FUSION-ALPHA-ENHANCED DISPLACEMENT & STABILITY OF ITER HELICAL CORE PLASMAS

ID: TH-W07

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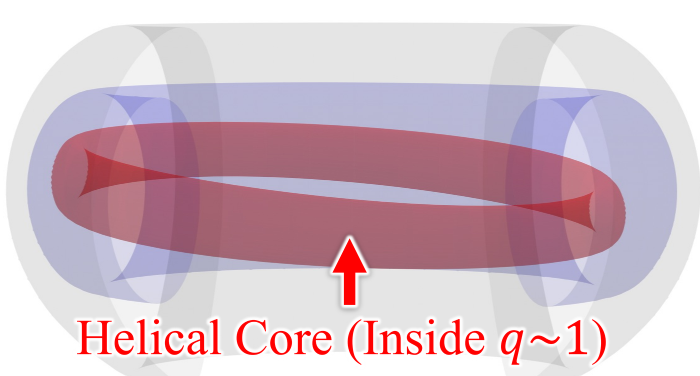
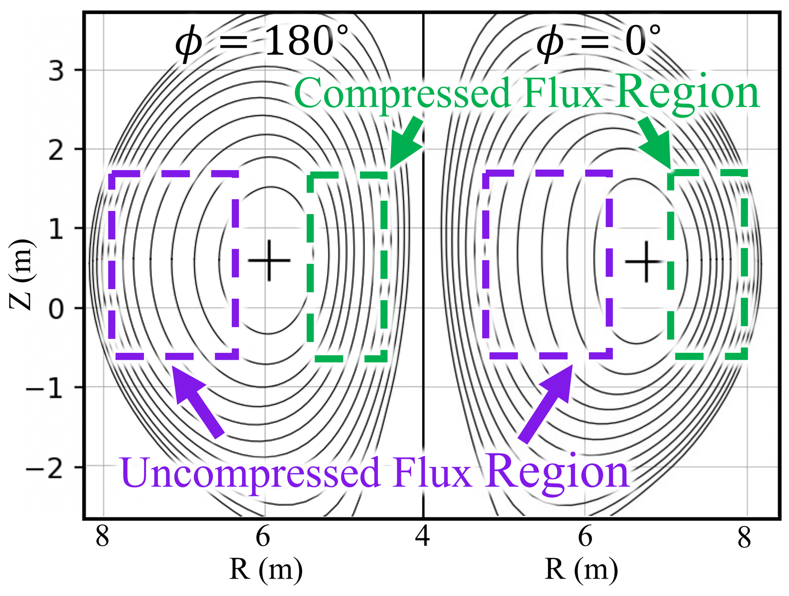
1. Background of Study & Research Objectives

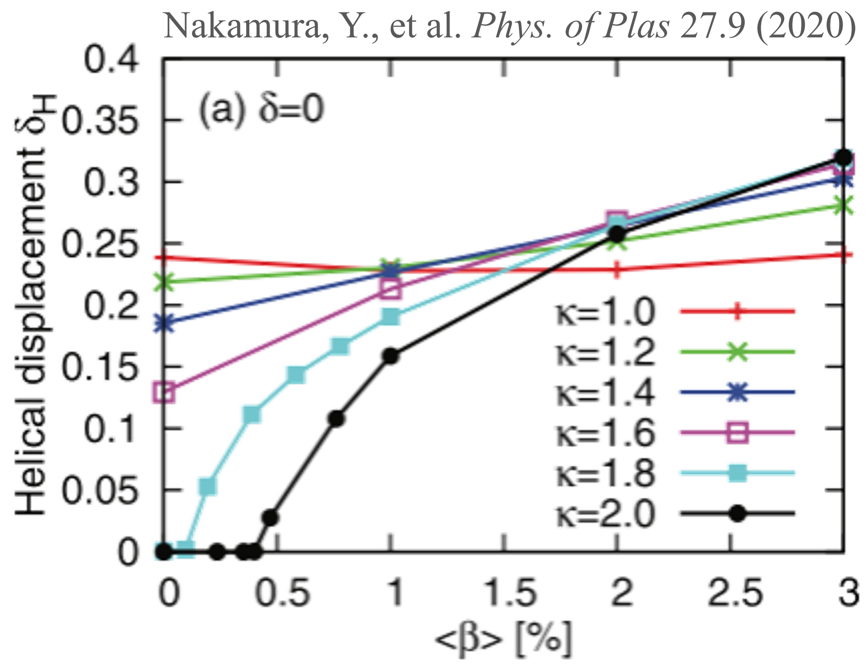
- In a **hybrid** scenario (**q≳1**), a kink/quasi-interchange mode can ideally saturated, leading to a formation of a **HELICAL CORE (HC)**
  - Reported in MAST, DIII-D, and JT-60U
    Chapman, I. T., et al. Nuclear Fusion 50.4 (2010): 045007
    Cianciosa, Mark, et al. Nuclear Fusion 57.7 (2017): 076015
    Bando, T., et al. Plas Phys. and Cntrl Fus. 61.11 (2019): 115014
  - Spontaneous formation is predicted in ITER
    Wingen A. et al. Nuclear Fusion 58.3 (2018)
- Have both "**Positive** ✓" and "**Negative** ✗" consequences on plasma performance.
  - ✓ Poloidal Flux pumping → Sawtooth-free
    P. Piovesan et al 2017, I. Krebs et al, 2017
  - ✓✗ Energetic Particle Profile broadening
    D. Pfefferle et al, 2014
  - ✗ Plasma Rotation Flattening
    I.T. Chapman et al 2010, Y. Yuan et al 2020
- To control the positive/negative aspects of **HC**, **good predictability** is needed!





