STEP Exhaust System – Architecture and Technology Development Overview

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Abstract

Spherical Tokamak for Energy Production (STEP) is a UK-led programme aiming to deliver a first-of-a-kind fusion prototype powerplant (SPP) [1].

Heat and particle exhaust is a fundamental challenge for the STEP SPP. The **smaller radius** of a **spherical tokamak** (reduced capital costs) increases the exhaust challenge due to the reduced area available to dissipate heat and manage particle exhaust.

Primary Divertor Configuration: **Dynamic Double-Null (DN),** however assumes variation in power sharing between upper and lower.

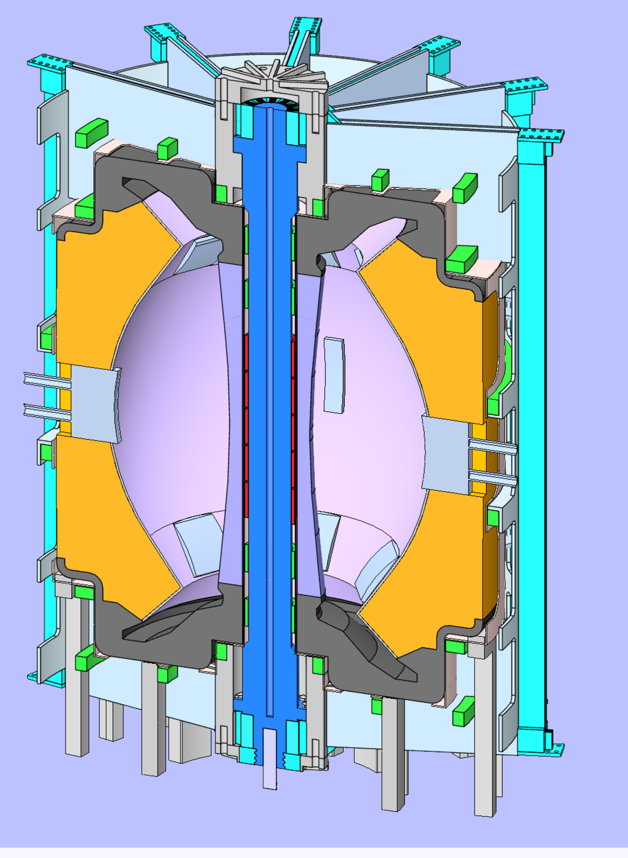
The divertor plasma will operate in **detached mode**, maintaining heat and particle loads within engineering limits.

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.

The SPP exhaust system has the following functions:

- **Managing heat and particle loads**: 'zoned' PFCs with Monoblock, Brushblock, Tile on Heat Sink PFCs
- **Shielding magnet coils**: CO2 cooled divertor cassette with embedded W alloy materials
- **Extracting impurities**: optimised wall shape and purposely positioned vacuum pumping duct

STEP



Fusion Power	1.6-1.8 GW
Net electric power	100-200 MWe
Inboard Build	1.9 m
Major Radius	4.275 m
Magnetic Field	3.0 T
Plasma current	20-25 MA
Elongation	~3
Triangularity	~+0.5
Plasma Edge	Edge Pedestal
HCD Mix	EC + EB
Primary Divertor Configuration	Dynamic DN
Secondary Divertor Config (Inboard)	Flat Top: X Type Ramp Up: Perpendicular
Secondary Divertor Config (Outboard)	Extended Leg
TF Conductor Type	REBCO
Primary Maintenance Access Route	Vertical
Remountable Toroidal Field Coils	12 TF coils (3 Remountable joints per TF)
Peak Steady State Divertor Heat Flux	<20 MW/m^2
Tritium Breeder Material / Breeding ratio	Li_2O / >1.0
Centre Column / Divertor Coolant	D_2O & H_2O / CO_2 & H_2O
OB First Wall, Blanket, OB Limiter Coolant	CO_2 / He
Blanket Coolant Outlet Temperature	600°C

System Architecture – Wall shape

The divertor wall shape has undergone multiple iterations, driven by a combination of increasing fidelity in divertor modelling and iteration of overall machine parameters (e.g. major and minor radii).

