TCV divertor and heating upgrades for contributing to DEMO physics basis

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Abstract. Major upgrades to the TCV infrastructure are implemented to increase the DEMO relevance of its research. An in-vessel divertor chamber of variable closure is foreseen to contribute to the qualification of alternative divertor concepts, including the demonstration of advantageous plasma exhaust performance, combining detachment with particle control, He compression and impurity retention in the divertor, and ELM control. Options to implement mechanically extendible or replaceable baffles are studied. The present design consists of one set of 32 solid graphite tiles on the high field side and several sets of 64 tiles on the low field side. The latter vary in tile protrusion to change the divertor closure. Enhancements of existing diagnostics together with new systems are envisaged to characterise the divertor performance. A new high capacity pump and an extended set of gas valves will enhance the particle control. One to three additional poloidal field coils close to the divertor may be needed to increase the range of accessible divertor configurations and improve the relevant control capabilities. Using high temperature superconductors would permit over an order of magnitude larger current densities compared to water cooled copper coils, reducing space requirements and facilitating in-situ construction. The divertor upgrade completes a set of major improvements to the plasma heating systems, which are conducted in two steps, one presently under way and another foreseen in 2017-2020. The installation of a 1MW 15-25keV NBI has recently been completed. The first step also includes the acquisition of two 0.75MW gyrotrons for ECH/ECCD at the 2nd harmonic (X2, 87GHz). The second step consists of the installation of a 1MW, 50 keV beam, directed opposite to the first beam, and two 1MW dual frequency gyrotrons, (83GHz, X2 and 126GHz, X3). EMC3-Eirene simulations indicate that realistic baffles together with the heating upgrade allow for significantly improved plasma performance, with $T_i/T_e>1$ and $\beta_N\sim3$, higher neutral pressure, impurity compression and power dissipation in the divertor (up to $P_{\mathrm{sep}}/R \sim$ 8MW/m).

1. Introduction

The mission of TCV is to contribute to the physics basis for ITER exploitation and to the optimization of the tokamak concept in view of DEMO. Significant developments in the TCV infrastructure are necessary to expand and increase the DEMO relevance of its research lines, presently focused on plasma shaping, advanced divertors, plasma control and electron cyclotron heating and current drive (ECH/ECCD) [1]. A major component of the upgrade plans for TCV is the creation of an in-vessel divertor chamber of variable closure. The development of a reliable solution for the power and particle exhaust is a major challenge. It is uncertain whether the conventional plasma exhaust solution chosen for ITER and based on a single null magnetic configuration and divertor targets with tungsten armour will be able to withstand the heating power and plasma fluence in DEMO. To mitigate this risk, alternative solutions must be assessed. TCV has contributed to the development of alternative divertor geometries with proof-of-principle experiments of the snowflake [2] and other divertor configurations [3], but important gaps in the qualification of alternative divertor concepts for DEMO remain. Among these gaps are the demonstration of advantageous plasma exhaust performance, combining detachment with sufficient particle control, He compression and impurity retention in the divertor, ELM control strategies, and the demonstration of the integration of edge and core scenarios. The TCV divertor upgrade aims at contributing to closing these gaps. Its main elements are a set of baffles providing varying divertor closure, diagnostic developments, a cryogenic pump for density control and additional divertor poloidal field coils.

The divertor upgrade completes a set of major improvements to the TCV infrastructure, which includes the installation of additional plasma heating systems, aimed at enabling TCV to access β values in the same range of ITER or higher, and a wide range of T_e/T_i values, including T_e/T_i~1. The heating upgrades are conducted in two steps, one presently under way and another foreseen in 2017-2020. One component of the first step is near completion, with the installation of a 1MW 15-25keV NBI. The first step also includes acquisition of two 0.75MW gyrotrons for ECH/ECCD at the 2nd harmonic (X2, 87GHz). The second step consists of the installation of another 1MW, ~50 keV beam, for studying plasma rotation and fast ion physics, and two 1MW dual frequency gyrotrons, (83GHz, X2 and 126GHz, X3).