- Prior studies using VMEC/ANIMEC, reveal the dependence of **HC** on:
  1. Plasma Shape
  2. Plasma Pressure
  3. Safety Factor

  Hirshman S.P., et al. Phys. of Fld 26.12 (1983)
  Nakamura, Y., et al. Phys. of Plas. 27.9 (2020)
  Kawagoe, S., et al. Plas. Phys. Cntrl. Fus 64.10 (2022)
  Cooper, W. A., et al. Plas. Phys. Cntrl. Fus 53.2 (2011)
- In **ITER**, significant population of **fusion-born alphas** are expected in the core.
  - **Alphas** can affect the stability of the **m/n=1/1** mode, thus affecting **HC**



Raise a Key Question : What is the interplay between **Helical Core** equilibrium and **alphas** dynamics?

2. Simulation Models

MEGA MHD-PIC Sim. *Todo, Y. et al. Phys. of Plas. 5.5 (1998)*

- Nonlinear Resistive MHD (bulk) + PIC (Alpha)

Full-f $\delta f \sim \mathcal{O}(f_0)$

$$\frac{\partial\rho}{\partial t} = -\nabla\cdot(\rho\vec{v}) + \nu_n\nabla^2(\rho)$$

$$\rho\frac{\partial\vec{v}}{\partial t} = -\rho(\vec{v}\cdot\nabla)\vec{v} + \left(\frac{\nabla\times\vec{B}}{\mu_o} - \vec{J}_\alpha\right)\times\vec{B} - \nabla P - \nabla\times(\nu\rho\nabla\times\vec{v}) + \frac{4}{3}\nabla(\nu\rho\nabla\cdot\vec{v})$$

$$\frac{\partial P}{\partial t} = -\nabla\cdot(P\vec{v}) - (\gamma-1)[P\nabla\cdot\vec{v} - \nu\rho(\nabla\times\vec{v})^2 - \frac{4}{3}\nu P(\nabla\cdot\vec{v})^2 - \eta\vec{J}\cdot\delta\vec{J}] + \chi_\parallel\nabla_\parallel^2 P + \chi_\perp\nabla_\perp^2 P$$

$$\frac{\partial\vec{B}}{\partial t} = -\nabla\times\vec{E} \qquad \mu_0\vec{J} = \nabla\times\vec{B} \qquad \vec{E} = -\vec{v}\times\vec{B} + \eta\delta\vec{J}$$

- **I**nitial **V**alue **P**roblem (Quasi-steady state solution)
- + Alpha kinetic effects
- + Multiple Saturation Mechanism:
  - Field line bending
  - Radial mixing
  - Particle trapping
- ✗ Numerically **Expensive**

VMEC 3D Ideal Equilibrium Solver *Hirshman, S.P., et al. Phys. of Fld. 26.12 (1983)*

