SCIENCE AND TECHNOLOGY CHALLENGES IN SUPPORT OF A DT SPHERICAL TOKAMAK DEMONSTRATION FUSION PLANT

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Spherical tokamaks (ST) provide a compact, potentially reduced cost path to fusion power. They share many science and technology features with conventional tokamaks, but have a number that are ST-specific. Using examples from the STEP (CML-5) design we explore some of the research and development needs, emphasising the ST-specific ones.

An ST has limited space on the inboard side to accommodate a substantial solenoid. While STEP does envisage a small one to initiate the plasma, operation will be largely non-inductive and rely on a high bootstrap current fraction (~90%) and microwaves to top up the remaining current. High bootstrap current pushes the plasma scenario to high elongation and high normalised plasma pressure, β_N. We will illustrate how the ST naturally aligns with these requirements, opening up the possibility of a self-consistent steady state plasma scenario. However, research challenges remain: (1) the high β plasma will be dominated by electromagnetic turbulence and the associated transport remains uncertain; (2) high β_N requirement can result in resistive wall modes that must be controlled; (3) high elongation further challenges the plasma control system; (4) microwave current drive efficiency is optimal if via the electron Bernstein wave, requiring understanding of mode conversion physics and current drive efficiency.

A characteristic of the ST is the limited inboard build space. However, by optimising blanket design, self-sufficiency in tritium only requires outboard breeding, which reduces complexity and enhances maintainability. The LIBRTI facility provides a valuable opportunity for experiments that validate our predictive modelling capability in areas such as neutron transport & shielding, tritium breeding and tritium transport: key physics associated with the compact inboard build and outboard breeding blanket design.

The maintainability of an ST is significantly improved if the centre column can be withdrawn. This requires joints to be broken and remade between the centre column toroidal field conductor and return limbs. For high temperature superconductors there is no such fully validated solution; we describe the STEP approach to demonstrate this novel technology.

The compact nature of the ST results in a challenging exhaust load. MAST-U experiments have shown the benefits of the Super-X divertor for managing this, which then informs the design for STEP. Employing carefully controlled double null geometry and injecting xenon into the core to radiate 70% of the power, we show a pathway to a detached divertor, accessed via argon seeding.

In order to meet its 2040 delivery timescale, STEP has developed an innovative approach to the validation of materials which does not rely on testing in a fusion neutron environment. The programme, called Design by Fundamentals, integrates experiments and modelling in an iterative and coherent way to deliver the required data. Specifically, the data from carefully designed ion, low-flux fusion-neutron or fission-neutron irradiation experiments inform and validate micro-scale models, which will then be employed to predict macroscopic materials performance in STEP. Like many aspects, operation of STEP itself provides the data for final validation, so care must be taken to ensure no materials subject to high energy fusion neutrons have a safety function.

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