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

ID:2143

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

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.
  - $\Longrightarrow$ Significantly higher energy than the background plasma (approx. 10 keV).
  - $\Longrightarrow$ Possess a large Larmor radius.
  - $\Longrightarrow$ 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/m² 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.

Results:

- TF Ripple field's confinement impact is minimal, unless coil position changes.
- The ELM mitigation field significantly impacts confinement.
- An acceptable energy flux can be achieved with the optimum coil rotation.

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.
- We numerically verified the above model's accuracy.
- We vary N_{coil} and R_{coil} in Fig. 2.
- The latest design for STEP has 16 TF coils and 32 ELM mitigation coils, with 16 in each row (see Fig. 1).
- The current in the kth upper and lower ELM mitigation coils is 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 k^{th} coil
    - I_0, n and $\Delta\phi$ are variable parameters, as shown n Fig. 3..
- The ELM mitigation field was numerically determined using the MARS-F code [2], which incorporates plasma response in its modelling.

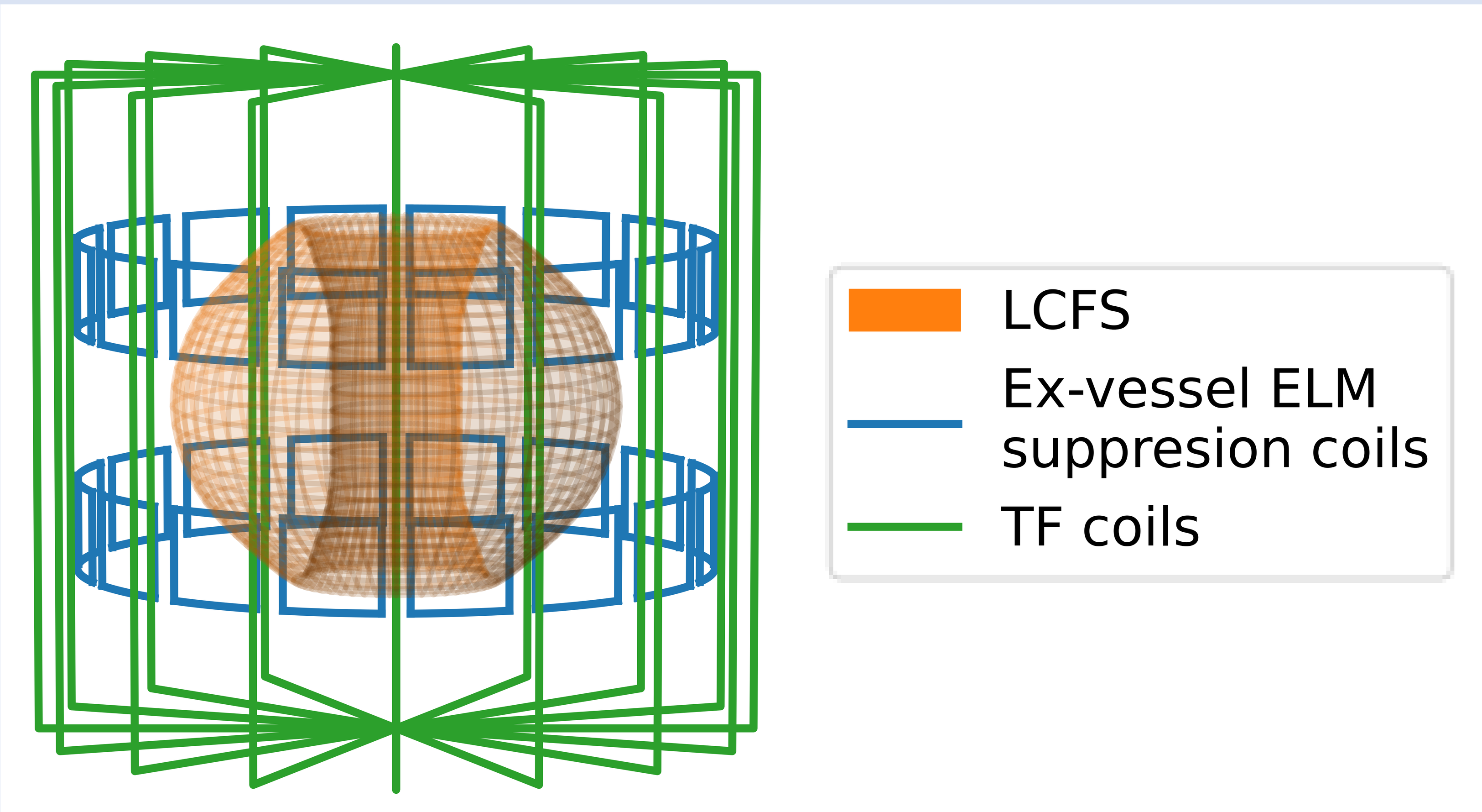

FIG. 1. Schematic representation of STEP's last closed flux surface (LCFS), ELM suppression coils (which are exterior to the vacuum vessel), and TF coils.