2. Divertor upgrade

Dissipative divertors, as required in ITER and DEMO, rely on the transfer of energy and momentum from charged to neutral particles and should operate with a high neutral density. In TCV, the neutral density in the divertor is limited by strong cooling of the Scrape-Off-Layer (SOL) and core fuelling as the extremely open divertor does not allow for a large neutral compression. This is defined as $C_D = n_D^{div} / n_D^{omp}$, where n_D^{div} is the neutral density in the divertor region and n_D^{omp} its value in the main chamber (at the outboard mid-plane).

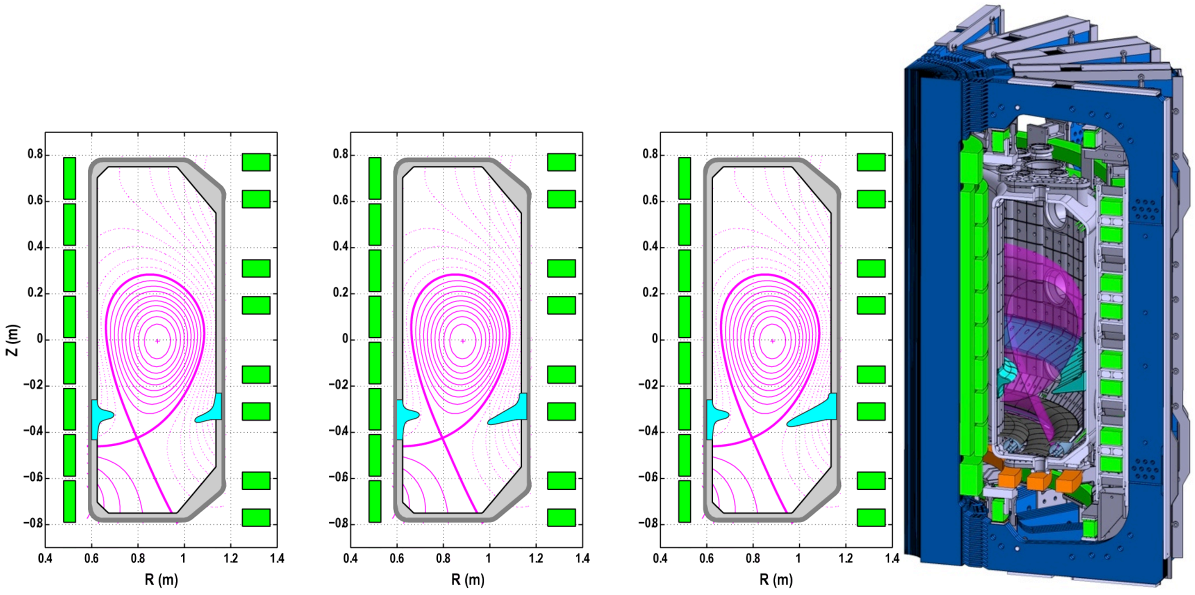

FIG. 1. Left: Baffles of varying divertor closure. Shown are baffles that limit the SOL at the flux surface with an outboard midplane separatrix separation of approximately 1cm, 2cm and3 cm, when the X-point is centred between the baffles. Right: 3D view for the 'long' baffles case.

Gas baffles

To increase the attainable values of C_D, it is envisaged to insert gas baffles that separate the TCV vessel in a divertor and a main chamber. The geometry of the baffles is chosen to simultaneously minimise additional constraints on the shaping flexibility of TCV and allow for the entire range of alternative divertor configurations with additional null points and target radii from the inner to the outer vessel wall. For NBH, plasmas are located close to the vessel mid-plane. Due to the location of the ECRH launchers at the mid-plane, in the upper lateral ports and on a port on the top of the vessel, the divertor chamber must be located at the bottom of the machine. A set of corresponding baffles that also allow the use of the lower lateral ports to diagnose the divertor is shown in Fig. 1.

The baffle closure can be quantified by the outboard midplane distance between the limiting SOL surface and the separatrix. The ratio of this parameter to the characteristic power decay length determines in turn the conductance of the gap between the plasma and the baffle for neutral particles. The proposed high-field side (HFS) baffle is sufficiently long to be effective in a large range of divertor configurations, including the snowflake and X divertors (FIG. 2) but sufficiently short to keep the plasma close to the inner wall and provide sufficient passive stabilisation of its vertical position. In addition, the placement of the X-point at relatively small major radius allows for large variations of the major radius along the outer leg, when the outer strike point is placed on the outer wall, the key element of the Super-X divertor concept. In order to accommodate such a large range of divertor configurations, all poloidal locations in the divertor chamber must be capable of handling the peak power of a strike line. This requires a protection of the leading edges of the lateral divertor ports.

