STEP EXHAUST SYSTEM – ARCHITECTURE AND TECHNOLOGY DEVELOPMENT OVERVIEW

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Heat and particle exhaust is a fundamental challenge for the STEP Prototype Plant (SPP). The STEP programme is pursuing a spherical tokamak design, in order to take advantage of reduced capital costs compared to conventional tokamak designs. The smaller radius of a spherical tokamak increases the exhaust challenge due to the reduced area available to dissipate heat and manage particle exhaust. Integrating the divertors into a prototype powerplant, as opposed to an experimental device, introduces additional challenges such as the need to demonstrate commercially relevant component lifetimes in a fusion environment and introduces constraints such as ensuring manufacturing cost and levels of activated waste are reduced as far as practicable. The successful realisation of the SPP exhaust system is therefore reliant on understanding and balancing a wide range of trade-offs, such as balancing heat load management and compatibility with the power generation cycle when specifying coolant temperatures. Here we will present an overview of the current SPP Exhaust System design and ongoing technology development activities.

The SPP design features an up-down symmetric double null configuration to reduce heat flux seen by plasma facing components (PFCs) [1]. The plasma design has gone through multiple iterations. Each divertor comprises of a tightly baffled super-X divertor and shorter inboard legs approaching an X-divertor. A ‘dome’ structure is included between the inboard and outboard legs, facilitating transport of neutral particles to the outboard legs, where the vacuum pumps are located, while minimising core plasma pollution. The divertor plasma will operate in detached mode, maintaining heat and particle loads within engineering limits.

Engineering constraints have driven many aspects of the integrated divertor design. For example, maintenance considerations have placed spatial constraints on the allowable radius of the inner and outer strike points to allow space for component removal, while manufacturing constraints have led to straight surfaces being preferred to curved surfaces in the wall shape where possible. Maintaining the field line angle at the divertor targets within acceptable limits to avoid damaging PFCs is a key driver in the development of the plasma scenario and coilset design.

Heat and particle loads vary spatially throughout the divertor [2]. All PFCs are water-cooled with tungsten armour as the plasma facing material, but with different cooling configurations providing a balance of performance and complexity (Fig. 1). The technology choice for the strike points is driven in part by the need to withstand Type-I ELMs, addressing a key risk that ELM-free plasmas cannot be guaranteed through all stages of operation. Tungsten ‘micro brushes’ are used at the strike points; a technology which offers increased resilience to repeated transient events such as ELMs compared to alternatives such as tungsten monoblocks due to the removal of surface cracking and subsequent crack propagation as a failure mode. This will increase the allowable time for the control system to react and mitigate ELMs if they occur. The micro-brush is a less mature technology than monoblocks and so technology development, particularly regarding resilient manufacturing processes, is required in order to achieve this performance benefit.

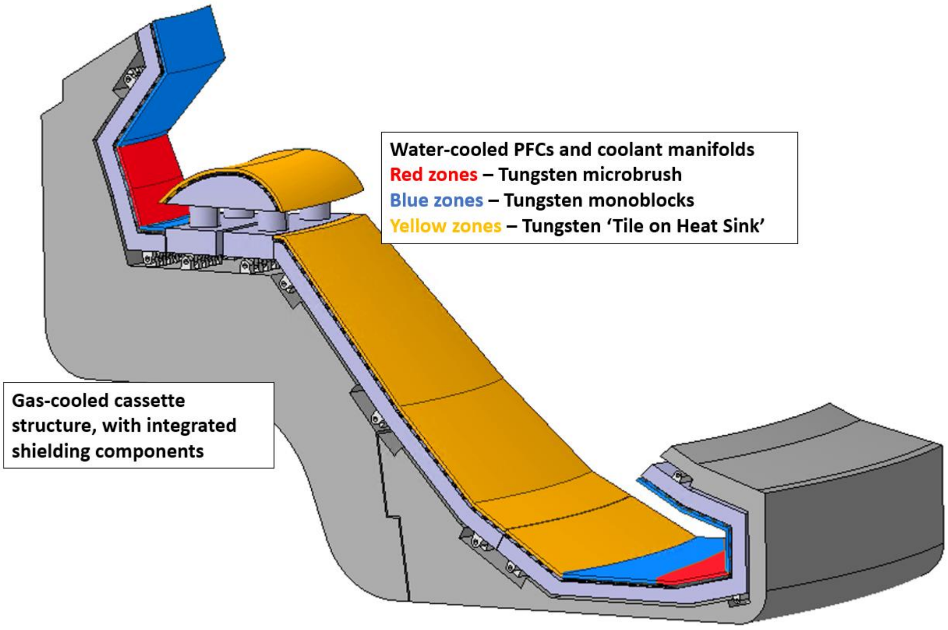

Fig. 1: Toroidal segment of the STEP Divertor design

The divertors provide shielding to protect the magnet coils located above and below the tokamak, an essential function to demonstrate a pathway to a commercially relevant machine lifetime. The PFCs are supported by structural 'cassettes', which are gas-cooled to allow the use of reduced activation steel and to provide useable heat to the power generation cycle. This leads to reduced shielding performance compared to water cooling, which is mitigated via the addition of tungsten-based shielding materials within the cooling channels. The required thickness of shielding components constrains the allowable location of the plasma facing surface affecting the shaping of the dome and introducing a need to move the plasma facing surface of the outboard divertor leg closer to the separatrix.

The vacuum pumping duct is positioned to achieve a balance of achieving sufficient pumping speeds and allowing sufficient pressure to build up near the outboard target to ensure detachment. A dome is included between the inboard and outboard divertors, allowing transport of neutral particles towards the outboard divertor minimising transport into the core plasma.

Successful realisation of the SPP Exhaust System requires addressing many technical challenges. Key challenges include characterisation of relevant materials, development of reliable manufacturing and joining methods and high heat flux testing of PFCs. Recent technology developments have addressed some of these challenges and increased confidence in the engineering design. Results of these manufacturing trials will be presented regarding tungsten microbrush manufacture, tungsten tile to CuCrZr joining and additive manufacture of steels for the divertor cassette. An overview of planned development activities over the coming years will also be presented.

REFERENCES

[1] S.S. Henderson, R.T. Osawa, S.L. Newton et al, "An overview of the STEP divertor design and the simple models driving the plasma exhaust scenario," Nucl. Fusion 65 (2025) 16-33.

[2] Cane J, Barth A, Farrington J et al, "Managing the heat: In-Vessel Components" Phil. Trans. R. Soc. A 382: 20230408 (2024).