- Minimized Ideal MHD Energy Functional

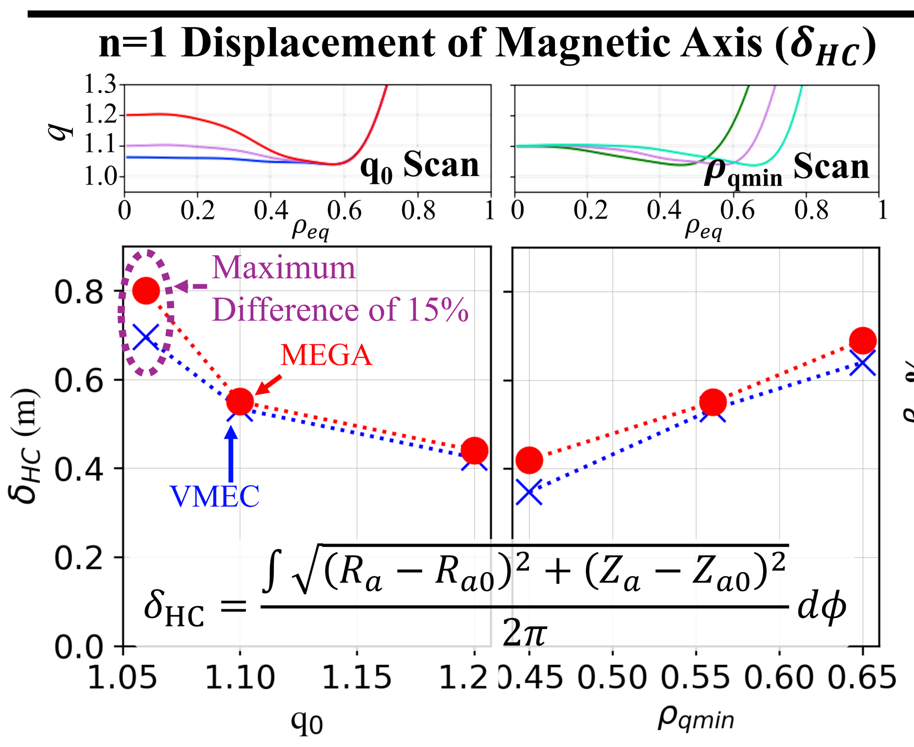
$$W = \int\left(\frac{B^2}{2\mu_0} + \frac{P}{\gamma-1}\right)\mathcal{J}d\psi d\theta^* d\phi$$

$$P_{tot} = P_{mhd}(\psi) + P_\alpha(\psi)$$

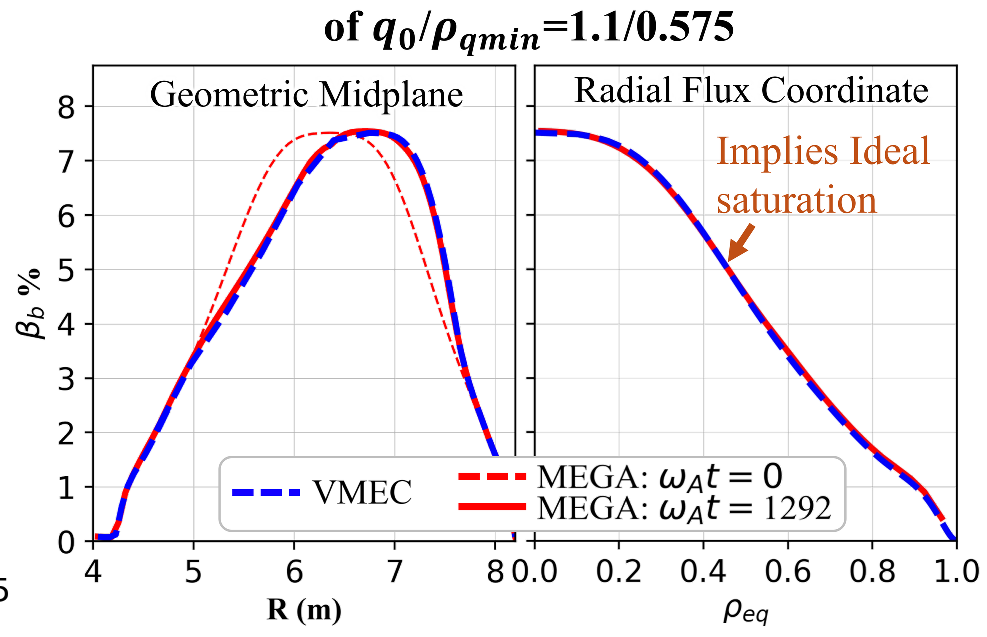
- **B**oundary **V**alue **P**roblem (Steady state solution)
- + Numerically **Inexpensive**
- ✗ No kinetic effect
- ✗ Stability is excluded

