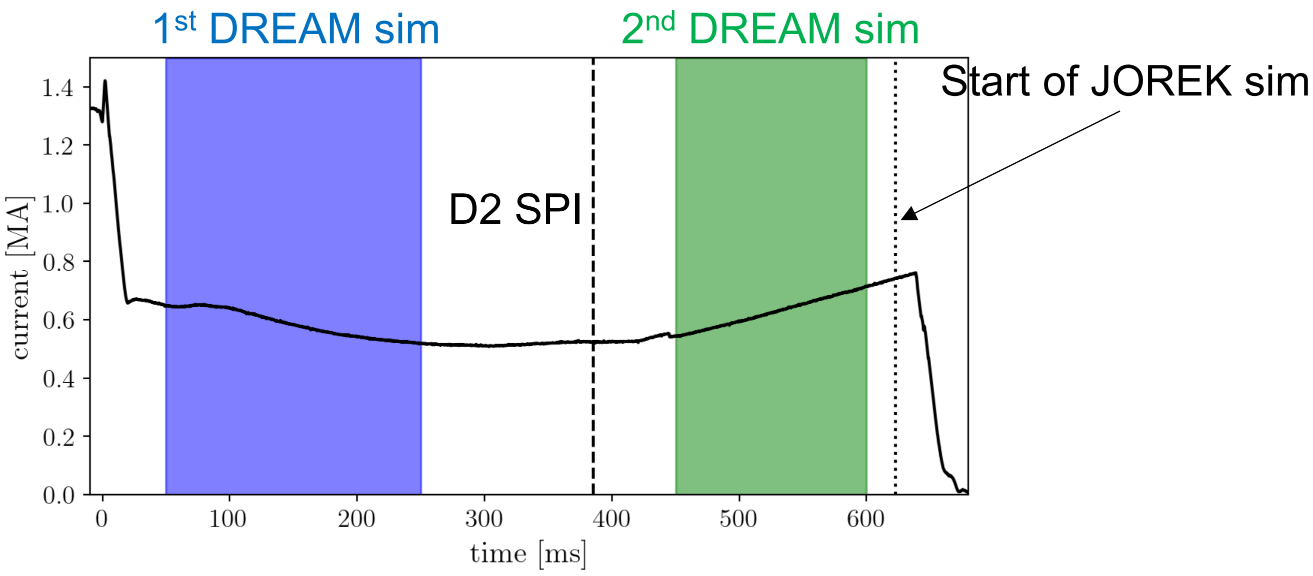


Idea: use DREAM (1D2P) to evolve distribution both pre and post 2nd injection.

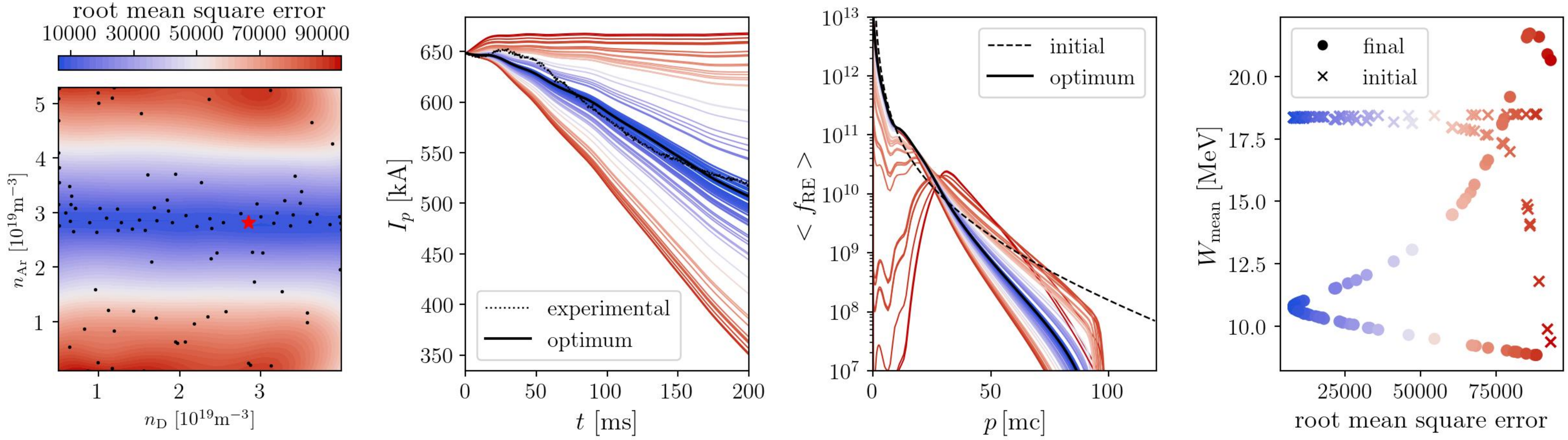
Material densities through Bayesian optimization