RESULTS

- For ELM mitigation, we plan to set $n = 3$. Greater values of n dissipate more quickly away from the coils, decreasing the power efficiency. Smaller values of n may activate locked modes.
- Nevertheless, the decision to use n may change and so we also model the case 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.

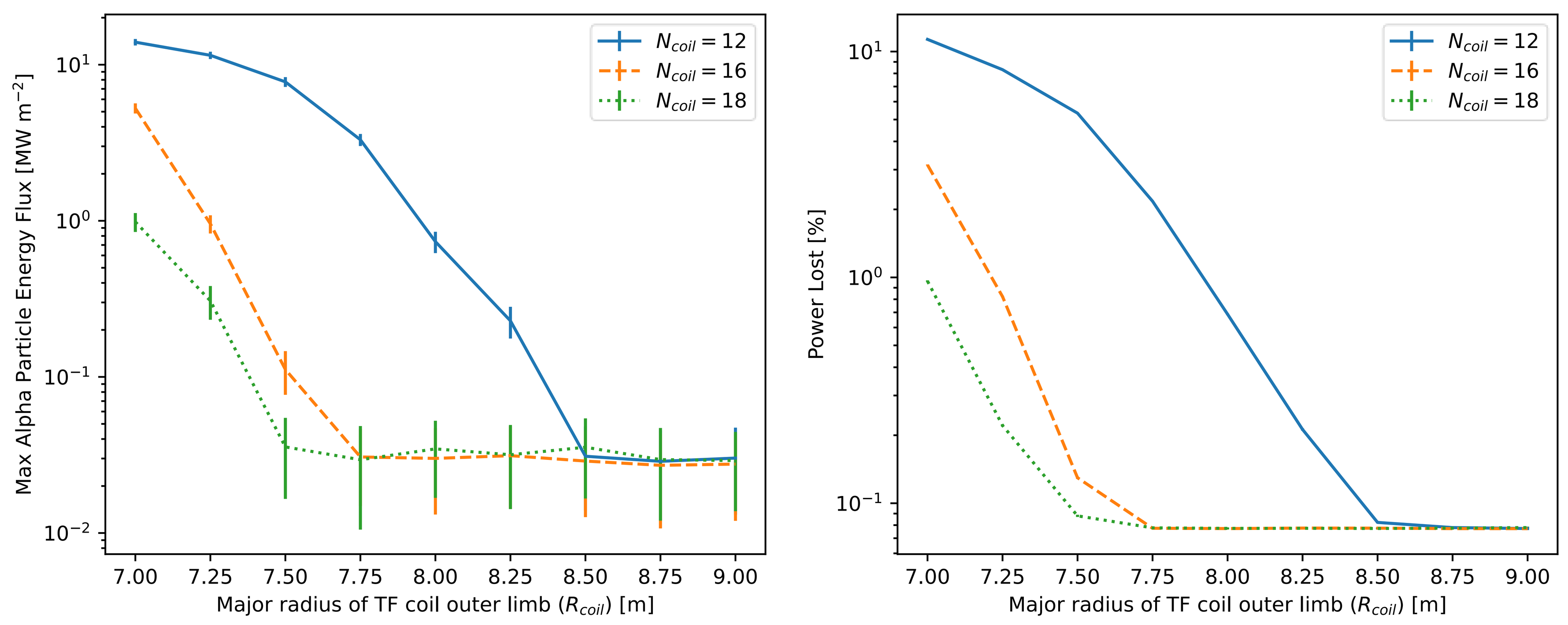

FIG. 2. Figure depicts results from 27 simulations. The left column presents the energy flux on the reactor wall. The right column indicates the percentage of the α-particle power escaping and impacting the plasma facing components. Error bars represent 95% confidence intervals, reflecting the statistical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