3. MEGA & VMEC Benchmark without *Kinetic Alphas*

n=1 Displacement of Magnetic Axis (δ_{HC})

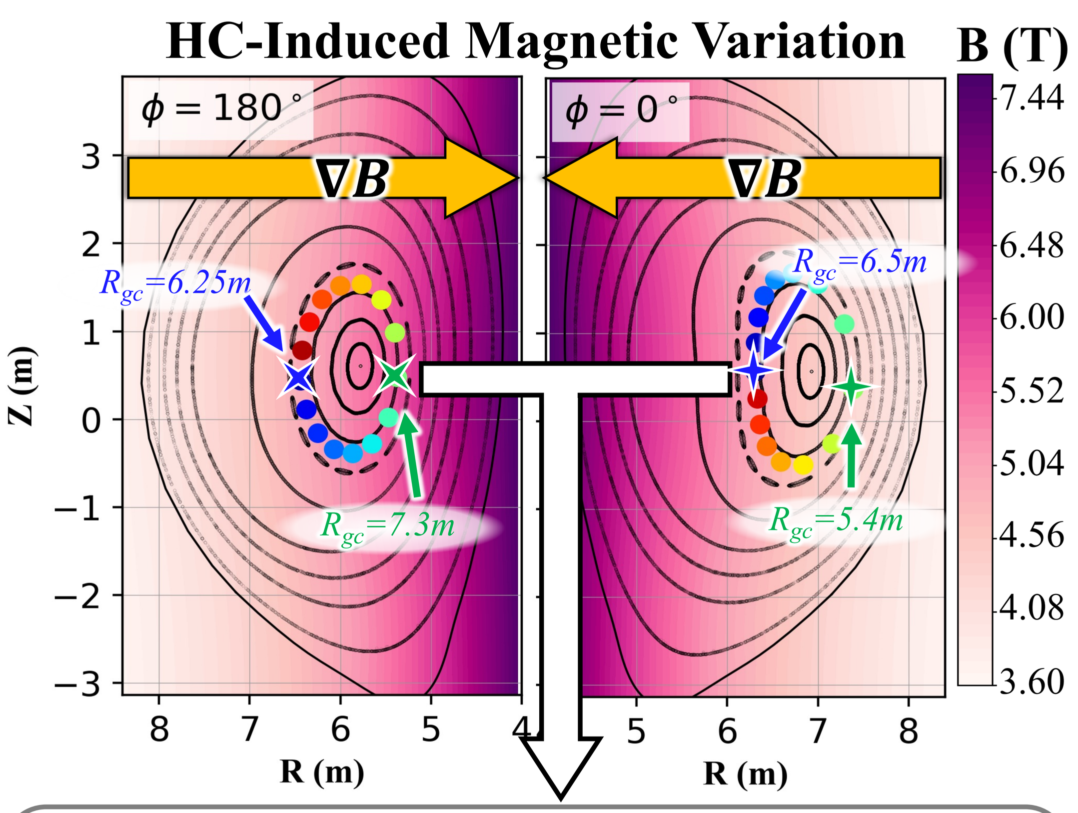


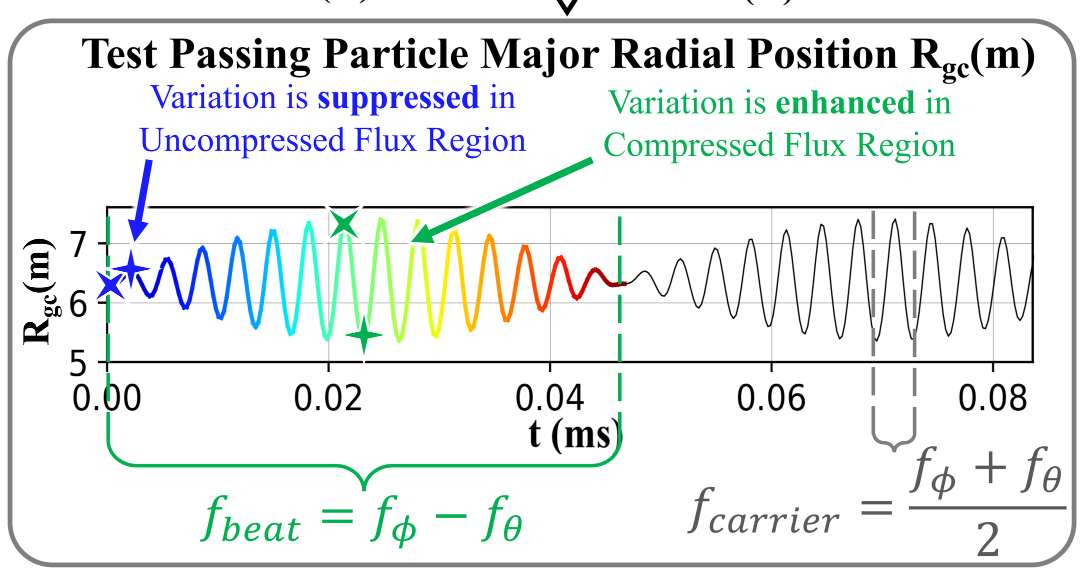
Redistributed Plasma Pressure Profile of q_0/ρ_{qmin}=1.1/0.575