- Plasma properties difficult to measure in this phase, in particular after 2nd injection.
- Self-consistent simulations also difficult.
- Simplified approach:
  - Starting with avalanche distribution, 0D in space.
  - E-field, temperature and charge states evolved self-consistently.
  - **D and Ar densities determined through Bayesian optimization w.r.t plasma current evolution.**





Preliminary DREAM results

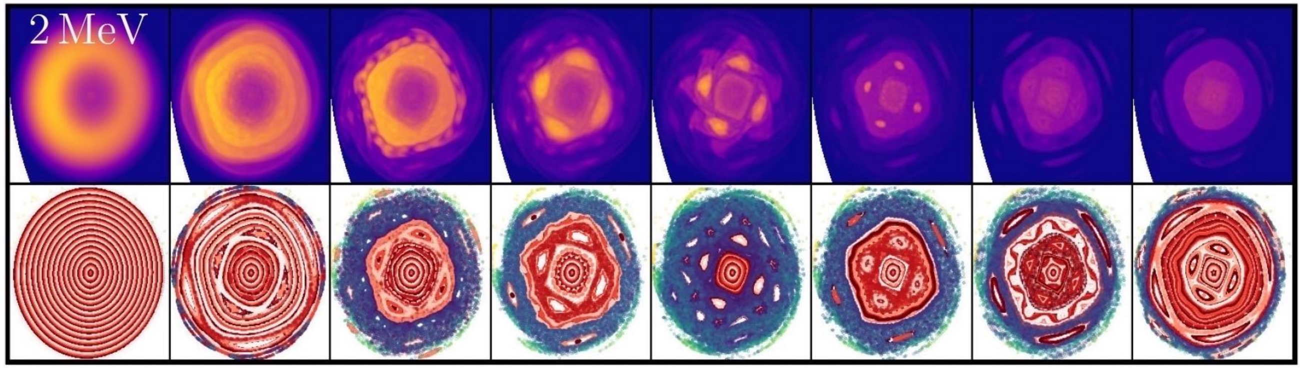


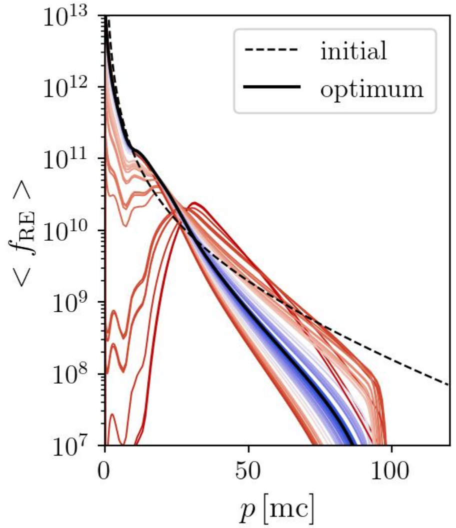
- So far optimization has been carried out for pre- 2nd injection phase.
- Optimum at: ~53% argon assimilation, not sensitive to deuterium density.

- Distribution changes notably, decrease of mean energy from ~18 MeV to ~10.8 MeV.
- Good convergence seen around optimum.

