STEP: NOVEL POWER INFRASTRUCTURE FOR FUSION POWERPLANTS

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The Spherical Tokamak for Energy Production (STEP), a programme pioneered by the United Kingdom Industrial Fusion Solutions (UKIFS), seeks to develop a first of a kind demonstration fusion pilot plant based on a spherical tokamak: the STEP Prototype Powerplant (SPP). The SPP must demonstrate generation of at least 100 MWe net power [1] to the national electrical grid network (in the UK: the *National Grid*). The SPP must therefore develop, not only a novel tokamak core, but a much wider holistic and integrated powerplant. The powerplant design must include the extraction and conversion of fusion energy, which is traditionally delivered by the "*Balance of plant"* systems [2]. On STEP, the *Power & Cooling (P&C)* systems and sub systems, will deliver a similar function by:

- Cooling the tokamak components, while extracting useful thermal energy.
- Generating power: conversion of thermal energy to electrical energy (power generation).
- Managing energy: management of the site-wide distribution, storage and energy export.

Ensuring highly efficient *P&C* systems is vital in achieving STEP's primary 100 MWe goal [1]. Furthermore, flexible *P&C* systems are required to match the dynamics of a fusion heat source, ultimately ensuring operability; this is the same as any demonstration/prototype fusion powerplant. For the SPP, these flexibility requirements are especially challenging when considering its scale and prototypic nature. STEP has made a number of key decisions and technology selections which has heavily influenced the integrated powerplant design. The highly adaptable yet efficient *P&C* systems, in turn will need considerable technology development, due to the holistic novelty.

Tokamak systems are highly dynamic. While STEP is targeting a steady state, non-inductive plasma scenario, tokamaks operated in a standard scenario are inherently pulsed [3]. Solutions have therefore been developed to show how thermal power across the plant is managed in frequent dwell/pulse arrangements as well as how the electrical power to the grid is sustained in dwell periods [2].

The Spherical Tokamak (ST) offers a particularly attractive pathway to steady state operation. The bootstrap current, self-driven by the plasma, is optimised for the SPP [4], greatly reducing the need for external current drive supplied either by the central solenoid or by (inefficient) non-inductive means. As a result the SPP will not need to pulse on a frequent basis to recharge a central solenoid. This offers significant advantage in attempting to reach baseload power from fusion, as the ST can, in theory, run indefinitely producing thermal power without a defined pulse pattern. This would be similar to incumbent baseload power generating technologies.

Significant considerations for the SPP must be made with respect to the dynamics of the plasma ramp up and ramp down at the start and end of each operational period. Significant fusion power (P_{fus}) will only be generated from the period starting from the rapid density rise phase ("densification") towards the end of the plasma ramp, lasting ca. 100 seconds. From a power perspective this is an effective ramp of 2GWth generated from the tokamak, during this 100 second time frame. Prolonging this densification time frame is undesirable as then significantly more auxiliary power would be required – at this time the auxiliary power achievable is limited by microwave gyrotron capacity, as well as the power that can be drawn from the *National Grid*. For similar reasons a 100 sec period is also targeted for shut down, where the thermal energy generated by the tokamak drops from 2 GWth to almost 0. Managing this very rapid and sudden (relative to conventional power sources) ramp up and ramp down of tokamak heat is a difficult engineering feat. This challenge is further exacerbated when considering the prototypic nature of the SPP. Indeed, at this point in the project the actual pulse trajectories still carry some uncertainty as the design develops and modelling fidelity is increased. In addition, so far only the DT pulse has been modelled and a possible plasma commissioning phase without tritium may require additional capability from the power systems. Equally operations may be paused or even systems tripped while we learn how to operate the plant reliably.