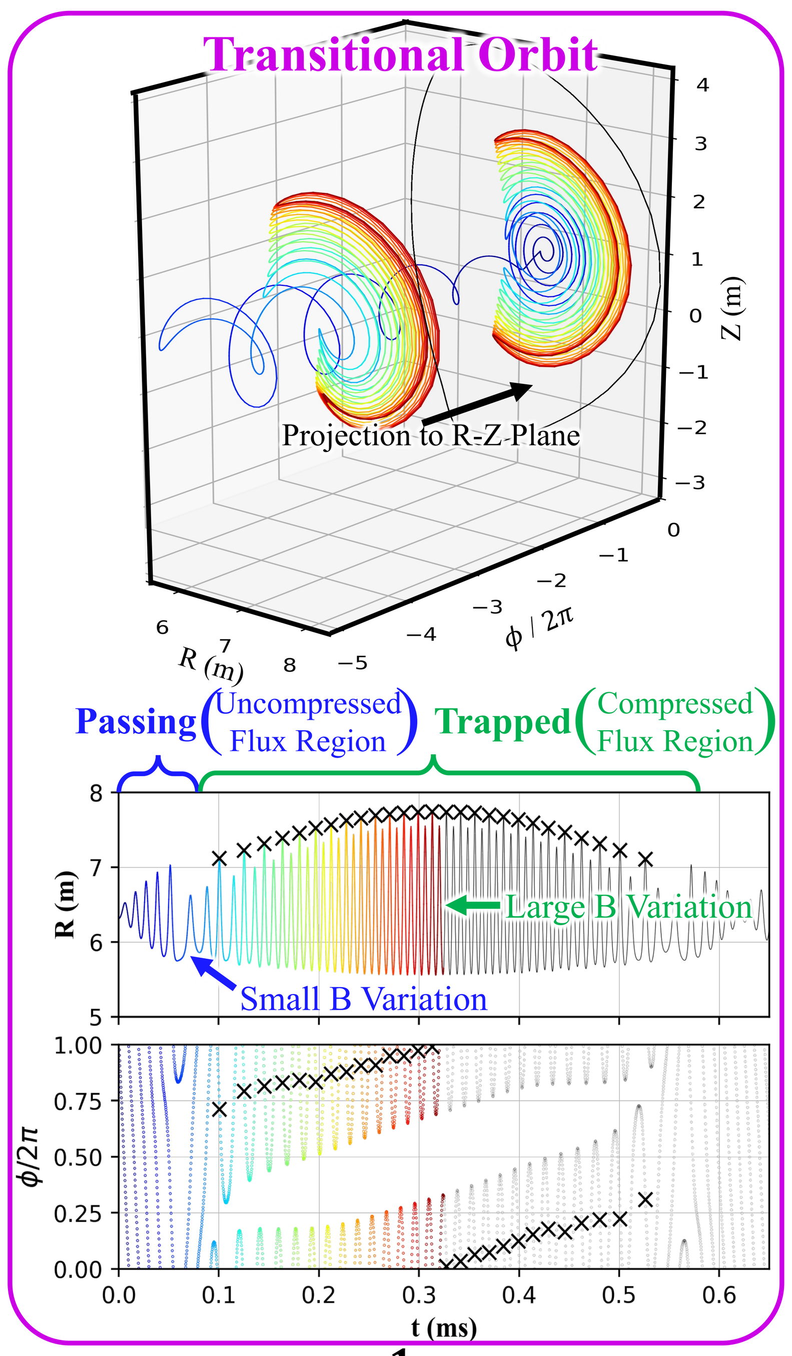


- Since **VMEC** has been **validated** against **experimental data**, benchmarking **MEGA** against **VMEC** helps ensure that **MEGA** provides a reliable **HC Solution**
- **MEGA** yields a good agreement with **VMEC** in the case without **kinetic alphas**

