

Hermes-3 simulations of plasmas confined by a levitated dipole magnet

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Outline

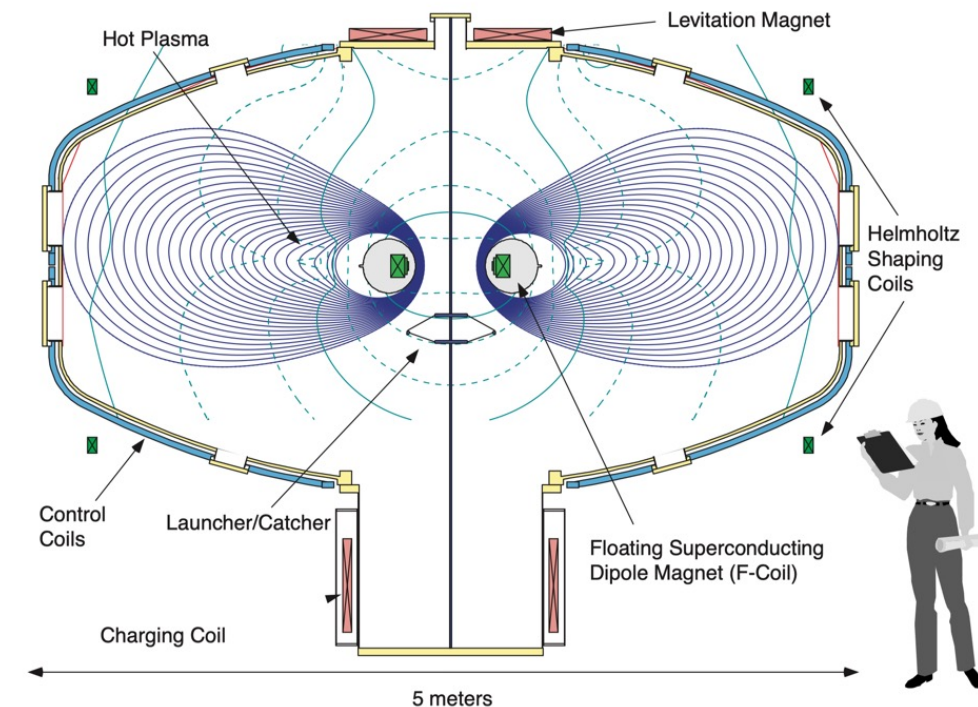
- Introduction
- Coordinates and mesh in dipole geometry
- 3-D profile-driven simulations
- 3-D flux-driven simulations
- Summary and discussion

Introduction: dipole as an alternative magnetic fusion configuration

- Dipole confinement was proposed by Hasegawa in 1987 as a possible route to fusion-relevant plasmas and has been explored in levitated-dipole experiments such as LDX, RT-1, and the recent Junior device.
- The magnetically levitated superconducting coil generates magnetic field, which is purely poloidal with no toroidal component.
- The key idea of dipole confinement is to create highly peaked profiles through strong magnetic compression.
 - In a point dipole field, magnetic field strength decays as $B \sim R^{-3}$.
 - Interchange stability predicts density and pressure profiles as

$$n_0 \sim R^{-4}, \quad p_0 \sim R^{-20/3}.$$

- Therefore, dipole magnetic field might be able to achieve high- β plasma near the center of the device.