The baffle tightness must be in the range from 95% to 99% for neutral leakage to be small compared with the neutral flows through the baffle opening in the presence of plasma. The top of the baffle must be able to handle full power loads for a wide range of grazing field lines angles. The baffles also have to withstand the electromagnetic forces resulting from the largest flux changes during disruptions, with dB_p/dt ~ 500T/s.

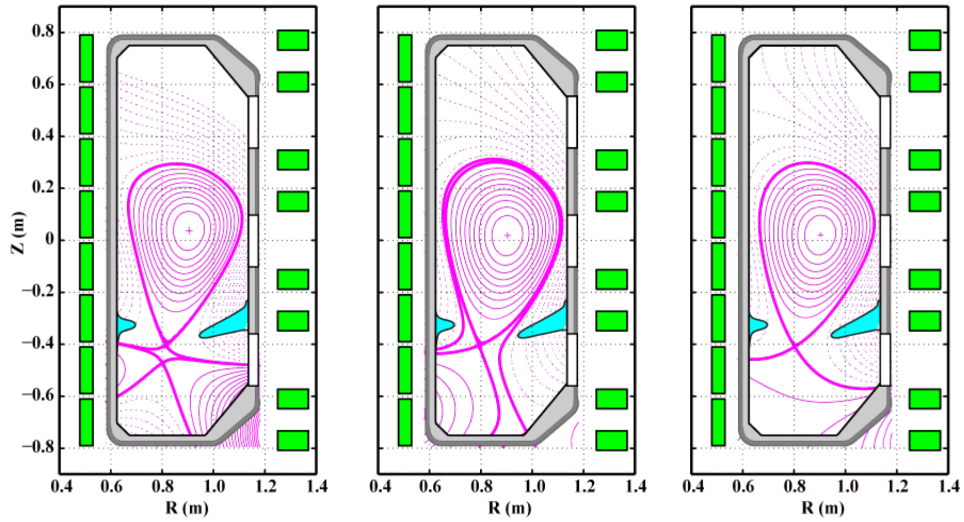

FIG. 2. Compatibility of the longest baffle shown in FIG. 1 with a snowflake divertor (left), an X divertor (center) and a Super-X divertor (right).

The neutral compression can be controlled using integrated bypasses in the baffle [4] or installing a mechanically extendible structure to modify the neutral conductance between the divertor and main chamber. Given the complexity and cost of moving mechanical solutions, using baffles that are easily replaceable in a manned entry is presently being considered as the baseline option. One set of 32 graphite tiles would be mounted on the high field side (HFS) wall, while several sets of 64 tiles would be installed on the low field side (LFS). The tiles of the LFS sets are of different lengths to vary the divertor closure (FIG. 3).

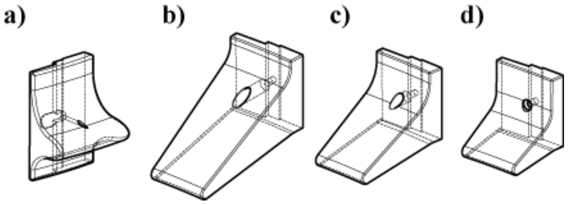

FIG. 3. CAD drawings of graphite tiles for (a) the inner wall and the (b) long, (c) medium and (d) short outer wall baffle.

The tiles are made of solid graphite, the standard material for TCV tiles. The new baffle tiles will be fixed on the same internal welded rails that hold the current tiles. The use of a structural material such as Inconel or stainless steel will be considered, depending on the analysis of the electromagnetic loads and thermal stresses. The expected thermal loads are similar to those the current tiles, which tolerate perpendicular incidence of the separatrix and low flux expansion. The highest electromagnetic loads will occur during disruptions, which require imposing 1.5mm gaps between the tiles to suppress large-scale eddy currents.

