Effects of Fusion-born Alpha Particles on Helical Core in ITER Hybrid Scenario

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The tokamak hybrid scenario, where the core safety factor profile is nearly flat and slightly above unity ($q \gtrsim 1$), is one of the candidates for the ITER long-pulse plasma scenario. It has been found that a non-resonant m/n=1/1 kink/quasi-interchange mode can be destabilized in such a configuration. The mode's saturation yields a long-lived toroidally asymmetric state known as helical core (HC)[1-2]. 3D MHD equilibrium calculations using VMEC/ANIMEC demonstrated that the radial displacement of the magnetic axis (δ_{HC}) for a HC in ITER can reach 0.4 m. The associated toroidal asymmetry can pose challenges for control and diagnostics. It may also affect plasma performance (rotation, stability, confinement, etc.), so it is necessary to identify possible disadvantages and opportunities that arise from the HC's interplay with other modes and with different plasma constituents. For instance, a HC may facilitate sawtooth-free operation with minimal to no external control via its role in dynamic self-organization processes. Meanwhile, it is also necessary to clarify how a HC interacts with fusion-born alpha particles, whose presence will be essential in ITER and future reactors. For instance, the alpha particles may affect the growth, magnitude, and controllability of a HC, and the HC may also affect alpha confinement. Aspects like these were not covered in earlier pioneering studies[1-2] and motivated this work.

We aim to improve our understanding of the HC in burning plasma conditions by simulating the HC formation in ITER in the presence of alpha particles. We use MEGA[3], a nonlinear MHD-PIC hybrid code that treats the bulk plasma as a single MHD fluid whose fluctuations are coupled to minority particle species (here alphas) that obey drift kinetic equations. For the chosen cases (partly based on ITER IMAS data), we find that alpha particles tend to enhance the radial displacement of the magnetic axis (δ_{HC}), as shown in Fig.1(a) via the red solid line with "x" markers. δ_{HC} continues to increase when we raise the alpha concentration until the normalized alpha pressure reaches $\beta_\alpha \approx 3\%$. Beyond this value, the HC becomes structurally unstable while the associated displacement saturates (δ_{HCmax}). We observe significant alpha particle transport only in this exaggerated regime. For comparison, the black solid line with "+" markers in Fig.1(a) shows results obtained with VMEC, where the alpha contribution can be included by raising the scalar MHD pressure. One can see that the displacements δ_{HC} predicted by both codes agree quantitatively for $\beta_\alpha \leq 1\%$, which coincides with ITER's operating range. The results differ only at higher β_α as VMEC does not capture transport and stability.

In our reference case, the HC had no detrimental effect on alpha confinement when $\beta_\alpha \leq 1\%$. As the example in Fig.1(b) and 1(c) for $\beta_\alpha = 0.75\%$ shows, the β_α field is distorted but remains peaked. The overlaid Poincaré contours of co-passing alpha particles (black) remain sharp and nested. Alpha particles with different energies and pitch angles show similar behavior.

The situation changes if one increases the radial width of the $q \gtrsim 1$ region while fixing the initial pressure profile. At some point, the steepening pressure gradient caused by HC compression begins to drive resistive pressure-driven MHD instabilities. These secondary resistive modes were found to nonlinearly undergo magnetic reconnection. Overlaps between the resulting multi-helicity island structures (and their counterparts in alpha drift-orbit space) lead to enhanced transport of both bulk plasma and alpha particles.

In summary, our results show that HCs can form in a burning plasma and that alpha particles tend to enhance the radial displacement of the core. Within the ITER operating range $\beta_\alpha \leq 1\%$, these alpha particles remain well-confined in the HC state as long as secondary instabilities are avoided (e.g., by ensuring that pressure gradients in the $q \gtrsim 1$ region are not too locally steepen after HC formation). 3D equilibrium code VMEC (with scalar alpha pressure) also reproduces MEGA results in this range. Our results motivate further work in search of opportunities to utilize HCs for beneficial purposes.

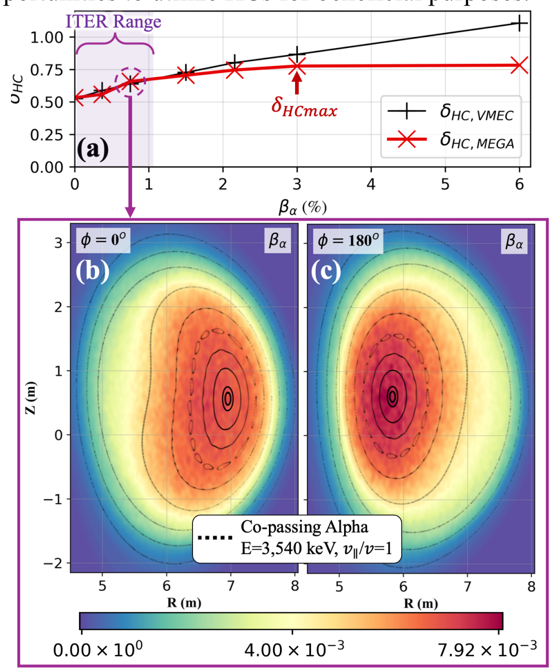

Figure 1: (a) Comparison of HC displacement (δ_{HC}) calculated by MEGA and VMEC; (b-c) Poloidal cross-section of alpha particle pressure in HC state at toroidal angles 0° and 180°.

References

[1] Cooper, W. A., et al. *Physical review letters* 105.3 (2010): 035003.

[2] Wingen, A., et al. *Nuclear Fusion* 58.3 (2018): 036004.

[3] Todo, Y., and Sato, T. *Physics of plasmas* 5.5 (1998): 1321-1327