Coordinate system in dipole magnetic field in a vacuum

- Since dipole only has poloidal field, we can write the magnetic field as

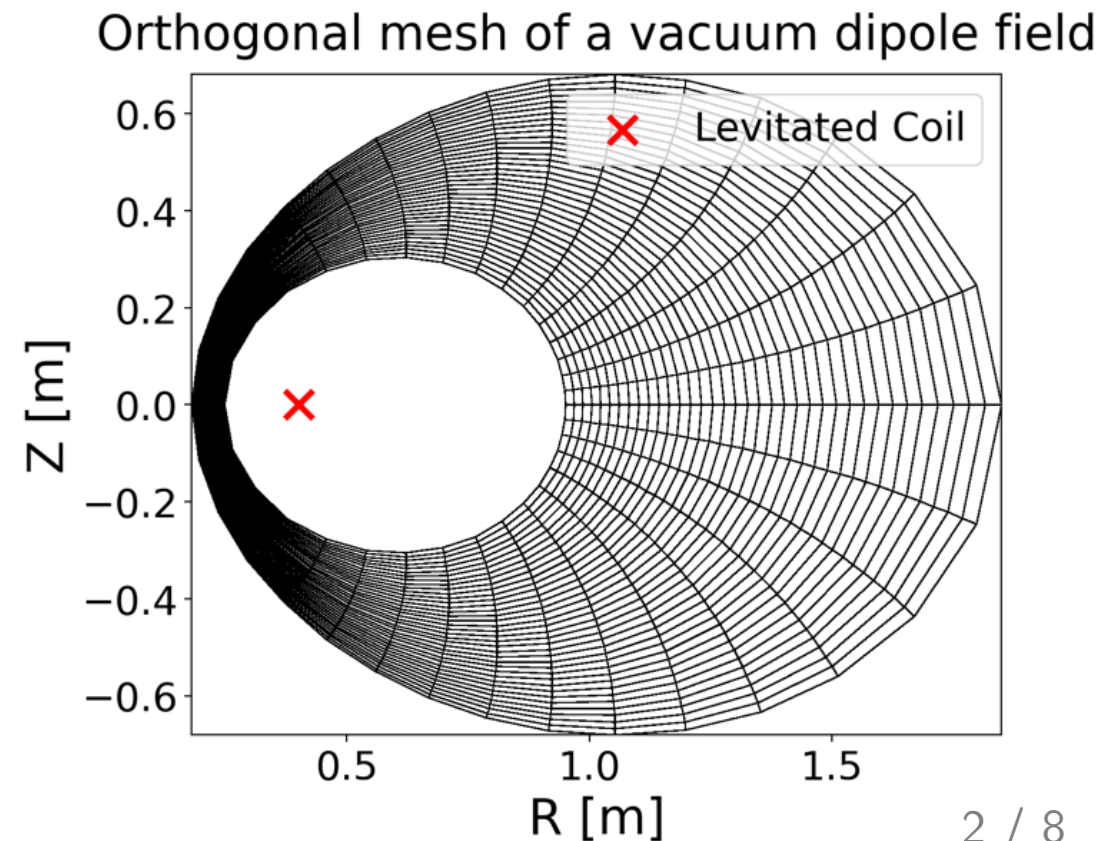
$$\mathbf{B} = \nabla\zeta \times \nabla\psi = \nabla\chi.$$

Here, ζ is the toroidal angle, ψ is the poloidal flux, and χ is the poloidal-angle-like coordinate.

- The Jacobian of the coordinates is

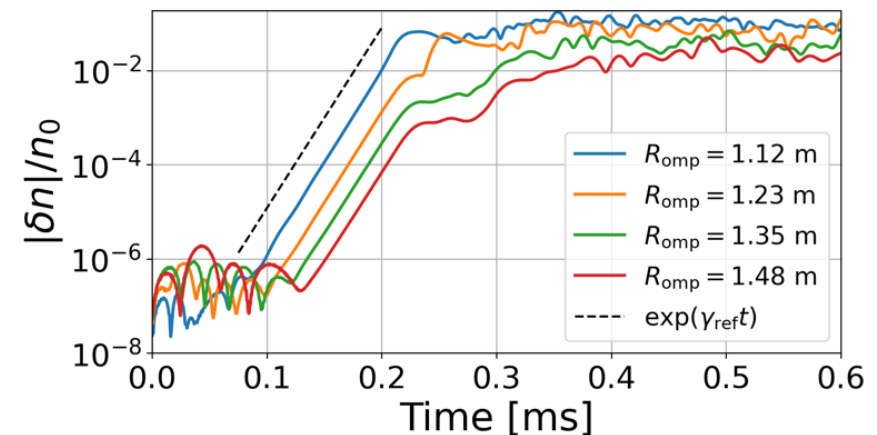
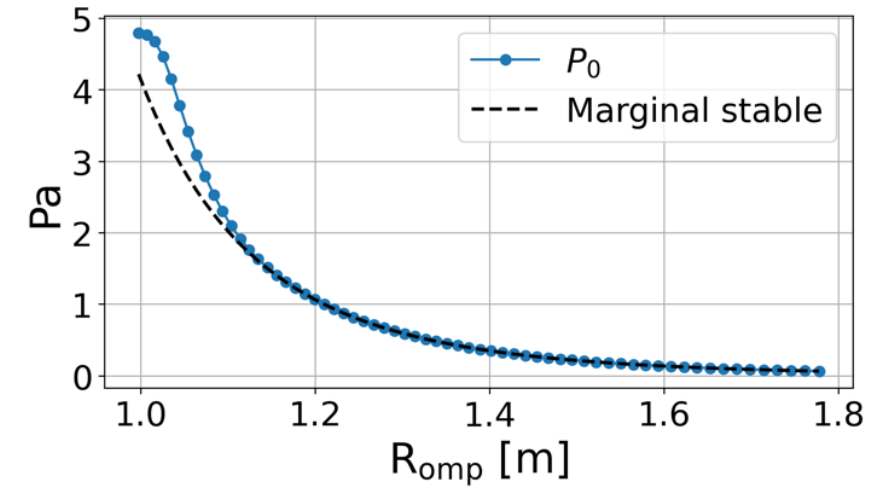
$$\mathcal{J}^{-1} = (\nabla\psi \times \nabla\chi) \cdot \nabla\zeta = B^2$$

