A tightly baffled long-legged divertor for TCV

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Introduction

The TCV tokamak contributes to the development of nuclear fusion energy through proof-of-principle experiments and by validating models that are used to extrapolate existing solutions to a reactor. As part of the Swiss Roadmap for Research Infrastructures, the SPC is upgrading TCV to test a tightly baffled, long-legged divertor (TBLLD), a novel concept designed to enhance power exhaust capabilities [1] with minimal modification of the magnetic configuration from a conventional single-null divertor. It combines strong neutral baffling and a poloidal extension of the divertor leg, which are, both, geometric variations that have separately demonstrated power exhaust mitigation in TCV. While the recent versions of the TCV divertor baffles [2] restrict neutral transport at a single poloidal location, the tight baffling in the TBLLD extends this restriction along the entire outer divertor length, thereby, significantly decreasing the probability for neutral particles that are sourced at the divertor target to reach the main plasma. This promises an increase of the neutral density at the target, which is generally found to increase the power exhaust capability of a divertor [3][4]. In an initial, proof-of-principle, phase the TBLLD concept will only be applied to the outer divertor. The main objectives of this phase are a validation of the predicted increase in the target neutral pressure and the resulting increase in plasma exhaust performance. Detailed measurements of the TBLLD divertor plasma will be used to test plasma edge models. The experiments should further evaluate the effect of the TBLLD on detachment window and detachment stability and identify the responsible physics mechanisms. Experiments will also address the TBLLD's potential to buffer transients.

Expected power exhaust performance

Simulations using the SOLPS-ITER code indicate that a TBLLD can improve TCV's power exhaust capability by an order of magnitude compared to the unbaffled configuration, Fig. 1, [5]. The simulations confirm the expectation that tight baffling can sustain a high poloidal neutral density gradient and increase the neutral density in front of the divertor target, thereby, enhancing volumetric power dissipation. These simulations informed the design of a proof-of-principle TBLLD.

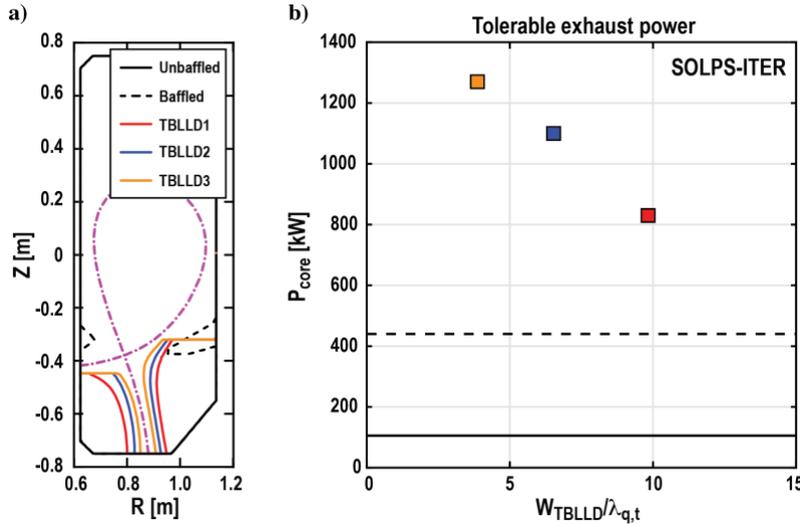[*] See author list of B.P. Duval et al 2024 Nucl. Fusion 64 112023.

Figure 1: (a) First wall contours investigated with SOLPS-ITER (adopted from [5]) and (b) corresponding predictions of tolerable heating power for detached operation with a separatrix density $n_{e,sep} = 1.5 \times 10^{19} m^{-3}$ (data from [5]).

