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Energetic particle confinement and stability in the Spherical Tokamak for Energy Production (STEP)

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The UK has launched a programme to build a prototype fusion power plant, the Spherical Tokamak for Energy Production (STEP), generating fusion power P_{fus}~1 GW and net electrical power ~100 MW [1]. Good confinement and low redistribution of fusion α-particles will be required to ensure acceptable first wall power loads and to realise the target plasma scenario. Waves in the electron cyclotron range will be used for external current drive, and therefore α-particles will be the only significant fast ion species. We report here on modelling of α-particle confinement and of toroidal Alfvén eigenmodes (TAEs) driven by these particles in STEP.

α-particle losses and associated power loads due to prompt orbit effects, toroidal field (TF) ripple and collisions have been calculated using the full orbit LOCUST code [2] for a target STEP scenario with major radius $R_0 = 3.6$m, toroidal field $B_0 = 3.2$T, plasma current $I_p = 20.8$MA, $P_{\text{fus}} = 1.76$GW. The TF ripple was calculated for $N = 16$ picture frame coils with outer major radius $R_{\text{coil}} = 7.25$m, assuming variations only with major radius R inside the separatrix and neglecting the plasma response (expected to be small). The ripple perturbation to the magnetic field in (R,φ,Z) cylindrical coordinates is then given by [3]

$$\tilde{B}_R = \frac{B_0 R_0}{R}\left(\frac{R}{R_{\text{coil}}}\right)^N \sin N\varphi \qquad \tilde{B}_\varphi = \frac{B_0 R_0}{R}\left(\frac{R}{R_{\text{coil}}}\right)^N \cos N\varphi \qquad \tilde{B}_Z = 0 \qquad (1)$$

Axisymmetric losses for this scenario are mainly of higher energy α-particles and occur in the upper divertor region (the ion grad-B drift direction is upward). However, most α-particle losses are due to the TF ripple, which causes about 1% of the α-particle heating power to be lost. The peak power loading (~0.5MWm^{-2}) occurs on the low field side main chamber wall (Fig. 1) and is at the upper limit of the acceptable range (this power flux would, of course, be in addition to those due to electromagnetic radiation and thermal plasma). Either N or R_{coil} may therefore need to be increased. Ripple-lost α-particles are born into deeply-trapped orbits, mostly inboard of the H-mode pedestal, and have an energy distribution with two peaks, at 3.5 MeV (the birth energy) and around 1.0 MeV.

Maximum power loadings have been calculated using ranges of R_{coil} and N values for a STEP design with $R_0 = 3.6$m, $B_0 = 2.3$T, $I_p = 23.2$MA, $P_{\text{fus}} = 1.56$GW: the results are shown in Fig. 2. The method of kernel density estimation was used to infer power load maxima, and error bars were obtained using a resampling method described in Ref. [4]. As expected, the power loadings are very sensitive to both R_{coil} and N.

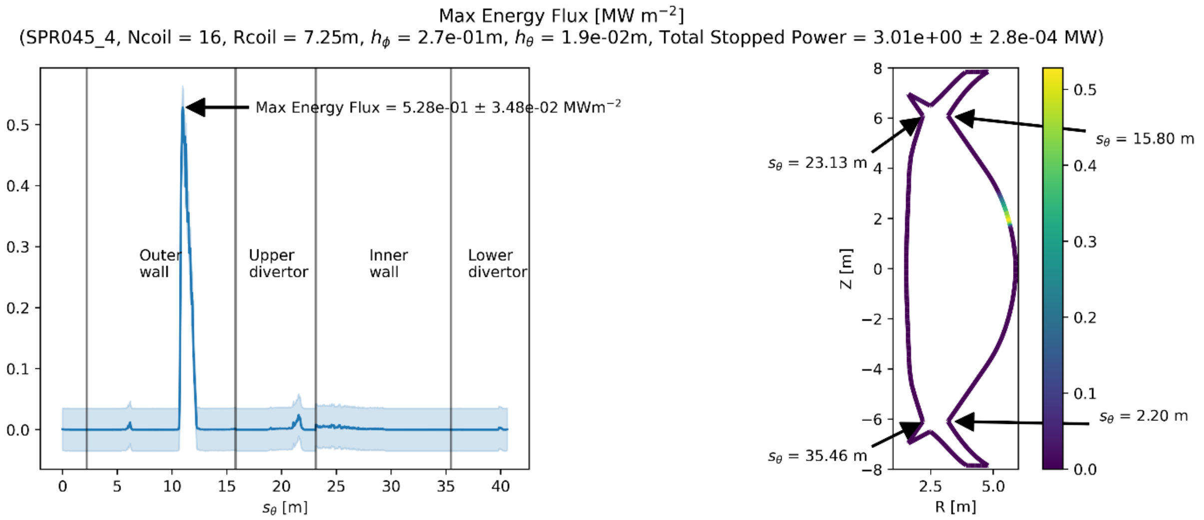

Fig. 1. Poloidal distribution of peak power flux due to axisymmetric and TF ripple-induced α-particle losses for STEP design with geometric major radius R_0 = 3.6m,