4. Effects of Asymmetry on Particle Orbit



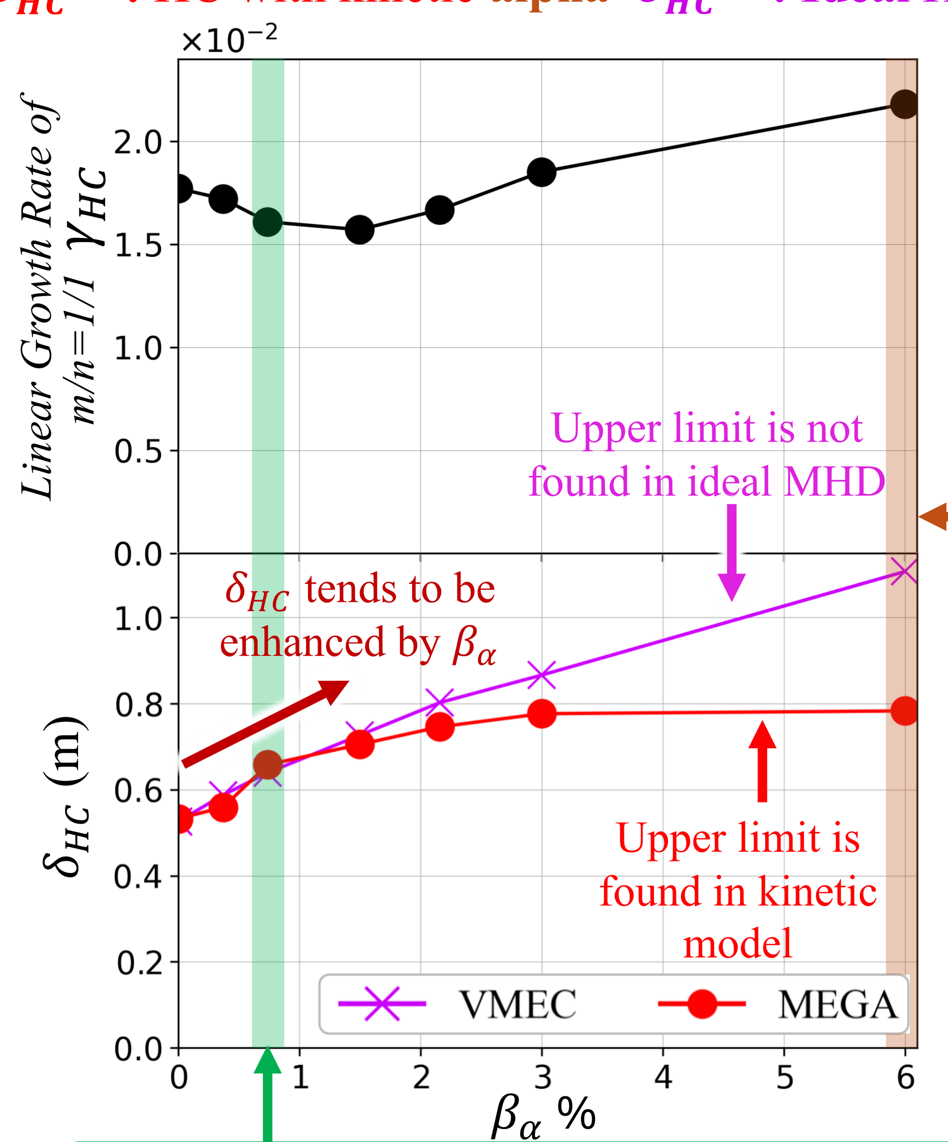




- B-field strength appears mostly axisymmetric in the lab frame, $B \propto \frac{1}{R}$; however, R_{gc}(m) is **modulated** by **HC**, leading to **B-field variation** in the **particle** frame
  - Beat-like pulsation in R_{gc} because $f_\phi \sim f_\theta$ (due to $q\sim1$)
  - Causing a **transitional** orbit for particle located near the passing-trapped boundary
    - Passing orbit in the **Uncompressed** flux region (**Small** B-variation)
    - Trapped orbit in the **Compressed** flux region (**High** B-variation)