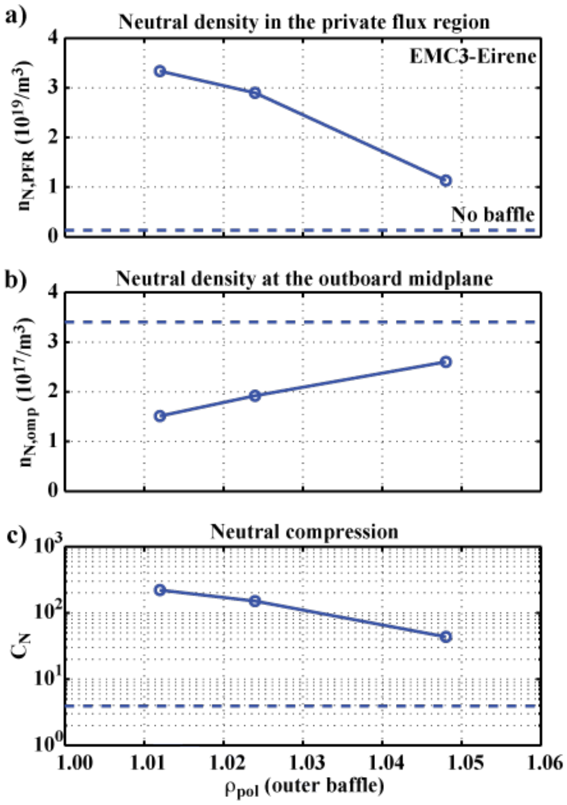

FIG. 4. EMC3-Eirene predictions of the dependence of (a) the neutral density in the private flux region, (b) the neutral density at the outboard mid plane and (c) the corresponding neutral compression on the closure of the outer baffle. The values are compared to predictions without a baffle (dashed line).

Simulation of the expected performance

The capability of the baffles to increase the neutral compression in TCV is evaluated through preliminary simulations using EMC3-Eirene [5]. The calculations use a computational mesh that was developed for previous studies of the snowflake divertor [6]. Schematic baffles with various degrees of closure and a gas-tight floor are added to approximate the upgraded divertor. It is assumed that 1.2MW of the heating power crosses the separatrix in the plasma channel, equally distributed between ions and electrons, and that 40% of this power is radiated by nitrogen outside the separatrix (due to nitrogen seeding or as a proxy for carbon). The outboard mid-plane density on the separatrix is fixed at $2x10^{19}$ m^{-3}. The effective cross-field diffusivities are assumed to be $0.5m^2/s$ and $1.5\ m^2/s$ for particles and heat, respectively.

To evaluate the effect of the baffle on the neutral compression, the neutral density is averaged over the private flux region for an estimate of n_D^{div} and evaluated in the outboard mid-plane far SOL for an estimate of n_D^{omp}. As shown in FIG. 4, the simulations predict a substantial increase of n_D^{div} and a decrease of n_D^{omp}, resulting in an increase of C_D, with increasing baffle closure. For the tightest baffle shown in FIG. 1, the simulations forecast an increase of the neutral compression by a factor of ~50 with respect to the no-baffle case.

Plasma and neutral density control

Access to a wider range of divertor conditions and, in particular, independent control of the neutral density in the divertor and the electron density of the plasma requires an upgrade of the existing gas-valve system and of the pumping capacity. Three gas valves are currently installed on the floor of TCV for discharge fuelling and impurity seeding. With the proposed divertor baffling structure, independent gas fuelling into the main chamber and the divertor will be a necessity, together with impurity seeding at different poloidal locations. As toroidally localized seeding can lead to significant toroidal asymmetries in the detachment, it nay be necessary to inject gas through toroidally distributed valves. Operating such valves individually would allow for a study of toroidal asymmetries without the need for measurements at different toroidal locations.

A first estimate of the pumping specifications is obtained from the EMC3-EIRENE simulations, which predict that for a high power, high density discharge in detached conditions, the longest considered baffle results in a maximum neutral density in the divertor chamber of approximately $10^{20}m^{-3}$. The total volume of the planned divertor chamber is approximately $1.2m^3$ resulting in a required pumping throughput of approximately 1 Pa m^3/s. Admitting for some conductance losses between the pump and the divertor chamber, a preliminary pumping speed between 5000 and 10000l/s is considered. Cryogenic pumps are thus suggested because of the required velocity and their efficiency for light gases. Among the investigated solutions for the cryopump is the installation of a false-floor on the bottom of the machine under which the cryogenic system could be accommodated.