- (ψ, χ, ζ) form an orthogonal coordinate system. We can build a grid file in the BOUT++ convention.
- Unfortunately, current mesh only resolves the “boundary” region of the dipole magnetic field. The “core” region is difficult due to smallness of the cell size.



3-D profile-driven simulation: stability of dipole plasmas

- We model dipole plasma near the dipole edge using the drift-reduced Braginskii equations [1].
- Profile-driven simulation was performed using Hermes-3, where the input is similar to its TCV-x21 benchmark case [2].
- Initial profiles are chosen to be supercritical flux functions, i.e., pressure gradient is larger than the stability boundary predicted by interchange instability.
- Hermes-3 simulation shows exponential growth during the linear phase, followed by nonlinear saturation. The growth rate fits well with the growth rate calculated from an independent 2-D eigenmode solver.



A pitfall: the Boussinesq approximation may alter the physics

- We found that Hermes-3 can NOT capture the growth rate of dipole plasma when its profiles are close to the stability boundary. In particular, we found that the growth rate from Hermes-3 strongly depends on its numerical normalization density, N_{norm} .

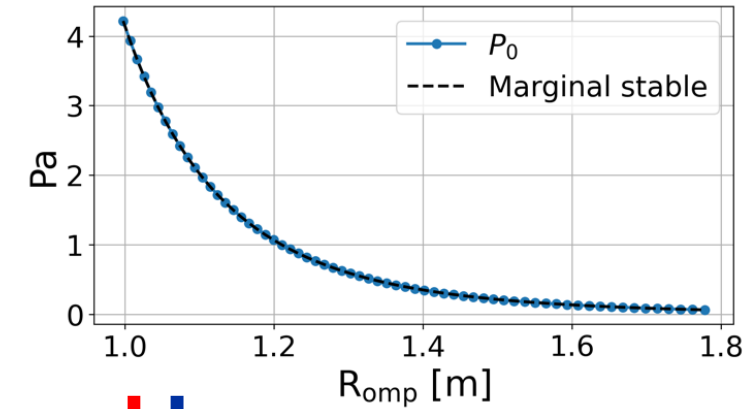
- We suspect that the difference is caused by the Boussinesq approximation implemented in the vorticity equation in Hermes-3. Roughly speaking, the vorticity equation reads:

$$\frac{\partial \omega}{\partial t} = \nabla \cdot (\mathbf{b} j_{\parallel}) + \nabla \cdot \left(\nabla \times \frac{\mathbf{b}}{B} \sum_s p_s \right) - \nabla \cdot (\omega \mathbf{v}_E) + \dots$$

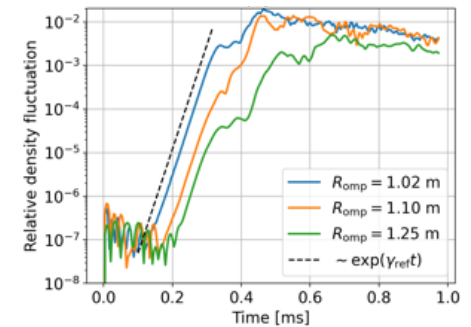
- The Boussinesq approximation uses a constant density inside vorticity:

$$\omega = \nabla \cdot \left[\frac{m_i}{B^2 q} (n q \nabla_{\perp} \phi + \nabla_{\perp} p_i) \right] \approx \nabla \cdot \left[\frac{m_i n_0}{B^2 q} \nabla_{\perp} \left(q \phi + \frac{p_i}{n_0} \right) \right].$$