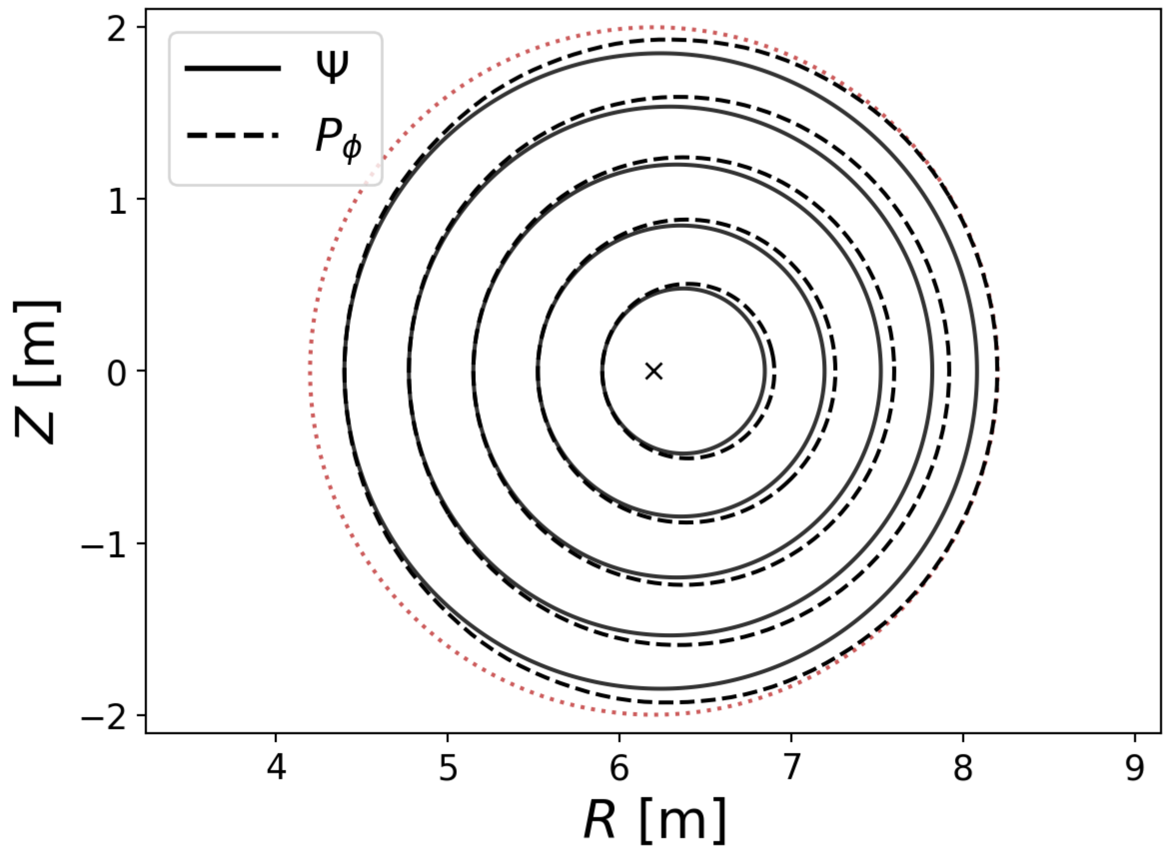
Conclusion

- Novel 3D full-f relativistic runaway electron model coupled to the fluid background in JOREK.
- Demonstrated highly non-linear JET beam termination case.
- Observed substantial kinetic effects onto MHD dynamics depending on RE energies.
- Working on realistic RE distribution functions using Bayesian optimization and DREAM:
  - Strong n_{Ar} dependency and mild n_{D} dependency.
  - Mean energy around 11 MeV suggests notable drift orbit effects.
  - Working on phase after secondary D-injection right now and JOREK simulations based on the distributions.
- Carrying out GPU porting and further optimizations to self-consistently cross the long time scales from stable RE beam towards termination.