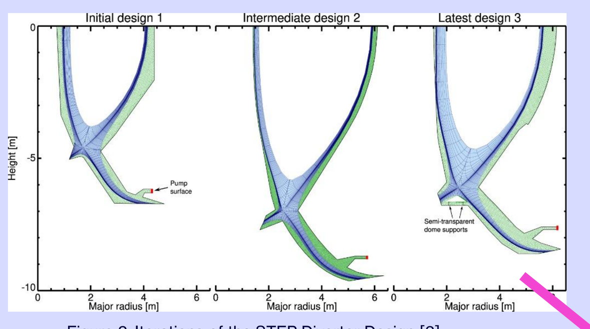


Figure 2: Iterations of the STEP Divertor Design [2]

Dome: 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 dome will ultimately involve a trade-off between pumping efficiency and detachment access.

Inboard: short inboard legs approaching an X-divertor. STEP as a spherical tokamak, with a smaller major radius, has less physical space to distribute the power, particularly on the inboard side. If STEP adopted a conventional divertor design, the unmitigated heat flux would be **three times** higher compared to EU DEMO concepts.

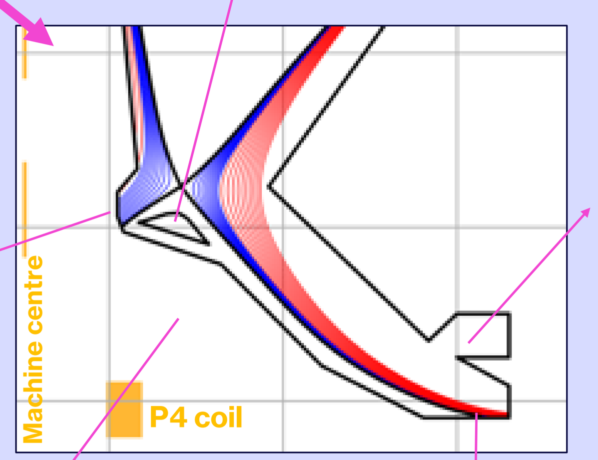


Figure 3: SPP Divertor wall shape

Pumping: Vacuum duct / pumps 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.

Shielding: The divertors protect the superconducting magnet coils located above and below the tokamak, an essential function to demonstrate a pathway to a commercially relevant machine lifetime.

Outboard: a tightly baffled super-X divertor/Extended leg. In MAST Upgrade, Super-X has already demonstrated at least a tenfold reduction in the heat on divertor materials. If STEP adopted a conventional divertor design, the unmitigated heat flux would be **twice** as high as EU DEMO concepts.

System Architecture - Subsystems

Heat and particle loads will vary spatially over the divertor surface under a range of normal and off-normal operating conditions. To achieve a balance of performance and reduced complexity, the STEP divertor uses different Plasma Facing Component (PFC) designs at different locations. This 'zoned' approach is illustrated below. [3]

Edge-Localised Modes (ELMs) pose a key design challenge and drive strike-point technology choice and PFC design. Brushblock PFC, i.e. Microbrush on a Monoblock, has been baselined as strike point PFC technology to replace Liquid Metal Armour (LMA) concept.

Zoned-approach PFCs

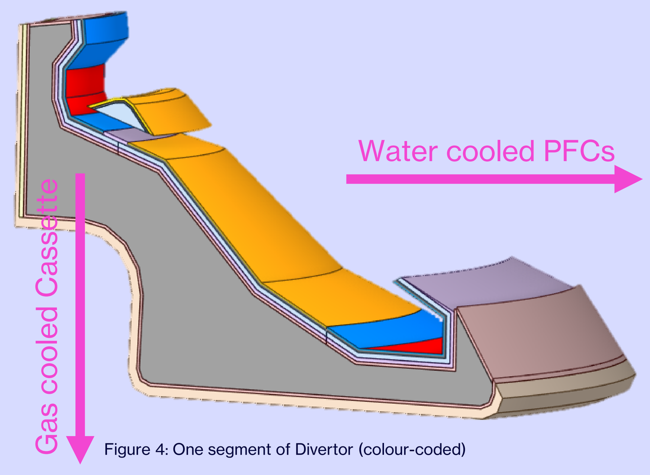
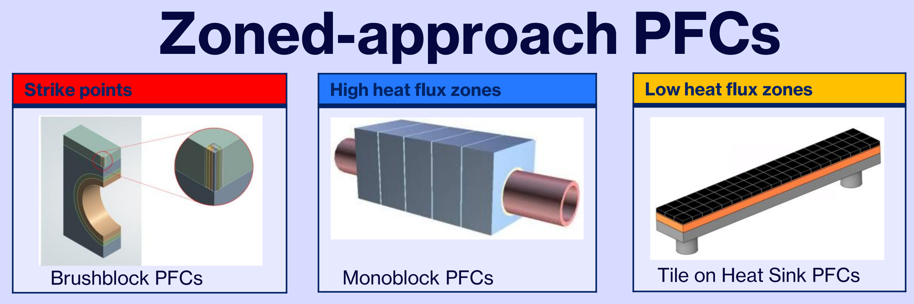


Figure 4: One segment of Divertor (colour-coded)



Gas cooled Cassette

Cassette will mainly provide shielding function in addition to supporting PFCs.