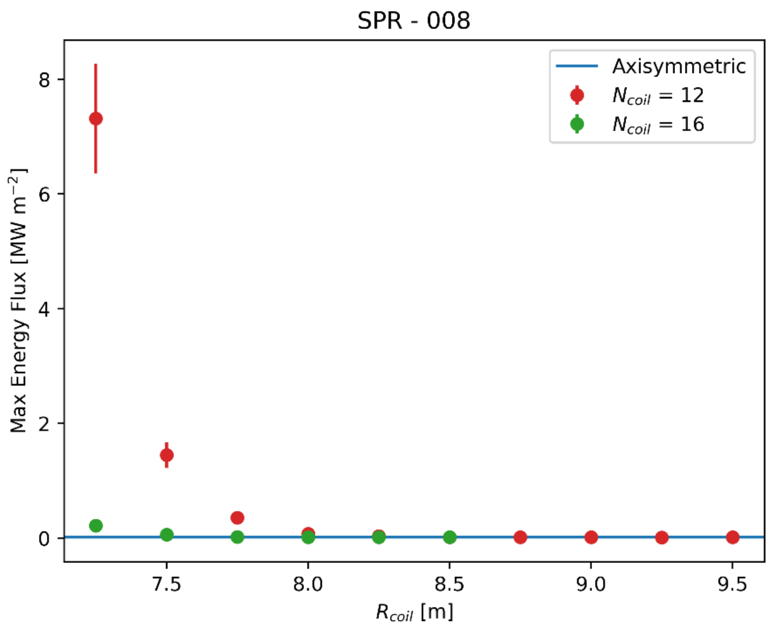

Fig. 2. Dependence on R_{coil} and N of maximum power flux due to lost α-particles in STEP design with R_0 = 3.6m, B_0 = 2.3T, I_p = 23.2MA and P_{fus} = 1.56GW.

TAEs are modes that are usually driven by fast ions and have been observed to degrade the confinement of these ions in existing devices. They can be driven unstable due to wave-particle resonances in the presence of fast ions whose orbital velocities match mode phase velocities, in particular through the primary Landau resonance $v_\parallel = c_A$ where $v_\parallel$ is fast ion speed parallel to the magnetic field and c_A Alfvén speed. The α-particle birth speed will be much larger than c_A in STEP and therefore the Landau resonance will be satisfied by α-particles as they slow down.

However, despite strong fast ion drive of these modes, substantial bulk plasma damping is also expected since the relatively low magnetic field will cause the bulk ion plasma beta in the plasma core to be a substantial fraction of unity, and therefore the ion thermal speed will be comparable to c_A, leading to strong Landau damping. Damping also occurs due to sideband resonances $v_\parallel = c_A/|2\ell - 1|$ where ℓ is an integer [5].

The stability of TAEs in STEP has been studied using the HAGIS [5] and HALO [6] codes. One particular STEP scenario, designated "V10", is relatively compact with $B_0 = 1.8$T and central fuel ion temperature $T_i(0) = 17$keV. Intrinsic growth rates (i.e. α-particle drive) of TAEs with a range of toroidal mode numbers n in the absence of all damping processes are plotted in Fig. 3. It can be seen that most TAEs have normalised growth rates γ/ω of a few percent but one $n = 2$ mode has much stronger drive, with γ/ω ≈ 0.18. In this case, the mode electric field extends further into the plasma core than that of other modes (Fig. 4a) and can thus interact with a high concentration of α-particles deep inside the plasma.