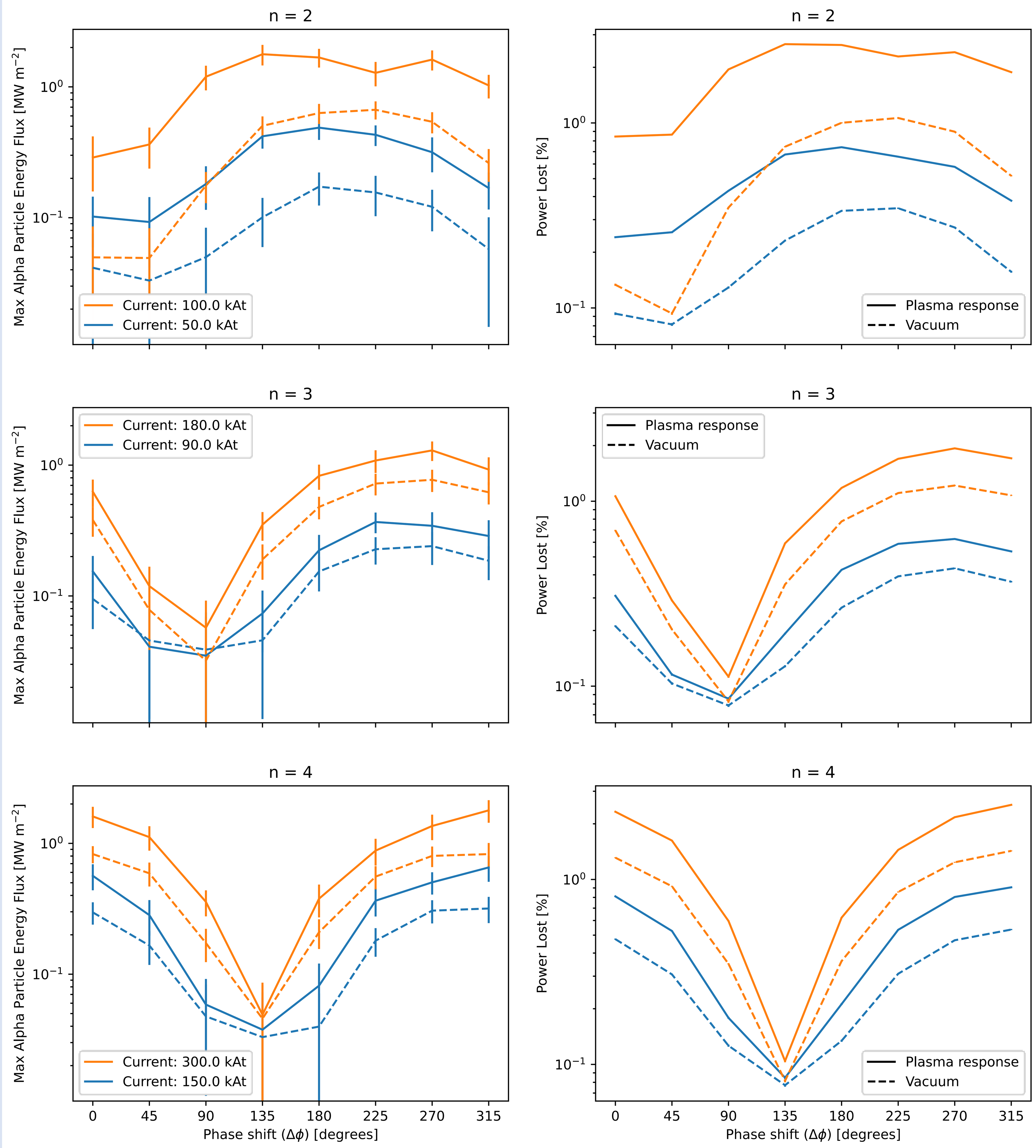

FIG. 3. Figure illustrates outcomes from 96 simulations, comparing α-particle losses across different ELM mitigation coil parameters. The column arrangement mirrors that of Fig. 2.

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. Increasing the design configuration beyond this will have a minimal effect on improving particle confinement from a fast particle perspective.
- Fig. 3 indicates that the results are highly sensitive to the phase shift ($\Delta\phi$) and a similar phenomenon is observed in [3].
- 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.
- For future work, we will investigate the losses in a field where resistive wall modes are excited.

ACKNOWLEDGEMENTS / REFERENCES

This work has been funded by STEP, a UKAEA program to design and build a prototype fusion energy plant and a path to commercial fusion.

[1] WARD, S, et al., Nucl. Fusion, **61** 8 (2021) 086029.
[2] LIU, Y., et al., Nucl. Fusion, **55** 6 (2015) 063027.
[3] SANCHIS, L., et al., Plasma Phys. Control. Fusion, **61**, 1, (2018) 014038.