Specifications of a proof-of-principle TBLLD for TCV

The proof-of-principle of the TBLLD concept must demonstrate its ability to increase the neutral pressure at the divertor target by establishing a poloidal neutral pressure gradient along the tightly baffled divertor leg. It must, furthermore, demonstrate that the increased neutral pressure translates into superior power exhaust performance. These objectives must be met while maintaining engineering simplicity and sufficient diagnostic access.

A straight, vertical outer divertor designed around TCV's reciprocating divertor probe array (RDPA) is proposed, Fig. 2. Compatibility with high-power plasma scenarios and, hence, TCV's neutral beam injection (NBI) heating system requires a plasma position near TCV's equatorial plane and constrains the vertical baffle length, L_{TBLLD}, to 0.34m, Fig. 2(a). The divertor width, W_{TBLLD}, defined as the horizontal distance between the inner and outer gas baffles, is chosen to be 0.113m to accommodate the RDPA with its boom hidden in the outer baffle, Fig. 2(a). SOLPS-ITER simulations indicate that a value of W_{TBLLD} that corresponds to 6-10x the SOL width for heat flux, λ_q, can increase the power exhaust potential of the divertor by an order of magnitude, Fig. 1(b). Poloidal flux expansion, $f_{x,t}$, that range from 2 to 10 can be used as a means to vary the plasma plugging in the TBLLD. It allows for outboard midplane SOL widths, $\lambda_{q,u}$, from as narrow as 1.6mm, observed in H-modes, to as wide as 8mm, expected in low current L-modes, [6] to meet the targeted range of $W_{\mathrm{TBLLD}}/\lambda_{q,t}$, Fig. 2(b).
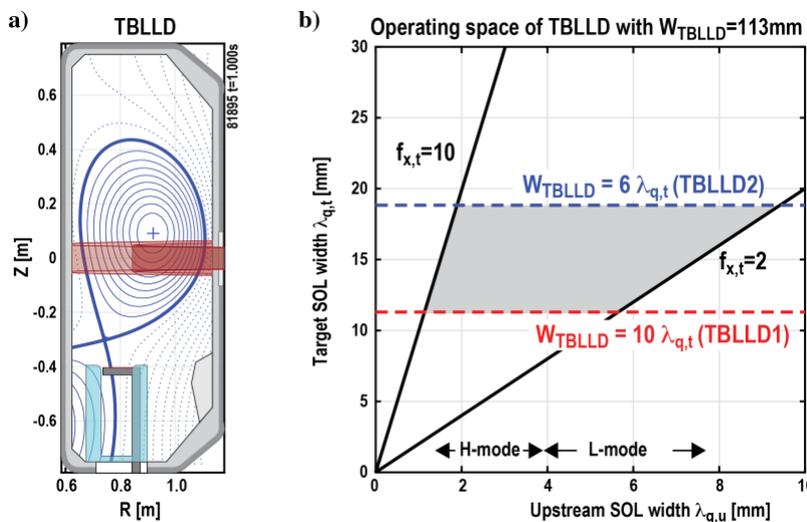

Figure 2: (a) Poloidal cross section of TCV with TBLLD (cyan) and NBI beam profile (brown) and (b) the resulting operating range for various SOL widths, $\lambda_{q,u}$ when varying the poloidal flux expansion, $f_{x,t}$, between 2 and 10.

The divertor baffles must restrict the movement of neutral gas. To demonstrate the effectiveness of the TBLLD concept the probability for recycling neutrals to escape the divertor via the divertor entrance must be larger than to leak through imperfection in the baffles. Postprocessing of SOLPS-ITER simulations characterises this escape probability with an effective pumping speed of $50m^3/s$ [7], which must be greater than any leakage though holes or gaps in the gas baffles.