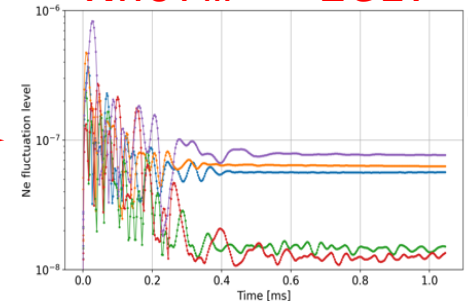
- Therefore, the Boussinesq approximation may change the balance of the terms in the vorticity equation, and then alternate plasma stability.



$N_{\text{norm}} = 1e16$

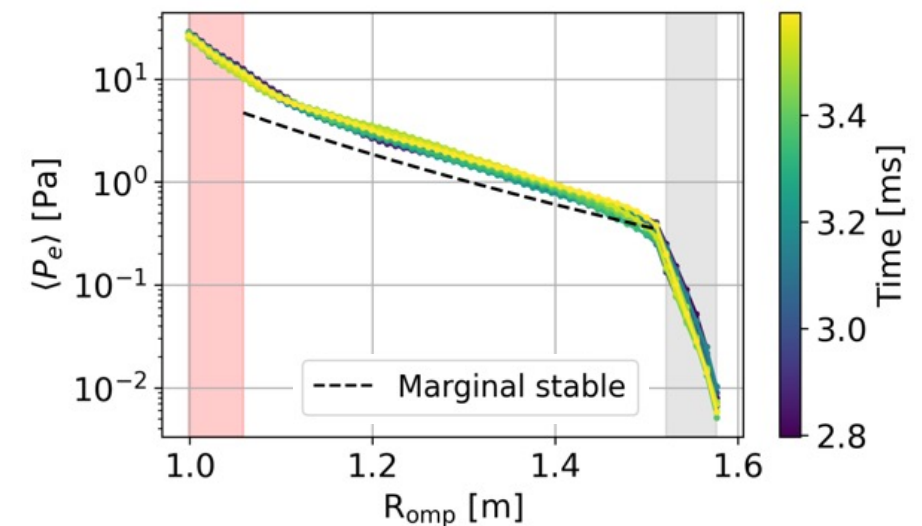
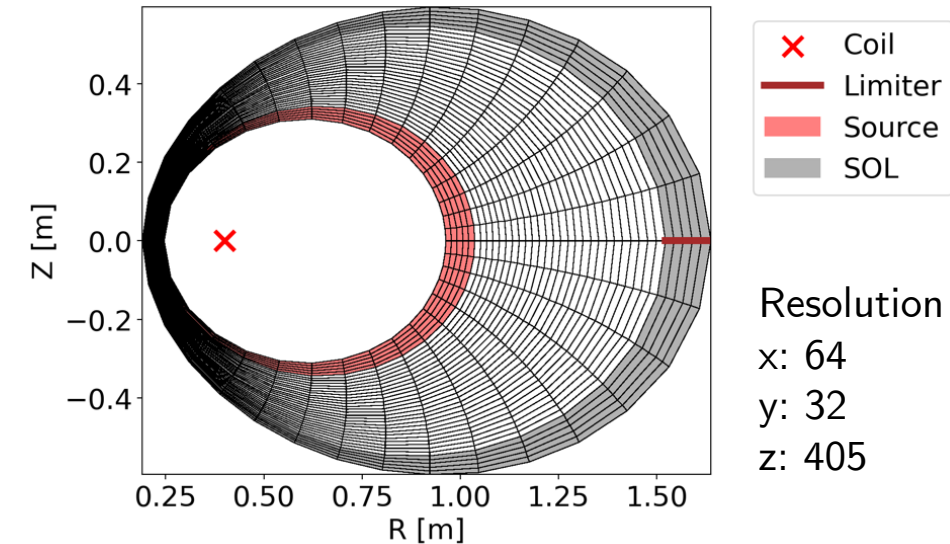