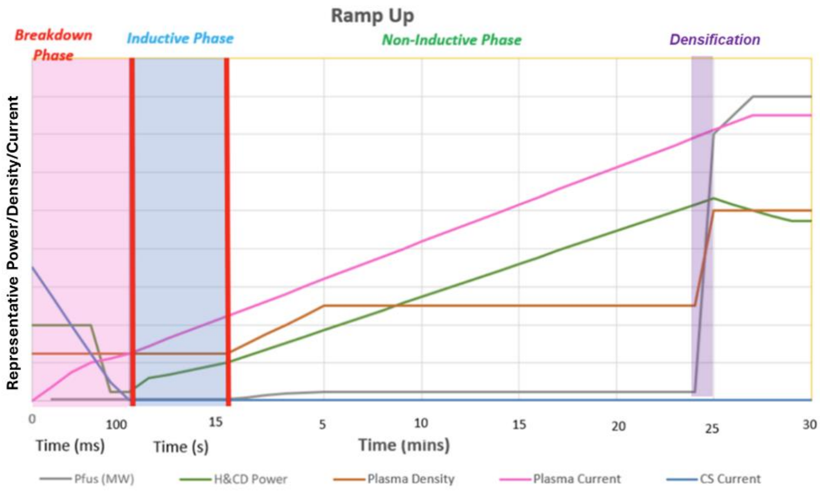

Figure 1: STEP Estimated Plasma Ramp Up

The supporting *P&C* systems must therefore be highly flexible to adapt to these uncertain prototypic operations. That is to say, these systems must have the ability to switch on and off, or ramp up and down, in similar timescales as the sudden generation/extinguishing of thermal power from the tokamak; even at unexpected times. These systems must also be highly efficient to enable the 100MWe production during flat top. The *P&C* systems have been broken down into sub systems that may support these operations. The SPP *P&C* design choices, including key technologies, that will satisfy the flexibility and efficiency ambitions, are shown in figure 2.

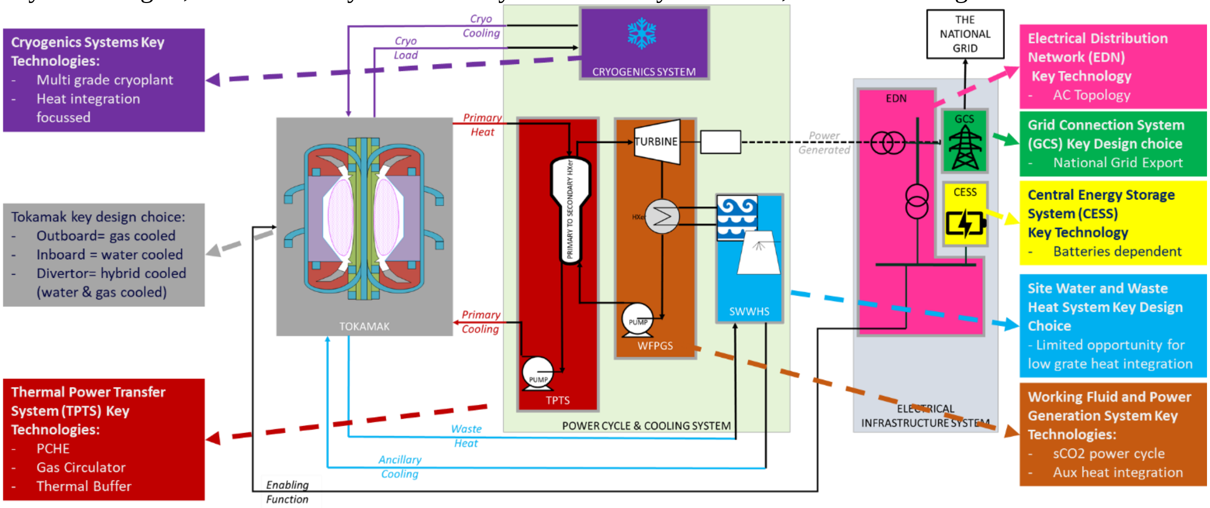

Figure 2: STEP Power & Cooling System breakdown with key technologies

The following rationale has dictated some of these key design choices highlighted in figure 2:

- A mix of water and gas coolants has been selected, ensuring the tokamak functions around shielding for the centre column, and neutron transparency for the outboard wall. The selection and conditions (temperature and pressure) of these coolants has been carefully tailored to maximise net power (through heat integration), while adhering to the other STEP objectives (notably TBR and availability) [1].
- A supercritical CO_2 power cycle has been selected as the preferred thermodynamic cycle. This is because it simultaneously ensures an efficient conversion of heat into electrical power (similar to a steam Rankine cycle [1]) – while also being highly flexible to manage rapid ramps of the power loads [5].
- A Printed Circuit Heat Exchanger (PCHE) is selected as a preferred heat exchanger type for the heat transfer from the primary coolant to the secondary coolant, which allows for compact and high efficiency heat exchange between the primary coolants and the supercritical CO_2 working fluid.
- An integrated cryo-plant has been designed which supplies cryogen to a large number of different cryogenic subsystems at varying temperatures, from a single cryo-refrigeration cycle; ensuring design simplicity and minimising parasitic losses linked to heat leak [6]
- An Alternating Current (AC) architecture has been developed for the electrical infrastructure, which uses conventional components while still ensuring a sufficiently efficient system.

This paper will explain the challenge of generating power from the SPP focusing on the dynamic elements, building on the efficiency requirements already established [1]. The *P&C* system designs will then be described, detailing the technology and design choices. The decisions and rationale that have led to these technology choices will be elaborated on (expanding on examples given, with new areas explored as per figure 2), highlighting how they ensure a powerplant that is both efficient and flexible as appropriate for the SPP.

ACKNOWLEDGEMENTS

This work has been funded by STEP, a major technology and infrastructure programme led by UK Industrial Fusion Solutions Ltd (UKIFS), which aims to deliver the UK's prototype fusion powerplant and a path to the commercial viability of fusion.

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