Confinement of Fusion α-Particles and Alfvén Eigenmode Stability in STEP

A. Prokopyszyn, K. McClements, H. Oliver, M. Fitzgerald, D. Ryan, G. Xia
United Kingdom Atomic Energy Authority (UKAEA)
alex.Prokopyszyn@ukaea.uk

ID:2143

UK Atomic Energy Authority

ABSTRACT

Context:

- Fusion-born α-particles are STEP's primary fast ion species.
- They have an initial energy of 3.5 MeV.
  - $\implies$ Significantly higher energy than the background plasma (approx. 10 keV).
  - $\implies$ Possess a large Larmor radius.
  - $\implies$ Confinement particularly susceptible to 3D perturbations in $\boldsymbol{B}$.
- For optimal operation, it's crucial to keep the α-particle energy flux below approximately 1 MW/m^2 in the main chamber.

Aims

- Estimate the steady-state α-particle energy flux on STEP's inner wall in the presence of 3D fields, specifically from the ripple field generated by the toroidal field (TF) coils and the field created by the edge localised mode (ELM) mitigation coils.
- Calculate the TAEs (Toroidal Alfvén Eigenmodes) and assess their stability.

Results:

- TF ripple field's confinement impact minimal, unless TF coil position or number are reduced.
- The ELM mitigation field can significantly impact confinement.
- An acceptable energy flux can be achieved with the optimum ELM coil phasing.
- While the intrinsic fast ion drive of TAEs is anticipated to be high in STEP, it's expected that the strong bulk plasma damping will be sufficient to suppress these modes.

METHODS

- We used LOCUST (Lorentz Orbit Code for Use in Stellarators and Tokamaks) [1] to simulate the α-particles.
- The TF ripple field was represented using the following equations:
  - $\delta B_R^{ripple} = \frac{B_0 R_0}{R}\left(\frac{R}{R_{coil}}\right)^{N_{coil}} \sin(N_{coil}\phi)$,
  - $\delta B_\phi^{ripple} = \frac{B_0 R_0}{R}\left(\frac{R}{R_{coil}}\right)^{N_{coil}} \cos(N_{coil}\phi)$,
  - $\delta B_Z^{ripple} = 0$,
  - where:
    - $N_{coil} =$ Total number of TF coils,
    - $R_{coil} =$ Major radius of the outer limb of the TF coils.
- The latest design for STEP has 16 TF coils and 32 ELM mitigation coils (exterior to the vacuum vessel), with 16 in each of two rows above and below midplane (see Fig. 1).
- The currents in the kth upper and lower ELM mitigation coils are expressed as:
  - $I_k^{upper} = I_0 \cos(n\phi_k + \Delta\phi)$,
  - $I_k^{lower} = I_0 \cos(n\phi_k)$,
  - Where:
    - ϕ_k is the toroidal angle at the centre of the kth coil.
    - I_0, n and $\Delta\phi$ are variable parameters, as shown in Fig. 3.
- The ELM mitigation field was numerically determined using the MARS-F code [2], which incorporates plasma response in its modelling.
- To calculate the TAE growth rates we used the HAGIS and HALO (HAgis LOcust) codes [3, 4].

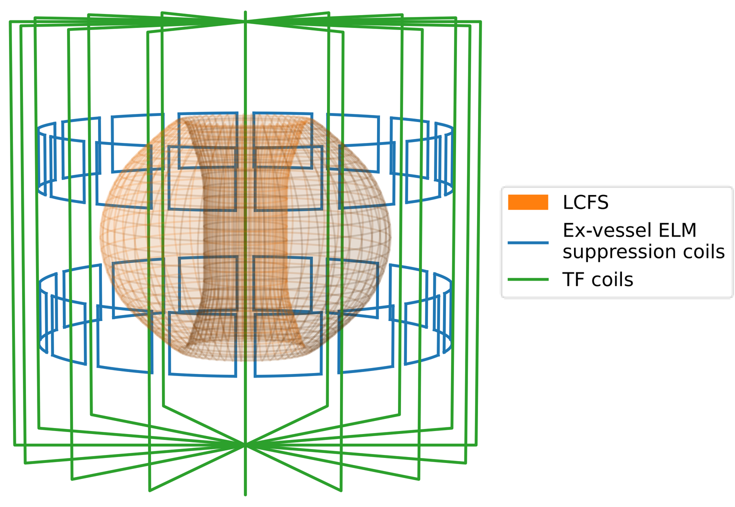

FIG. 1. Schematic representation of STEP's last closed flux surface (LCFS), ELM suppression coils (which are exterior to the vacuum vessel), and TF coils.

