CONFINEMENT OF FUSION ALPHA-PARTICLES AND ALFVÉN EIGENMODE STABILITY IN STEP

A. PROKOPYSZYN, K.G. MCCLEMENTS, H.J.C. OLIVER, M. FITZGERALD, D.A. RYAN, G. XIA

United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, United Kingdom

Email: Alex.Prokopyszyn@ukaea.uk

The Spherical Tokamak for Energy Production (STEP) programme aims to design and build a prototype fusion power plant that will generate around 1.6-1.7 GW of deuterium-tritium fusion power [1]. Good confinement and low redistribution of fusion alpha-particles will be required to realise the target plasma scenario and to ensure acceptable first wall power loads. Microwaves will be used for external heating and current drive, meaning alpha-particles will be the only notable fast ion species. We report on modelling alpha-particle confinement and toroidal Alfvén eigenmodes (TAEs) driven by these particles in plasma scenarios that have been identified through transport modelling as candidates for the flat-top operating point in the STEP prototype.

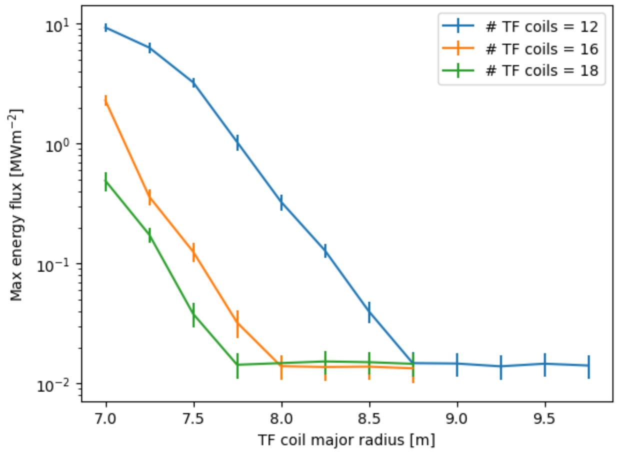

Fig. 1. Maximum alpha particle energy flux on first wall due to prompt and TF ripple losses for range of TF coil

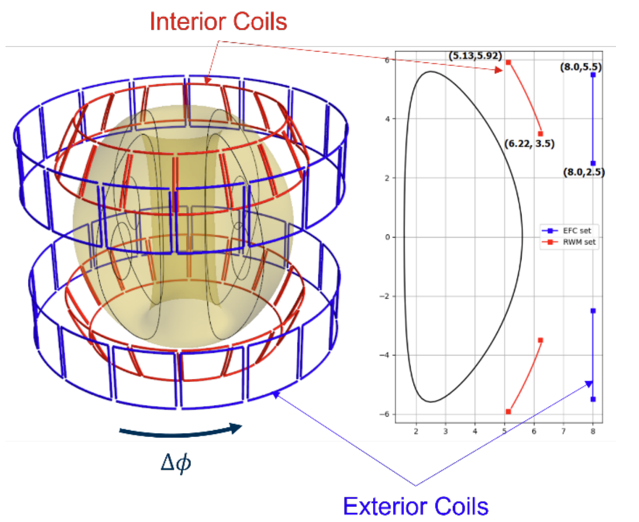

Fig. 2. Layout of the interior (RWM) and exterior (EFC) coils that could be used for ELM mitigation.

The LOCUST code [2] has been used to calculate alpha-particle losses and associated wall loads due to prompt orbit effects, toroidal field (TF) ripple and 3D resonant magnetic perturbations (RMPs) designed to suppress ELMs in one of the STEP flat-top operating points discussed in [1]. The total alpha-particle power is 338 MW in all the cases presented here. The TF ripple amplitude is determined by the number of TF coils and the major radius R of their outer limbs (picture-frame coils are assumed). For the baseline case (16 coils), ripple-induced alpha-particle losses are acceptably low if $R \geq 8$m (Fig. 1).

We have investigated losses due to RMPs for the following cases:

- coils inside and outside the TF cage, designed respectively for resistive wall mode control and error field correction (Fig. 2);
- a range of RMP coil currents;
- with and without ripple field included;
- a range of toroidal mode numbers (n) of the RMP field;
- a range of toroidal rotation angles ($\Delta\phi$) of the top set of RMPs relative to the bottom set;
- RMPs with and without the plasma response modelled using MARS -F [3].

We need to examine this broad parameter space because it is not yet known which, if any, of these RMP scenarios would result in complete ELM suppression. The advantage of placing the RMP coils inside the TF cage is that they can generate a stronger 3D field in the plasma with less current. However, the disadvantage is that providing adequate cooling inside the TF chamber may be too difficult. We present results obtained for various $n = 3$ RMP scenarios in Table 1. As expected, alpha-particle losses rise with RMP coil current. For example, in scenario B a doubling of the current in Scenario A caused the lost alpha-particle power to rise from 4.1 MW to 9.3 MW. In general, removing the TF ripple increases the alpha-particle confinement. For example, in Scenario E, removing the ripple from scenario D caused the total lost power to drop from 0.54 MW to 0.27 MW. However, removing the ripple can occasionally reduce alpha-particle confinement. For example, in scenario C, we removed the ripple field from scenario B, and this caused 13 MW of alpha-particle power to be lost instead of 9.3 MW.