$N_{\text{norm}} = 2e17$

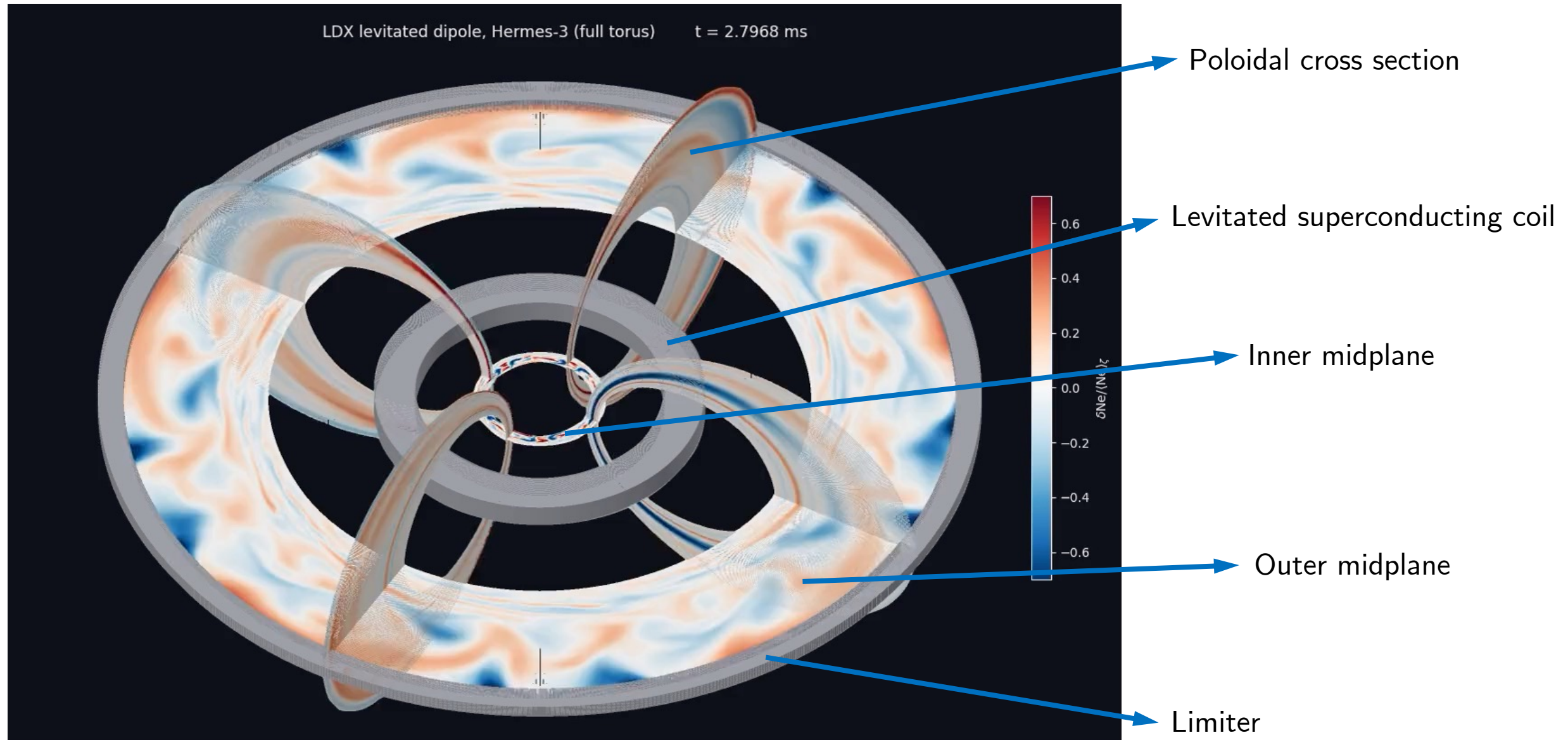


3-D flux driven simulation: stationary profile near marginal stability

- Now we move on to flux-driven simulation with:
 - Particle and heat sources near the core boundary
 - Limiter near the outer boundary
- Flux-driven simulations are performed using Hermes-3, with 2 nodes on Perlmutter, simulating one millisecond plasma time needs ~ 260 hours (~ 11 days).
- After running ~ 3.5 ms plasma time, the profile reaches a steady-state, where the toroidally averaged pressure profile becomes close to a marginal stationary profile.
- This flux-driven simulation confirms that dipole plasma can self-organize into a highly peaked pressure profile under proper sources and sinks.