Dedicated divertor coils

Additional divertor coils, located between the vacuum vessel and the toroidal field coils may be needed to control the divertor regime and configuration. The present arrangement, including eight poloidal field coils on the high field side and eight on the LFS, is adequate for a large range of core shapes and divertor configurations. However, in order to create an X-point in the middle of the vessel, as required for the closed divertor configurations, these coils must apply a dipole field, which naturally results in snowflake configurations and characteristic low gradients of the poloidal field in the vicinity of the X-point and, consequently, long connection lengths. To investigate the effect of the connection length on divertor physics, it is desirable to extend the range of attainable connection lengths also to lower values and to vary the gradient of the poloidal field in the X-point region. This can be achieved with one or more coils located below the X-point, which would also extend the range of flux expansions at the strike points to lower values and improve the ability to control their location. The current in the new divertor coils has to be a large fraction of the plasma current, about 300 kA in the planned divertor configurations and for $q_{95} \approx 3$.

As a step towards the demonstration of a potential key technology for magnetic fusion, the use of high temperature superconductors is considered. These would allow larger current density compared to conventional water-cooled copper coils, and a high flexibility of coated conductor tapes, facilitating in-situ construction.

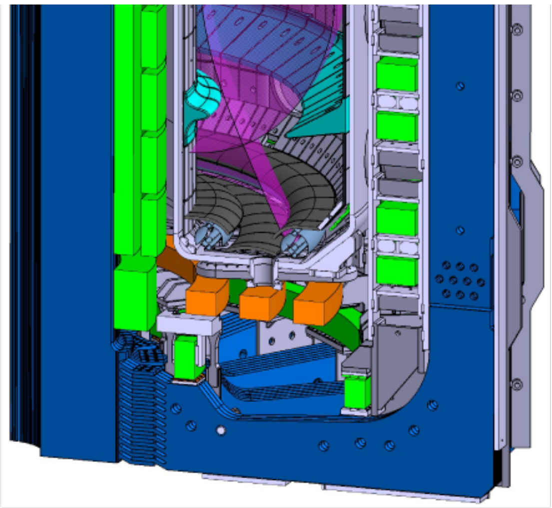

FIG. 5. Drawing of the TCV divertor upgrade including the baffles (cyan), cryo-pumps (light blue) and possible divertor coils outside the vacuum vessel (orange).

3. Diagnostics upgrade

Enhancements of existing diagnostics together with new systems are envisaged to characterise the higher plasma and divertor performance. Moreover, some of the existing systems will require modifications to be compatible with the baffles. Among the diagnostic systems that will be upgraded or installed ex novo are: pressure gauges, Langmuir probes (of various tip shapes including roof-top and domed tips); magnetic probes (to detect and control of the divertor configuration and directly measure magnetic turbulence in the vicinity of the X-point); infrared thermography (imaging the entire divertor and the top of the baffles), bolometers (with high spatial resolution in the divertor and near the null point to provide accurate radiation emission localisation); divertor Thomson scattering (for local electron kinetic parameters in the divertor leg and in the X-point region) and spectrometer system (to track plasma constituents and their plasma/neutral state distribution by measuring the spectrum in the near-UV/visible range using multiple chords [7]). Most of the diagnostic information will be provided in real time for control of the plasma discharge trajectory and for active divertor performance control such as detachment front tracking.

4. Heating upgrades

To further increase the DEMO relevance of TCV research, it is necessary to enhance the performance of its plasmas, in particular to access normalised β values in the same range of ITER or higher, and a wide range of T_e/T_i values, including T_e/T_i~1. This will open the way to investigations of innovative plasma exhaust configurations, ELM control, transport and shape studies, and to disentangle effects of electron-ion coupling, rotation, current density profile, edge density control and shape, in reactor relevant ELMy H-mode with dominant electron heating. With this goal, TCV has launched a series of upgrades to its heating systems, consisting of two steps, one presently under way and another foreseen in 2017-2020.

