The Physics of the Preferred Plasma Scenario for STEP

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With steady progress on ITER project and the design of DEMO, the international community is now entering an era in which fusion power on the grid could become a reality within the next 20 – 30 years. In this environment the UK has started the ambitious Spherical Tokamak for Energy Production (STEP) programme, aiming to develop a compact prototype reactor based on the spherical tokamak (ST) concept by 2040 to deliver net electric power $P_{el} > 100\ MW$ to the grid. The ST concept makes it possible to maximise fusion power and bootstrap fraction in a compact device at relatively low toroidal field by allowing operation at high normalised pressure $\beta_N \approx 5.5$ and high elongation $\kappa \approx 2.8$ but it also poses unique challenges. The compactness restricts significantly the available inductive flux for the plasma pulse and therefore the required plasma current of $I_p \approx 15\ \text{MA} - 25\ \text{MA}$ needs to be predominantly generated, maintained, and ramped-down non-inductively. The non-inductive current must be driven mainly off axis as MHD stability and operation at high κ require broad current profiles with low internal inductance l_i and elevated safety factor $q_{\min} > 2$. Using the integrated scenario modelling suite JINTRAC – which is at the core of the plasma development – confidence has been gained that a ramp-up with ~ ½h is possible using ~200 MW of heating and current drive (HCD). At the high density beneficial for fusion, conventional microwave HCD techniques (ECCD) are inefficient and electron Bernstein waves (EBW) may need to be employed even though the scenario is designed to allow access to ECCD. To validate this EBW HCD for STEP ~2 MW of EBW power is being implemented on MAST-U. Using alternative divertor configurations on both the inner and outer divertor legs SOLPS-ITER calculations show access to full detachment using D_2 and moderate Ar injection and divertor pressures of the order of 10 Pa during the flat-top. The encouraging SOLPS-ITER predictions are supported by initial results on MAST-U with the super-X divertor. Whilst operation in double null (DN) is envisaged, each divertor is designed to also handle heat and particle loads in single null. Operating in a highly self-organised high β non-inductive DN scenario with a high radiation and high bootstrap fraction requires sophisticated and novel control concepts. DN operation at high κ requires the vertical position control to achieve mm accuracy to protect the inner leg, which seems feasible with in-vessel stabilising coils behind the outer blankets and small passive ring structures at the low field side. In vessel coils are also needed to control resistive wall modes allowing high β operation above the no-wall limit. A particular challenge is the prediction of the confinement in the conditions relevant for STEP. Scaling laws and present reduced transport models may give an indication but for a high β ST plasma such as STEP they are well outside their domain of experimental validation. Indeed, parameter dependencies differing from those in the IPB98(y,2) scaling have already been observed in present day large STs and reduced models such as TGLF need to be upgraded to describe transport from the electromagnetic turbulence that is expected to be present. Linear gyrokinetic (GK) modelling has shown that the turbulence in STEP reference flat-top plasmas is dominated by micro-tearing modes (MTM) and kinetic ballooning modes (KBM). Diamagnetic flow shear is stabilising for KBMs and other modes at higher $k_\perp\rho_s$ and the turbulence is likely to be dominated by MTMs at low $k_\perp\rho_s < 0.6$, which have very extended eigenfunctions in ballooning space. These slowly growing low n modes make the non-linear GK modelling very challenging. Comparison with converged non-linear GK simulations for MAST indicate that this may be related to the high Shafranov shift. The actuators to control the ensuing turbulent transport are being investigated, to seek routes to optimised confinement. Reduced models capturing the magnetic flutter driven electron transport are being tested in JINTRAC. α-particle driven toroidal Alfvén Eigenmodes (TAE) as well as neoclassical tearing modes (NTM) pose no threat for the flat-top operating point. The former whilst strongly driven are even more strongly damped in the high-β plasma and the latter are avoided by operating with $q > 2$. Employing a plasma assumption integrator based on a reduced version of JINTRAC and input from the systems code PROCESS, many prototype concept families with different plasma and technological assumptions have been generated out of which the STEP team has selected a preferred scenario. The talk will give a brief overview of the STEP programme and will discuss in more detail the physics design of the preferred plasma scenario as well as the scenario sensitivity around the preferred point. It will present the key plasma challenges and assumptions that lead to the scenario choice and discuss the modelling framework and results that are used to reduce the uncertainties in the plasma solution. Whilst many challenges remain this work gives confidence that an electricity-producing prototype compact fusion power plant based on the plasma performance of an ST is likely to be feasible.