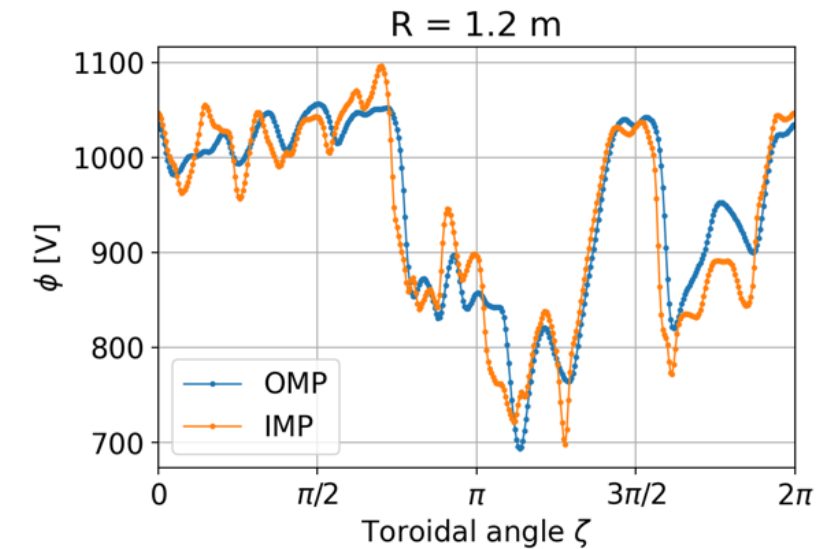


Visualization: 3-D full torus simulation



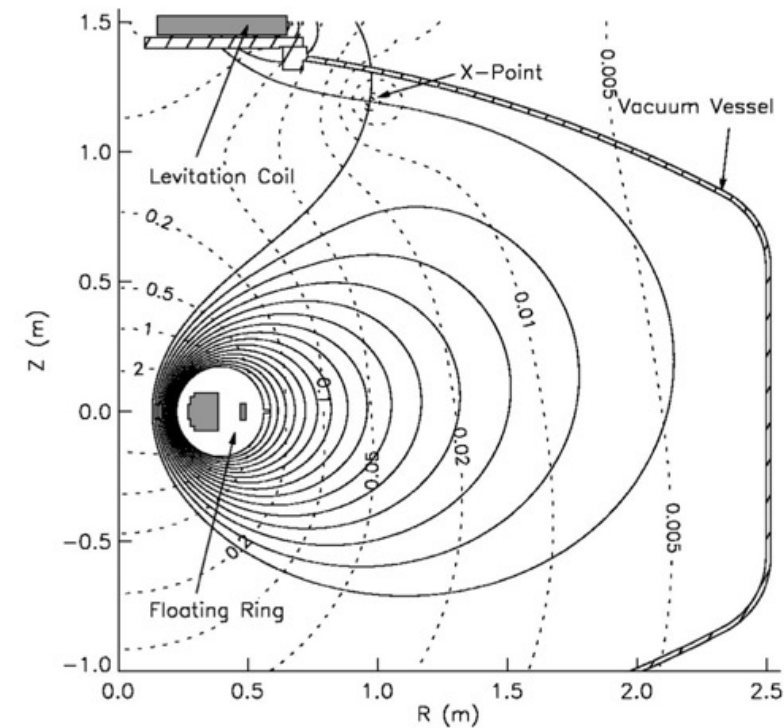
Preliminary evidence of non-flute fluctuation

- The majority of the existing literature [3,4] believe/assume that the turbulent fluctuations in magnetic dipoles are flute-like, i.e., $k_{\parallel} \approx 0$.
- Therefore, the majority of existing theoretical and numerical analysis are performed after a flux-tube average.
- However, from 3-D turbulence simulation, we found that non-flute mode can show up on top of a dominant flute mode. This could alternate the picture of flute-like transport of the turbulence in dipoles.
- Theoretical understanding of the non-flute mode is currently ongoing.
- We're also looking into old experimental data for potential verification of our simulation results.