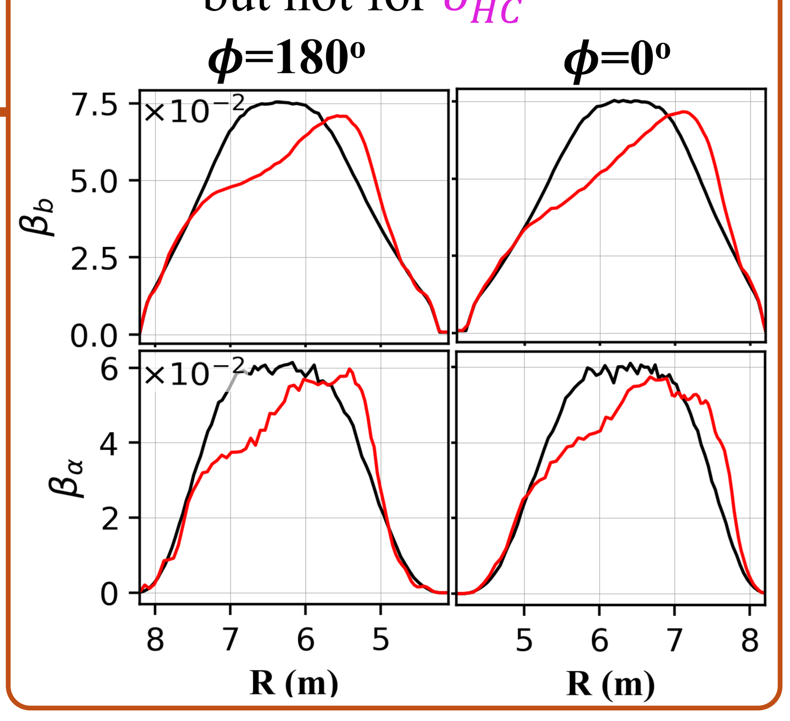
5. HC Formation with Kinetic Alphas

δ_{HC}^{MEGA}: HC with kinetic **alpha** δ_{HC}^{VMEC}: **Ideal** HC w/o flow $\beta_{tot} = \beta_b + \frac{1}{2\pi}\int_0^{2\pi}\beta_\alpha d\theta$



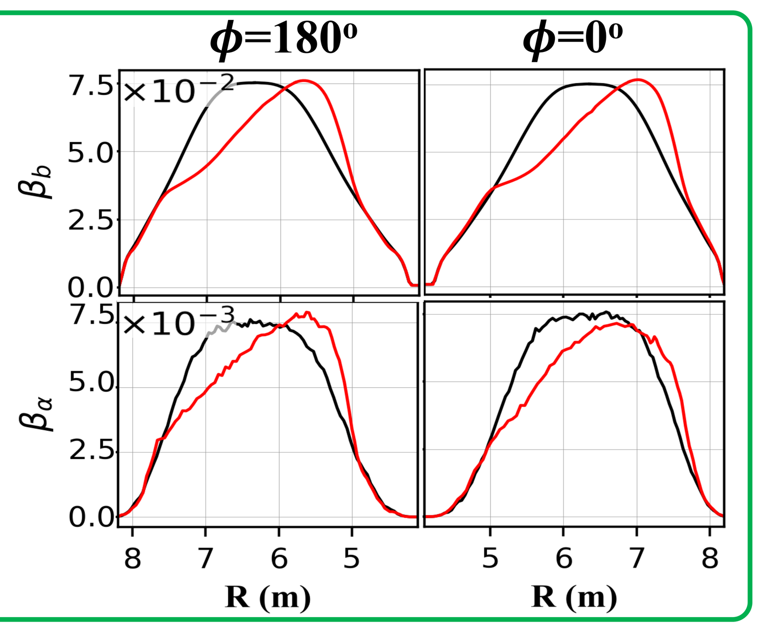
$1.5\% \le \beta_\alpha \le 6\%$

Kinetic & transport effect become **important.** δ_{HC}^{MEGA} exhibits an upper limit, but not for δ_{HC}^{VMEC}