One component of the first step is near completion, with the installation of a 1MW 15-25keV NBI [8], after modifications to the TCV vessel to accommodate two 17×22cm oppositely directed quasi-tangential injection ports. The beam path undergoes a double pass through the plasma cross section for enhanced absorption. The positive-ion-source based injector can operate for 2s with D or H and a full-energy fraction of 75% [9]. Although the beam system is not yet fully commissioned, NBH has been used in over 580 TCV discharges. The overheating of the beam duct caused by excessive beam divergence required, in addition to active water-cooling of parts of the duct, an operating instruction to limit the injected beam energy to 0.5MJ. Improvements in the duct cooling and a correction of the beam profile by acting on the ion optics are under way to be able to inject the full beam energy of 2MJ into a TCV discharge.

Ion temperatures up to 2.5keV and toroidal rotation velocities of 160km/s have already been measured in the first few L-mode discharges, far exceeding previous TCV values [10]. Net current drive from the beam ions has also been demonstrated, based on a reduction in the loop voltage detected when the NB power is injected. A clear difference in the current drive effect and in the plasma β is observed between on- and off-axis injection (off-axis injection is obtained by shifting the plasma vertically), confirming the expected role of the fast ion orbits.

The first step of the heating upgrades also includes acquisition of two 0.75MW gyrotrons for ECH/ECCD at the 2nd harmonic (X2, 87GHz), of which one has recently been commissioned, and the second one is presently in the final commissioning phase. The second step consists of the installation of another 1MW, ~50 keV beam, for plasma rotation and fast ion physics studies, to be installed in the second tangential access created on the vessel, directed opposite to the first beam, and two 1MW dual frequency gyrotrons, (84GHz, X2 and 126GHz, X3).

The industrial design of the dual frequency gyrotrons has recently been finalised, based on a conceptual design developed at the Swiss Plasma Center with contributions from the Karlsruhe Institute of Technology and based on the gyrotron manufactured by Thales Electron Devices for the W7-X stellarator (140GHz/1MW) [11]. The construction phase is starting with the procurement of the long delays items, including the special ceramics for the electron gun and the emitter. The contract for the procurement of the He-free magnet has been signed, and the delivery of the first tube is expected before the end of 2017.

	Present	**Step 1 (2016)**	**Step 2 (2017-20)**
$P_{\max}$ ECRH X2 (MW)	1.25	2.75	3.5
$P_{\max}$ ECRH X3 (MW)	1.25	1.25	3.25
$P_{\max}$ NBI (MW)	-	1.0	2.0

TABLE 1. Maximum available heating power in the upgraded TCV.

The three existing 118GHz gyrotrons will be relocated to inject power from the LFS using the existing X2 transmission lines and launchers. Single pass absorption in excess of 70% can be achieved even in this configuration in plasmas pre-heated by top-launch X3. Bulk electron heating will be provided by the 2MW from the top launcher, while localised deposition necessary for MHD control will be possible using the power launched from the LFS. TABLE

1 summarises the maximum available power from the two steps in the upgrades. In total, the maximum available auxiliary power coupled to the plasma will be 6.75MW, including 2MW of neutral beam heating.

5. Summary

The planned divertor upgrade foresees the installation of an in-vessel structure in the TCV tokamak to form a divertor chamber of variable closure, with the goal of obtaining and investigating the physics of divertor configurations and regimes of interest for ITER and DEMO, yet maintaining the present flexibility of plasma configurations to a large extent. Modifications of existing diagnostic systems and the installation of new ones will be necessary to take advantage of the divertor upgrade. Pumping of the divertor chamber and the insertion of three new divertor coils made of high temperature superconducting material between the vacuum vessel and the toroidal field coils constitute the second and third stages of this project, respectively. Financial support for the TCV upgrades will be provided partly by ad hoc funds attributed by the Swiss government and the EPFL to the newly created Swiss Plasma Center for developing its infrastructure. These could be complemented by European funds in the context of the EUROfusion medium size tokamak program.

These developments will be paralleled by significant modelling efforts and will be conducted in the context of a larger upgrade to the TCV tokamak systems, in particular of its heating systems. First EMC3-Eirene calculations with varying degrees of divertor closure indicate that realistic baffles together with the planned heating upgrade, designed to reach $T_i/T_e>1$ and $\beta_N\sim3$, will allow for significantly higher neutral pressure and impurity compression in the divertor. High power dissipation in the divertor (P_{sep}/R up to ~8MW/m) will be possible.

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