RESULTS

- For ELM mitigation, we plan to set $n = 3$. Fields due to higher values of n fall off more quickly with distance from the coils, decreasing the power efficiency. Fields due to smaller values of n may activate locked modes.
- Nevertheless, the decision to use n may change and so we also model the cases where $n = 2$ and $n = 4$ (see Fig. 3).
- To suppress ELMs, I_0 must be large enough, but not so large that it reduces α-particle confinement by too much.
- We estimate that for $n = 2$, $I_0 = 50$ kAt is necessary, for $n = 3$, I_0= 90 kAt is required, and for $n = 4$ a current of 150 kAt is needed.
- However, there is a high degree of uncertainty over what current is needed, so we also model a current with twice these values.
- HAGIS results show that the most unstable TAE has toroidal mode number $n = 2$ and normalized eigenfrequency $(\omega/\omega_{A0})^2 = 0.044166$ (see Fig. 4).
- HALO calculations indicate that bulk ion Landau damping of this mode γ_d is even stronger than the drive: we find that $\gamma_d/\omega \approx -1.4$.

ACKNOWLEDGEMENTS / REFERENCES

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[1] WARD, S, et al., Nucl. Fusion, **61** 8 (2021) 086029.
[2] LIU, Y., et al., Nucl. Fusion, **55** 6 (2015) 063027.
[3] PINCHES, S.D., et al, Computer Phys. Commun., **111** (1998) 133.
[4] FITZGERALD, M., et al., Computer Phys. Commun., **252** (2020) 106773.
[5] SANCHIS, L., et al., Plasma Phys. Control. Fusion, **61** 1 (2018) 014038.