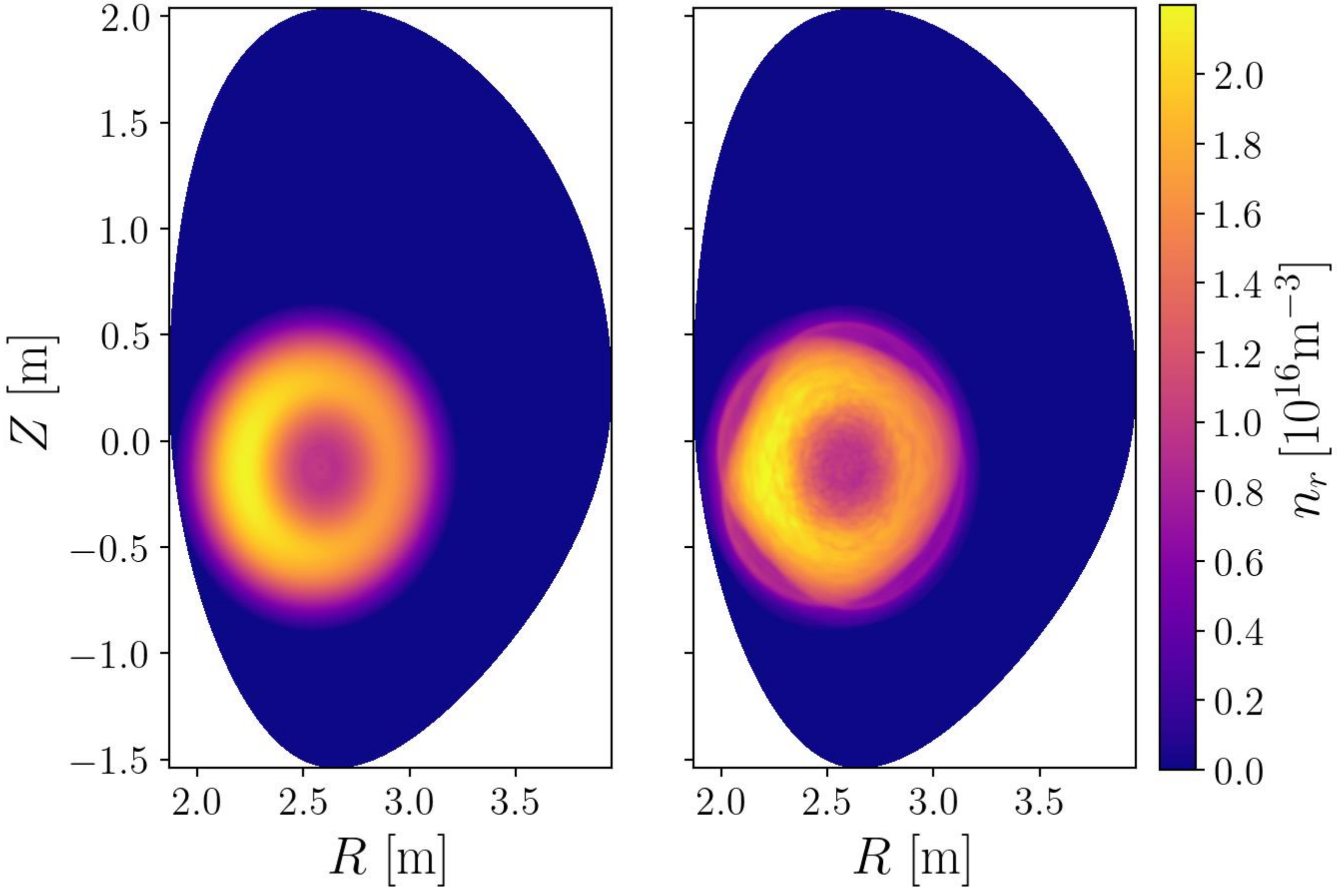


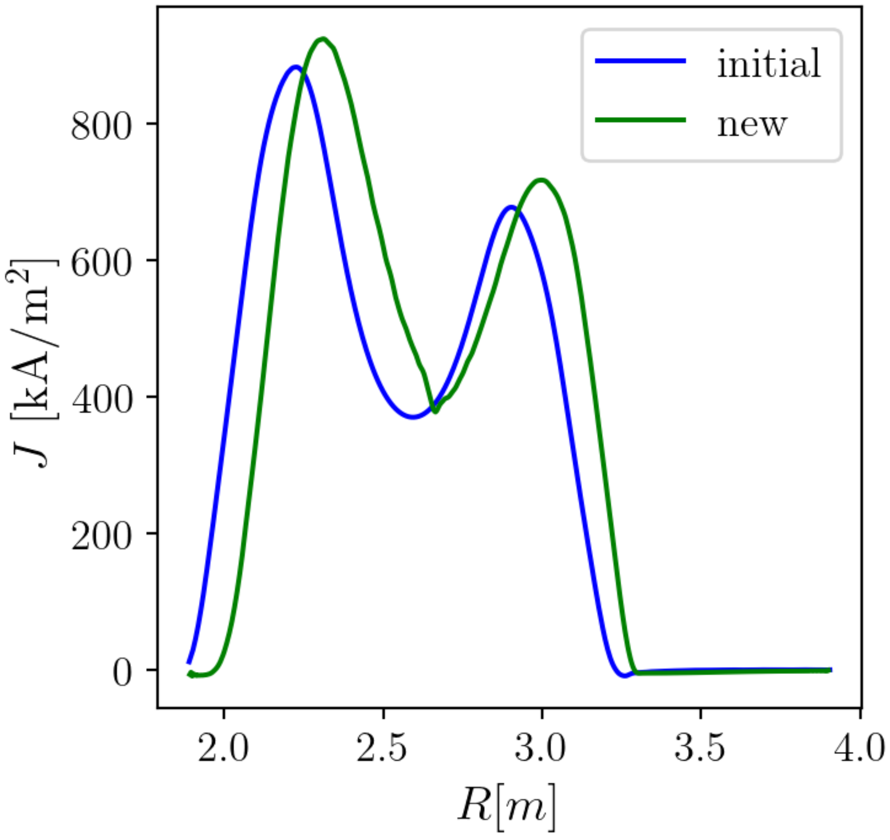


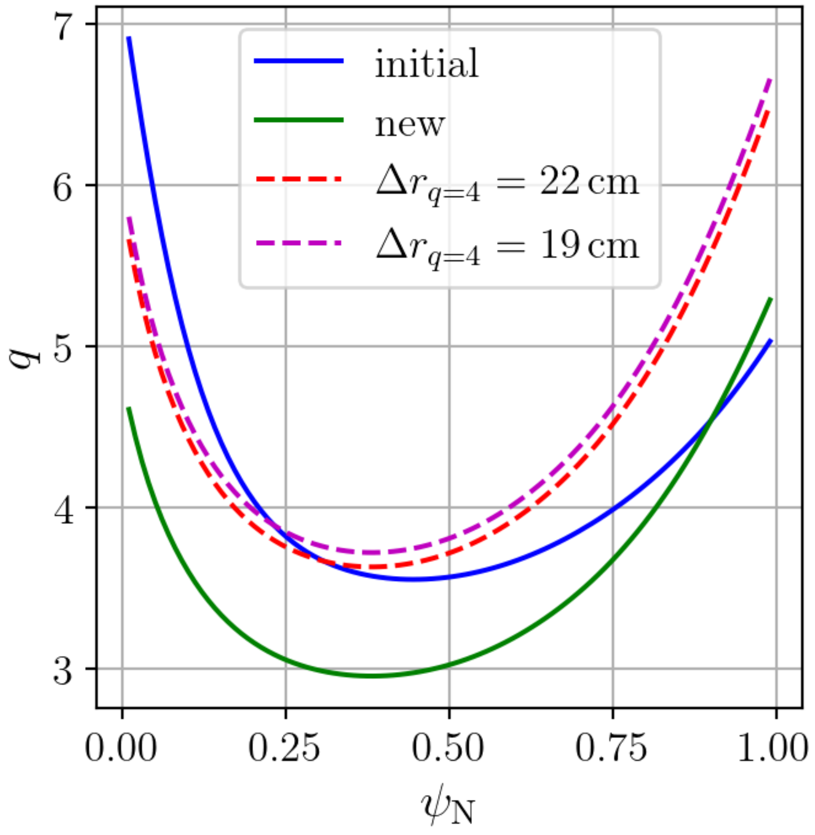
Backup slides



Ψ
P_ϕ
2
1
0
−1
−2
Z [m]
4
5
6
7
8
9
R [m]


2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Z [m]
2.0 2.5 3.0 3.5
R [m]
2.0 2.5 3.0 3.5
R [m]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
n_r [10^{16}m^{-3}]


initial
new
800
600
400
200
0
J [kA/m^2]
2.0
2.5
3.0
3.5
4.0
$R[m]$


initial
new
$\Delta r_{q=4} = 22\,\mathrm{cm}$
$\Delta r_{q=4} = 19\,\mathrm{cm}$
7
6
5
4
3
q
0.00
0.25
0.50
0.75
1.00
ψ_N