The coil current needed to generate a large enough 3D field to suppress ELMs increases with n. However, smaller n carries a higher risk of triggering MHD instabilities. Hence $n = 3$ or $n = 4$ are considered to be optimum. We find that changing $\Delta\phi$ can have a significant impact on fast particle confinement, as reported for AUG in [4]. For example, changing $\Delta\phi$ from 135° (Scenario A) to 0° (Scenario F) increased the lost alpha-particle power from 4.1 MW to 8.4 MW. Including the plasma response (using MARS-F) in our model tends to reduce the alpha-particle confinement. For example, comparing Scenarios A and G, we see that the plasma response caused the lost alpha-particle power to rise from ~0.68 MW to ~4.1 MW. However, we are investigating the possibility that the latter figure may be an overestimate arising from the plasma response fields being under-resolved.

Scenario	Exterior/ Interior coils?	RMP coil current [kAt]	TF ripple included?	$\Delta\phi$	Vacuum or plasma response RMP field?	Maximum α-particle energy flux [MWm^{-2}]	Lost alpha power [MW]
A	Exterior	91	Yes	135°	Response	~0.2	~4.1
B	Exterior	182	Yes	135°	Response	~0.4	~9.3
C	Exterior	182	No	135°	Response	~0.8	~13
D	Interior	47	Yes	45°	Vacuum	~0.04	~0.54
E	Interior	47	No	45°	Vacuum	~0.03	~0.27
F	Exterior	91	Yes	0°	Response	~0.5	~8.4
G	Exterior	91	Yes	135°	Vacuum	~0.05	~0.68

Table 1. Alpha-particle power loss and associated maximum first wall energy load for a range of RMP scenarios.

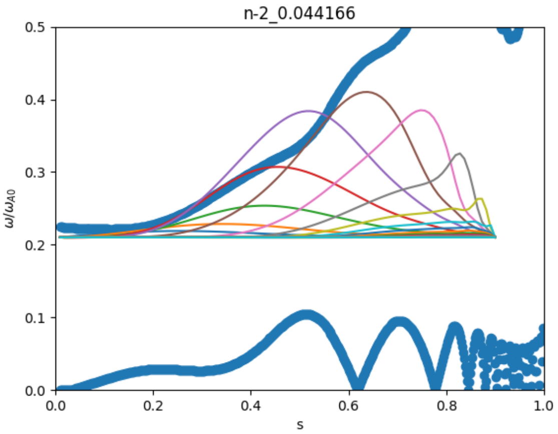

Fig. 3. Alfvén continua for $n = 2$ (thick blue curves) and poloidal harmonics of TAE eigenfunction (thin curves) computed respectively using CSCAS and MISHKA codes for STEP equilibrium with $B_0 = 1.8$ T .

TAE stability calculations for a relatively compact STEP scenario with a toroidal field B_0 =1.8T at the geometric axis have been carried out using the HAGIS [5] and HALO [6] codes, the eigenfunctions having been obtained using the CSCAS [7] and MISHKA [8] MHD codes. Due to high magnetic shear in the plasma edge, many TAEs exist in these plasmas, some with intrinsic normalised growth rates as high as ~20%. The eigenfunction of this mode is shown in Fig. 3, which also illustrates the high width of the toroidicity-induced gap characteristic of spherical tokamaks. It can be seen that the mode lies at the top of the TAE continuum gap and is global, making it possible for it to interact with a high concentration of alpha-particles deep inside the plasma: this helps to explain its high intrinsic growth rate. However, the thermal ion damping of these modes in flat-top conditions is generally found to be even higher, and TAEs are, therefore, unlikely to be driven unstable during this phase. Work is ongoing to determine whether these modes could be driven during the ramp-up phase of STEP plasmas through resonant interactions with hot electrons arising from using microwaves for auxiliary heating and current drive.

REFERENCES

[1] H. Meyer, 29th IAEA Fusion Energy Conference, London, UK (2023); [2] S. H. Ward et al., *Nucl. Fusion* **61** 086029 (2021); [3] Y. Q. Liu et al., *Nucl. Fusion* **55** 063027 (2015); [4] L. Sanchis et al., *Plasma Phys. Control. Fusion* **61** 014038 (2018); [5] S. D. Pinches et al., *Comput. Phys. Commun.* **111** 133 (1998); [6] M. Fitzgerald et al., Comput. Phys. Commun. **252** 106773 (2020); [7] S. Poedts and E. Schwarz, *J. Comput. Phys.* **105** 165 (1993); [8] A. B. Mikhailovskii et al., *Plasma Phys. Rep.* **23** 844 (1997)