TF Ripple Field

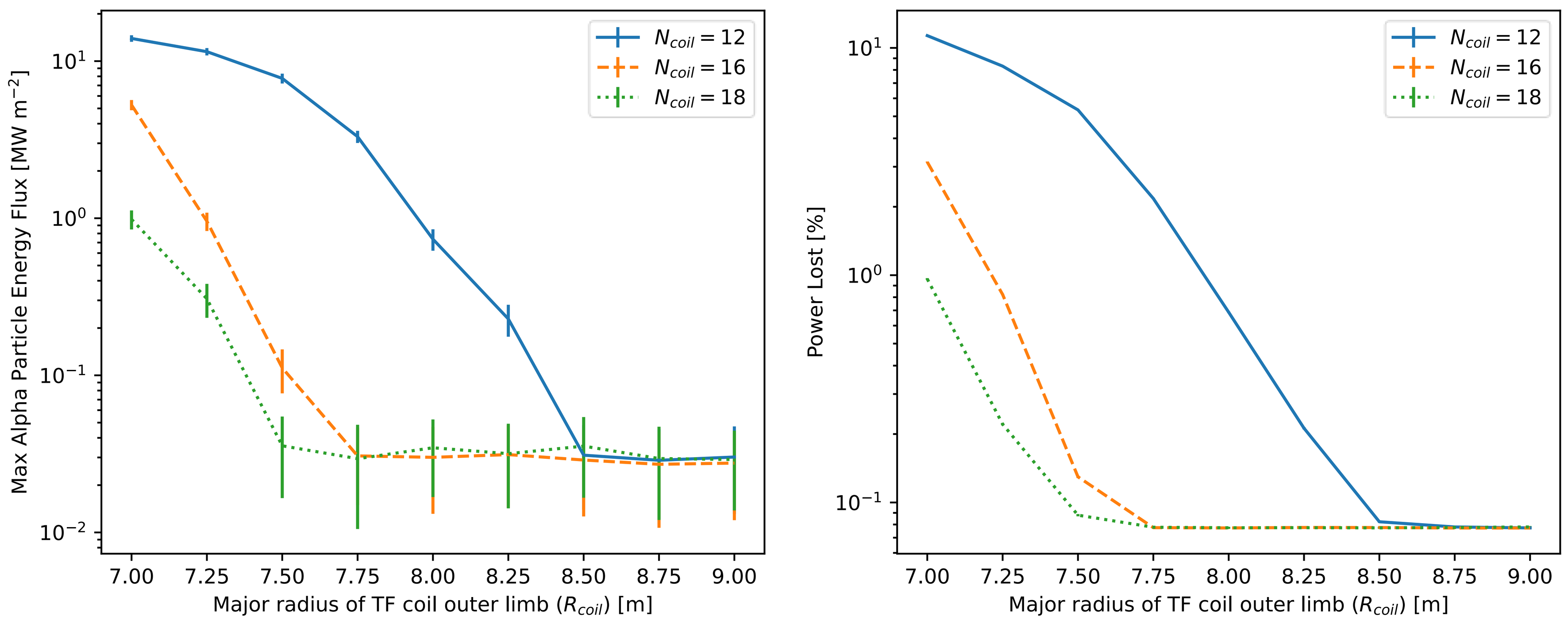

FIG. 2. TF ripple loss results from 27 simulations. The left column presents the energy flux on the reactor wall. The right column indicates the percentage of the α-particle power escaping and impacting the plasma facing components. Error bars represent 95% confidence intervals, reflecting the statistical uncertainty inherent in the Monte Carlo methodology of the simulation.

ELM Suppression Field

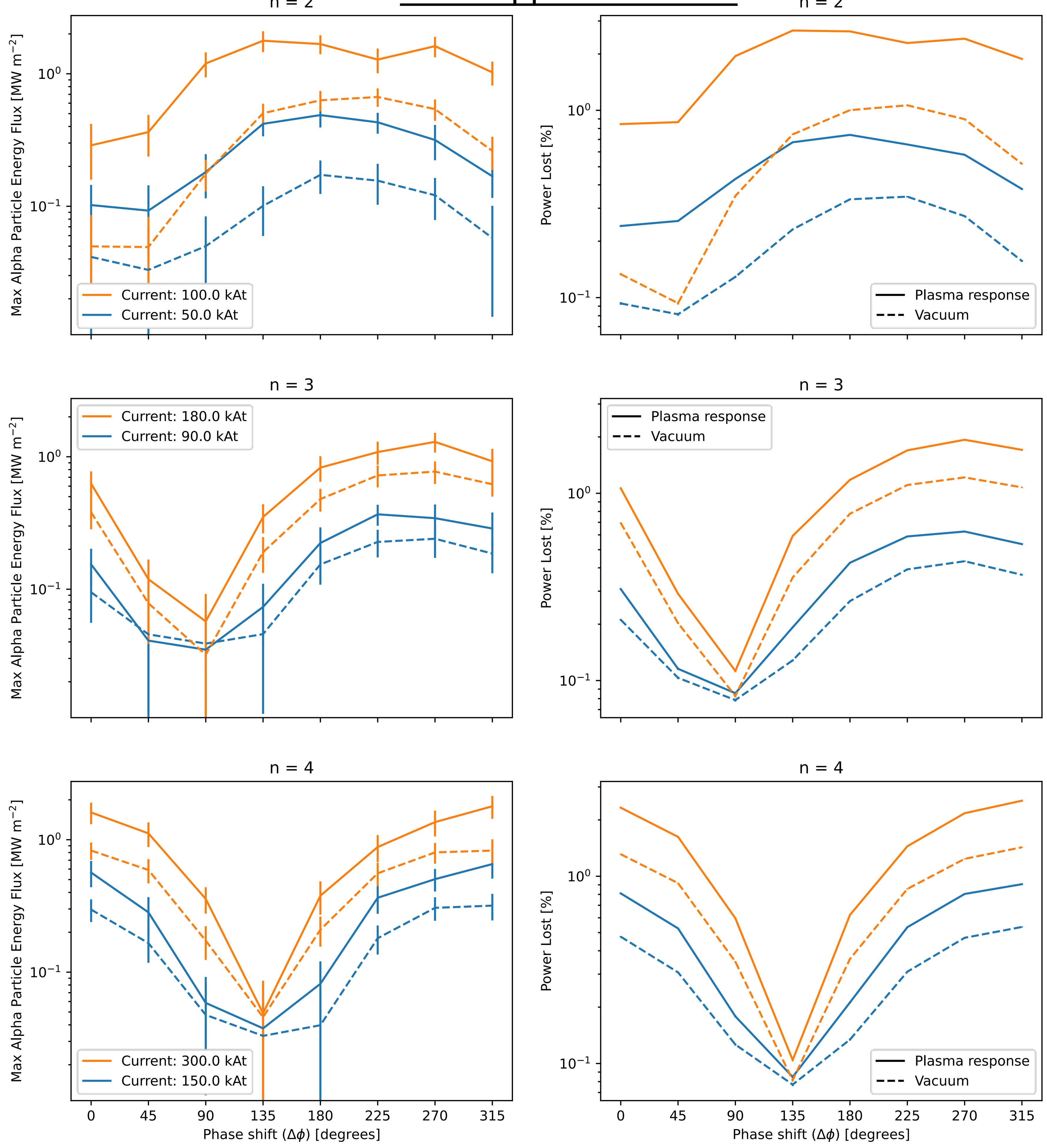

FIG. 3. Results from 96 simulations, comparing α-particle losses across different ELM mitigation coil parameters. The column arrangement mirrors that of Fig. 2.