Design of a proof-of-principle TBLLD for TCV

The envisaged engineering solution based on graphite TBLLD baffle tiles leverages the experience gained in the previous divertor upgrade [2]. The baffles will consist of 64 inner and 64 outer tiles mounted with one screw each onto new steel plates, which are themselves attached to welded rails in the vacuum vessel, Fig. 3. A tile thickness of 55mm provides mechanical strength to withstand disruptions. The tiles are designed with no gaps. Their tolerances should not lead to gaps of more than 0.5mm corresponding to leakage of less than $10m^3/s^†$, thereby meeting the specification. The baffle tiles have no gas breaches for diagnostics and precautions are taken that floor ports in the TBLLD do not leak gas into the main chamber. Ceramic breaks inserted at four toroidal locations between baffle tiles suppress toroidal currents.

The TBLLD divertor will be equipped with five gas valves located at four equidistant toroidal locations and connected to three gas lines. The arrangement allows to inject main ion or seeding gases at four different toroidal location to detect the existence of any toroidal asymmetries due to toroidally discrete gas injection points. The arrangement also allows for simultaneous fuelling and seeding from two toroidally opposed locations.
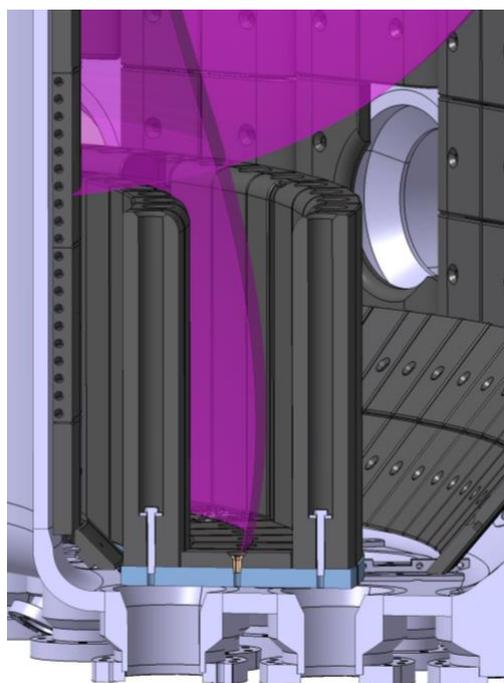
The TBLLD divertor will be equipped with a limited set of diagnostics to ensure gas tightness. The neutral pressure will be measured with seven ASDEX-type pressure gauges located at the target and along the inner and outer baffles. Particle fluxes, electron temperatures and plasma densities will be measured with arrays of 57 wall mounted Langmuir probes in three toroidal locations, providing a spatial resolution of 7.5mm at the target and 22mm and 11mm along the inner and outer baffles, respectively. Heat fluxes will also be inferred from TCV's vertical IR system, which will be supplemented with an array of surface thermocouples at the TBLLD

Figure 3:CAD drawing of graphite TBLLD baffles tiles (dark gray), steel plates (blue) and their attachments.

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† Assuming a neutral temperature of 5eV.

target. Plasma parameters across the TBLLD volume will be accessed with the RDPA. Twelve horizontal optical lines-of-sight will provide the necessary information for detailed divertor spectroscopy and optically filtered high time resolution systems. The latter will provide the necessary information to assess the TBLLD's ability to buffer fast transients, such as ELMs. In addition to diagnosing the TBLLD, the existing set of diagnostics remains adequate to evaluate the state of the inner divertor (with Langmuir probes and IR thermography) as well as core performance (with TCV's interferometry [8], Thomson scattering (TS) [9] and charge-exchange recombination spectroscopy [10] diagnostics). Core radiation remains measurable with the bolometric system [11] and multi-spectral imaging [12]. The main diagnostics restrictions will be the absence of divertor TS, and divertor bolometry.

Outlook

The procurement of essential components is underway, with a dedicated experimental campaign planned for 2026. Following a successful validation of the TBLLD concept, a second phase of upgrades would optimise the baffle geometry, extend the exhaust solution to the inner divertor, address particle exhaust, e.g. through pump ducts at the top of the TBLLD, similar to the mid-leg pumping proposed in [13], and integrate it with an attractive core plasma scenario.

Acknowledgements

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