Summary and discussion

- We have extended Hermes-3 simulation into the dipole magnetic fields for 3-D turbulence simulations.
- Profile-driven simulation enables the study of growth rates of dipole plasmas. However, we found that the growth rate calculation is not accurate near the stability boundary.
- Flux-driven simulations reproduce the predicted peaked pressure profiles in dipole and found evidence of non-flute fluctuations. This may enable new perspective of transport in dipole geometry.
- Current code can only simulate the “boundary” region of magnetic dipole due to the small cell distance near the core. New methods are needed if simulation region needs to be extended.
- We also plan to explore a diverted dipole geometry, where the X-point is a true magnetic null ($B=0$). Numerical as well as physical difficulties may raise during the process.



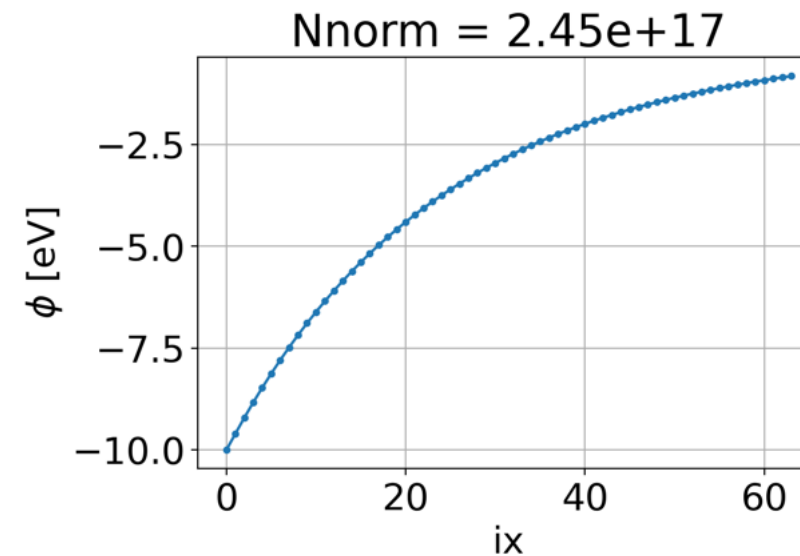
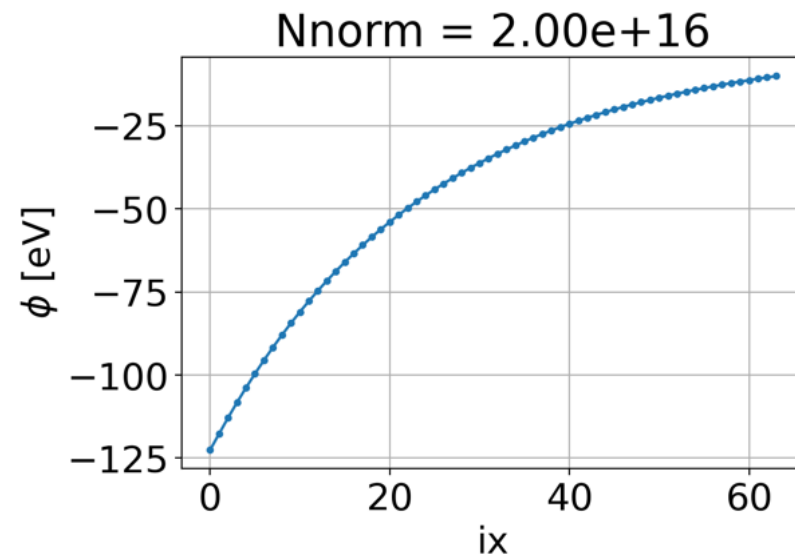
D. T. Garnier, Phys. Plasmas (1999)

Appendix: the Boussinesq approximation and equilibrium potential

- Consider the case where the vorticity vanishes at the beginning of simulation:

$$\omega \approx \nabla \cdot \left[\frac{m_i n_0}{B^2 q} \nabla_{\perp} \left(\phi + \frac{p_i}{n_0} \right) \right] = 0 \quad \Rightarrow \quad \phi = C - p_i / n_0.$$

- We find that the equilibrium potential profiles are different at different **Nnorm**:



- So different reference density leads to different equilibrium potential, which may affect the shearing profile and change stability and transport.