TAE intrinsic growth rates

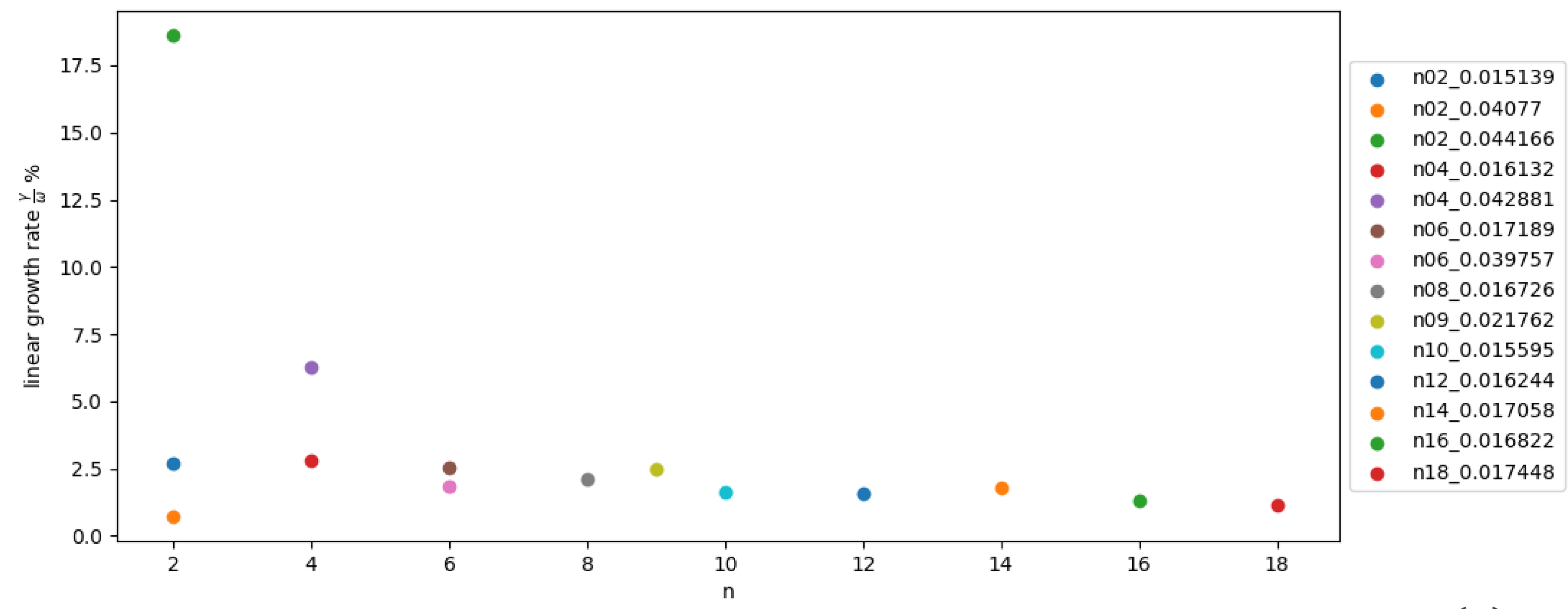

FIG. 4. Growth rates of TAEs with damping neglected in equilibrium with $B_0 = 1.8$ T, $T_i(0) = 17$ keV computed using HAGIS. The legend indicates the mode n and squared frequency normalised to $\omega_{A0} = c_A/R_0$ where $c_A$is the Alfvén speed at the magnetic axis, $R = R_0$.

CONCLUSION

- Fig. 2 shows that the current design, with a major radius of approximately 9m and 16 TF coils, has power losses that remain within acceptable limits.
- Fig. 3 indicates that the results are highly sensitive to the phase shift ($\Delta\phi$) and a similar phenomenon is observed in [5]. Even when larger current values are used and the plasma response is included, acceptable confinement can be achieved if the right phase shift is chosen.
- The results show that the TAEs will be damped by the bulk ions. However, It should be noted that this damping rate is exponentially sensitive to the bulk ion plasma beta, and therefore it is important to carry out a sensitivity scan of the plasma parameters.
- For future work, we will investigate the losses in a field where resistive wall modes and the corresponding control coils are activated.