CO_2 cooled divertor cassette design with Eurofer97 as structural material aims to reduce activated waste inventories and provide high grade of heat.

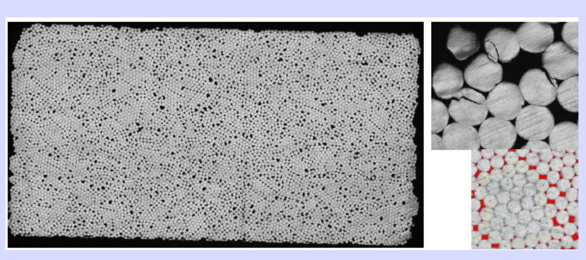
Tungsten (W) alloys will be embedded to aid shielding performance.

Spatial constraints are prominent in this area.

	Strike Point	High Heat Flux zones	Low Heat Flux zones
Steady-State (flat-top)	10MW/m^2	10MW/m^2	10MW/m^2
Steady-State (ramp-up)	20MW/m^2	20MW/m^2	10MW/m^2
ELMs	0.1-1MJ/m^2	N/A	N/A
Key features	Brushblock	Monoblock	Tile on Heat Sink
Material	W wire/ W/CuCrZr	W/CuCrZr	W/CuCrZr/Steel
Coolant	D2O		
Rationale	Crack resilient during Type-I ELMs.	ITER proven technology.	Significantly reduced part count.

Technology Demonstration - Progress

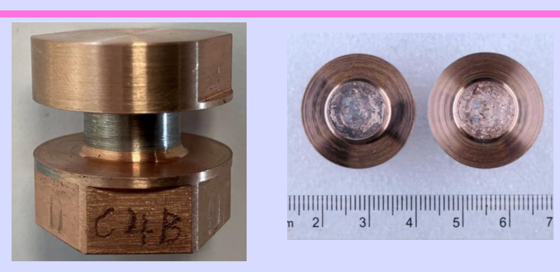
Brushblock PFC manufacture



Tungsten wire 'bristle pack'
- Successfully manufactured
- Good wire density achieved
- Bristle pack successfully joined to W block at PFC relevant scale in next step

Initial demonstrators
- The joints characterised
- Some cracking observed in tungsten block
- High Heat Flux (HHF) test (in progress): both steady-state and transient loads

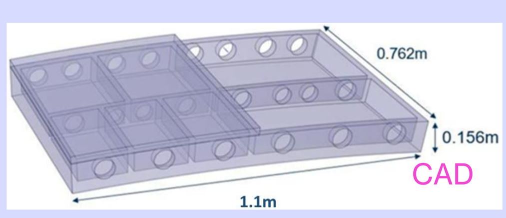
Tile on Heat Sink PFC sizing study

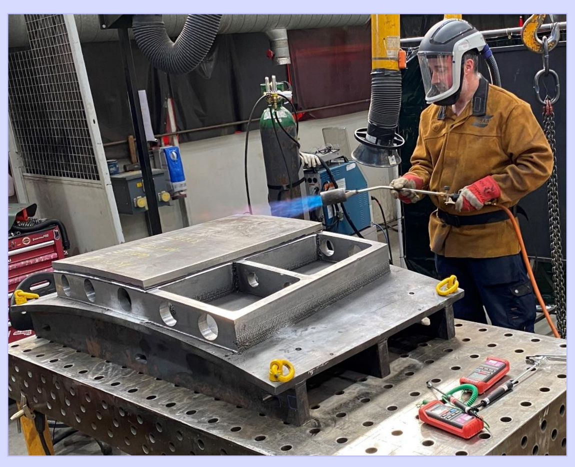


W to Cu alloy joint coupon trials
- Different joining methods compared
- Different interlayers/fillers/coating applied
- Joint characterised & strength tested

Tile on Heat Sink (ToHS) PFC demonstrators
- Variants in W tile sizes/thickness & interlayer
- HHF test planned in 2025
- W-Cu alloy Joint ion irradiation test planned