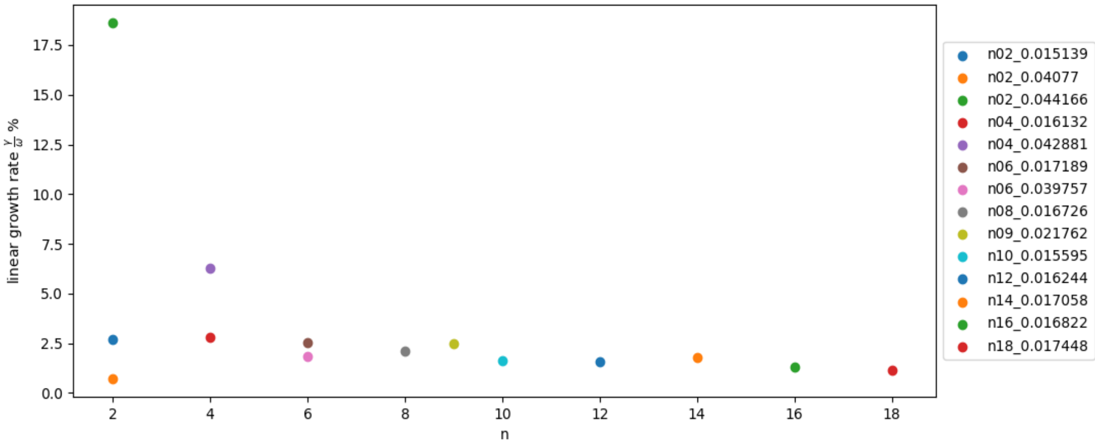

Fig. 3. Growth rates of TAEs with damping neglected in equilibrium with $B_0 = 1.8$T, $T_i(0) = 17$keV, computed using HAGIS. The legend indicates the toroidal mode number and normalised squared frequency of each mode, the normalising frequency being c_A/R_m where R_m is the major radius of the magnetic axis.

Bulk ion Landau damping of this mode (γ/ω ≈ -1.4) is even stronger than the drive, but this is exponentially sensitive to the bulk ion plasma beta. It is therefore important to consider TAE stability in STEP scenarios with higher magnetic field and hence lower beta. Fig. 4b shows the structure in the poloidal plane of the most strongly-driven TAE in a scenario with $B_0 = 4.0$T, $T_i(0) = 28$keV. In this case the normalised damping rate (-0.25) is only slightly stronger than the drive (0.19). However, dropping the core fuel ion temperature to 23.5keV has only a very small impact on the damping rate, and in such a scenario the α-particle drive would also fall since the fusion reactions are all thermonuclear (neither neutral beams nor waves in the ion cyclotron range will be used for auxiliary current drive or heating). We estimate that net growth of TAEs in this scenario would require $T_i(0)$ to fall suddenly to about 10keV, with no significant change in the α-particle population.

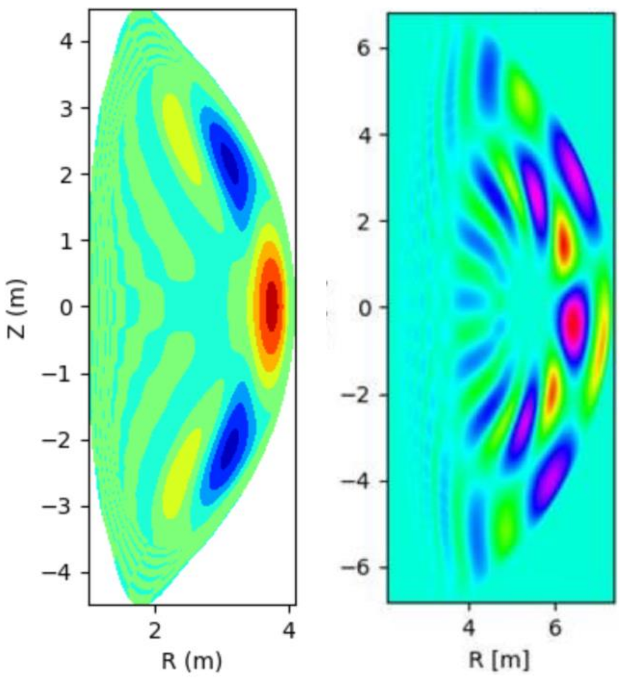

Fig. 4. Electrostatic potential of most strongly-driven TAEs in STEP equilibria with (a) $B_0 = 1.8$T, $T_i(0) = 17$keV and (b) $B_0 = 4.0$T, $T_i(0) = 28$keV.

In future work on TAEs in STEP we will prioritise a comprehensive analysis of mode stability in the target scenario corresponding to Fig. 1, and an investigation into possible TAE drive by hot electrons resulting from the use of waves in the electron cyclotron frequency range during the current ramp phase of a plasma pulse.

In conclusion, TF ripple-induced losses of α-particles in a target scenario of the STEP device with baseline values of the number N and outer radius $R_{\rm coil}$ of TF coils produce a localised power loading of up to around 0.5MWm^{-2} on the main chamber wall: this is at the upper limit of acceptability, and it is likely therefore that either N or $R_{\rm coil}$ will need to be increased. We have found that the α-particle losses and associated power loadings are very sensitive to $R_{\rm coil}$ and N. TAEs in STEP scenarios investigated so far are damped due to the bulk ion beta being relatively high for a tokamak burning plasma. However, the effects of hot electrons on TAE stability still need to be determined, along with the drive of ellipticity-induced and non-circular triangularity-induced Alfvén eigenmodes.

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