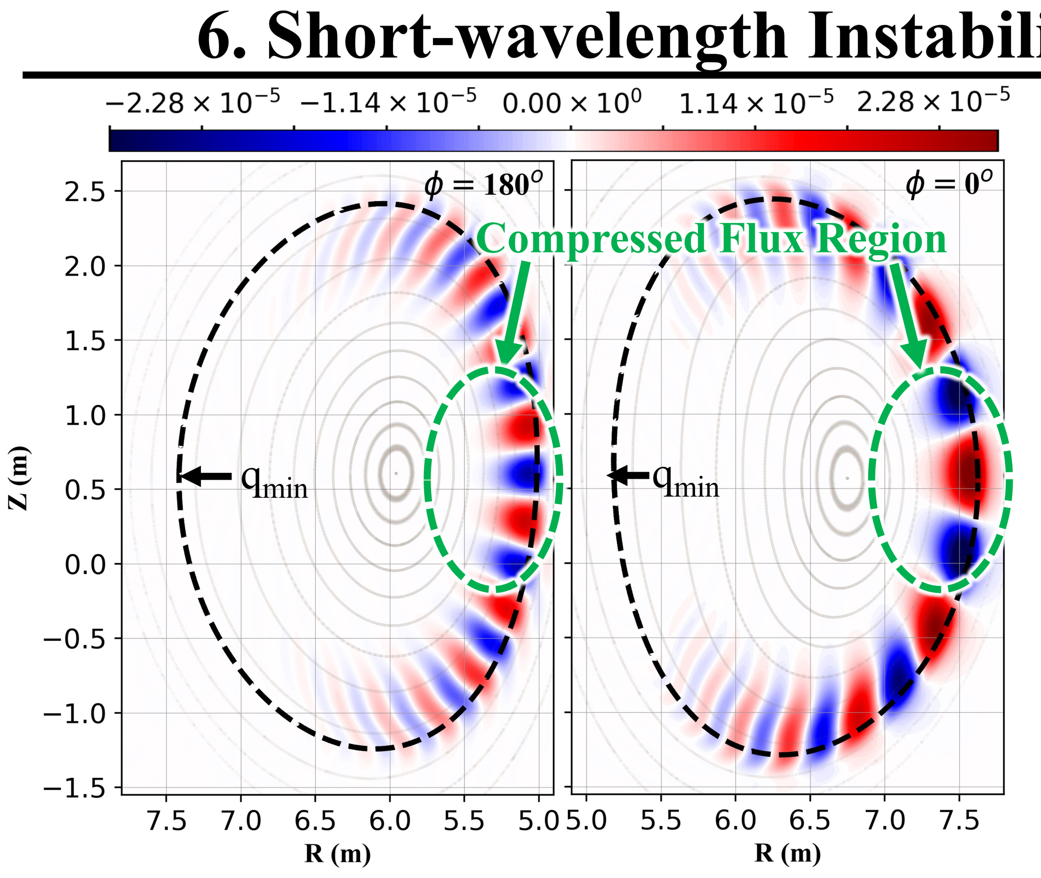


$0 < \beta_\alpha < 1.5\%$

Crossfield transport is minimal and $\delta_{HC}^{MEGA} \approx \delta_{HC}^{VMEC}$; hence, **alpha contribution** can be approximated using fluid model



6. Short-wavelength Instability in HC Equilibrium



- **Short-wavelength mode** is destabilized after HC formation in **some equilibria**
- Fluctuation is **localized** along the **compressed flux region** of HC
  - At q_{min} radial position
- They can cause **magnetic chaos**
  - → Facilitate radial mixing of bulk plasma and alphas

* This mode is suppressed in other sections, using a n=1 toroidal low-pass filter.
** Short-wavelength spectrum of this mode may require EM turbulence models

7. Conclusion

- We investigated the interplay between **alphas** and **Helical Core** in **ITER-scale** (~**13 MA**) plasma

1. We found that **HC displacement (δ_{HC})** tends to be **enhanced** by **alphas**
   - **HC steady state** is determined mainly from the **quasi-steady** state β_b & β_α
     - $\beta_\alpha \le 1.5\%$: $\delta_{HC}^{MEGA} \approx \delta_{HC}^{VMEC}$ (Ideal MHD is sufficient because transport is small)
     - $\beta_\alpha \ge 1.5\%$: $\delta_{HC}^{MEGA} < \delta_{HC}^{VMEC}$ (Transport is significant)
2. **HC** induces a **B-field** variation in the particle frame by modulating R_{gc}
   - **Connecting passing** and **trapped** domains, leading to a **transitional orbit**

Preprint is available: https://arxiv.org/abs/2509.11749
"Helical Core Formation and MHD Stability in ITER-Scale Plasmas with Fusion-born Alpha Particles"