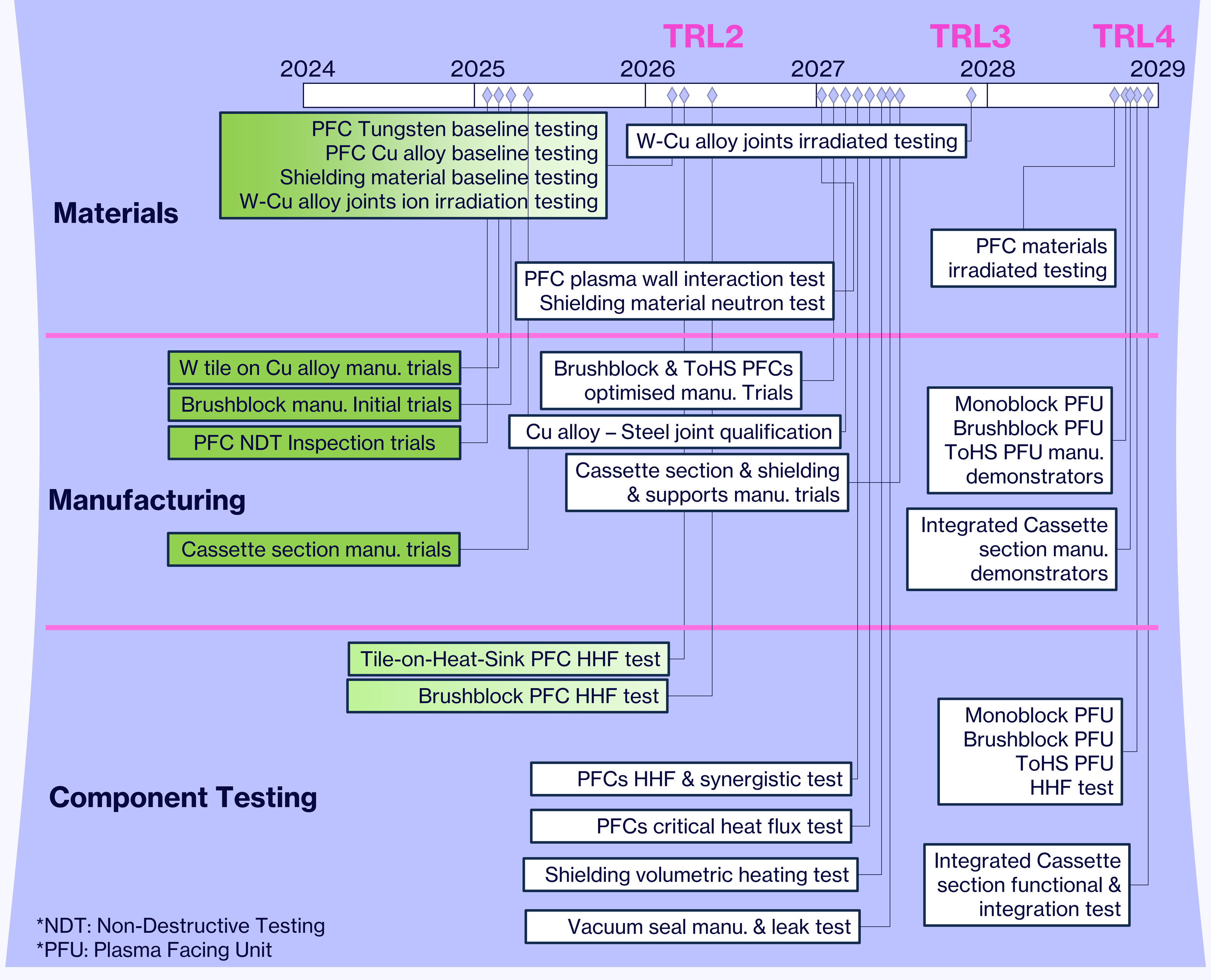
Manufacture trial of Cassette section





Key features:
- P91 material (rather than Eurofer97)
- Ribs with constant thickness
- Welding of top lid

Technology Demonstration - Plan



*NDT: Non-Destructive Testing
*PFU: Plasma Facing Unit

Technology development plan covering the materials, manufacturing and component testing activities for the Exhaust system with the target of achieving at least Technology Readiness Level (TRL) 4 by 2029.

References:
[1] J. Cane et al, "Managing the heat: In-Vessel Components," Philosophical Transactions of the Royal Society A, vol. 382, no. 2280, 2024
[2] S. Henderson et al, "An overview of the STEP divertor design and the simple models driving the plasma exhaust scenario," Nuclear Fusion, 2025.
[3] A. Barth et al, "STEP Divertor - PFC layout, recent design changes and development activities", SOFE 2025