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The Spherical Tokamak for Energy Production (STEP): a Steady-State Fusion Reactor

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The UK-based STEP programme aims to develop by 2040 a prototype reactor based on the spherical tokamak (ST) concept, thereby establishing a basis for developing commercial electricity production from fusion [1]. The compact design restricts the possible inductive flux, hence the flat-top plasma current will be entirely non-inductive, enabling long-pulse operation. External current drive will be delivered using electron cyclotron and electron Bernstein waves. Modelling using the transport code JETTO, with input from the systems code PROCESS, indicates that the time required to ramp up the current will be around 1000s or longer, in part to avoid large back-EMFs. To demonstrate the viability of an ST-based commercial reactor, the flat-top phase will ultimately need to be much longer than the ramp-up, while the energy confinement time will be a few seconds. STEP will therefore need to be a steady-state device, with a fuel cycle and control system that keep the plasma close to a target scenario. 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 and elongation, but it also poses unique challenges. Double null operation will be used, with divertors that are resilient to losses of up-down symmetry. Operating in a highly self-organised, high beta scenario with large radiation and bootstrap fractions will require novel control techniques. The prediction of confinement is particularly challenging. For a high beta ST such as STEP, presently-available scaling laws and reduced transport models are well outside their domain of experimental validation. Moreover, parameter dependencies differing from those in scaling laws derived for conventional tokamaks have been observed in present day STs, and reduced models need to be modified due to the electromagnetic nature of the turbulence expected to dominate. Linear gyrokinetic (GK) modelling shows that the turbulence in reference flat-top plasmas is dominated by micro-tearing modes (MTMs) and kinetic ballooning modes (KBMs). Diamagnetic flow shear is stabilising for KBMs and other modes at high wave number k, and the turbulence is likely to be dominated by MTMs at low k: this makes the non-linear GK modelling very challenging. Actuators to control the transport are being investigated to seek routes to optimised confinement. Reduced models capturing the magnetic flutter-driven electron heat transport are being tested using the integrated modelling suite JINTRAC. Results so far support assumptions made for the simpler Bohm-gyro-Bohm model used for the concept evaluation. We have identified a preferred scenario based on the exploration of several prototype concepts with different plasma and technology assumptions. In this scenario fusion alpha-particle-driven toroidal Alfvén eigenmodes are predicted to be suppressed due to high beta. I will give an overview of STEP and discuss the physics design of the preferred scenario. I will present the key challenges and assumptions leading to the scenario choice and discuss the modelling framework being used to reduce uncertainties. This work gives confidence that a compact fusion reactor will be feasible.

[1] https://step.ukaea.uk/

Author: MCCLEMENTS, Ken (United Kingdom Atomic Energy Authority)

Co-author: MCCLEMENTS, Ken (United Kingdom Atomic Energy Authority)

Presenter: MCCLEMENTS, Ken (United Kingdom Atomic Energy Authority)

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