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Reimerdes, H., Alberti, S., Blanchard, P. et al. (18 more authors) (2017) TCV divertor upgrade for alternative magnetic configurations. Nuclear Materials and Energy. ISSN 2352-1791

https://doi.org/10.1016/j.nme.2017.02.013

TCV divertor upgrade for alternative magnetic configurations

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The Swiss Plasma Center (SPC) is planning a divertor upgrade for the TCV tokamak. The upgrade aims at extending the research of conventional and alternative divertor configurations to operational scenarios and divertor regimes of greater relevance for a fusion reactor. The main elements of the upgrade are the installation of an in-vessel structure to form a divertor chamber of variable closure and enhanced diagnostic capabilities, an increase of the pumping capability of the divertor chamber and the addition of new divertor poloidal field coils. The project follows a staged approach and is carried out in parallel with an upgrade of the TCV heating system. First calculations using the EMC3-Eirene code indicate that realistic baffles together with the planned heating upgrade will allow for a significantly higher compression of neutral particles in the divertor, which is a prerequisite to test the power dissipation potential of various divertor configurations.

1. Introduction

The development of a reliable solution for the power and particle exhaust in a reactor is one of the major challenges towards the realisation of a nuclear fusion power plant based on the tokamak concept. It is, therefore, important to evaluate whether the conventional solution based on a single null configuration and a partially detached divertor in ITER will extrapolate to the higher degree of detachment and core radiation fractions required for future fusion reactors, such as DEMO, and, simultaneously, to explore alternative solutions as risk mitigation. The medium-size TCV tokamak (major radius $R_0 = 0.88$ m, toroidal field $B_0 \leq 1.45$ T) has contributed to the development of alternative magnetic divertor configurations with proof-of-principle experiments of the snowflake divertor [1] and other alternative concepts [2, 3]. TCV was conceived with unique shaping capabilities to study the effect of the plasma shape on transport and stability. The highly elongated TCV vessel with its ~90% coverage by carbon protection tiles and 16 independently powered poloidal field coils also allow for a wide variety of divertor configurations, albeit generally with an extremely open divertor geometry. A

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proposed upgrade of the TCV divertor now aims at extending this research to operational scenarios and divertor regimes of greater relevance for ITER and DEMO.

The main element of the proposed upgrade of the TCV divertor foreseen in 2017-2020 is the installation of an in-vessel structure to form a divertor chamber of variable closure to gain access to divertor regimes with a high neutral density and impurity compression in the divertor. This effort will be complemented with enhancements of diagnostic capabilities. In addition, an increase of the pumping capacity is considered to further enhance the range of accessible divertor regimes. The final element of the proposal is the installation of dedicated divertor coils, which enhance the range of accessible divertor configurations and improve their control. The divertor upgrade will be conducted in the context of a larger upgrade to the TCV tokamak systems, in particular of its heating systems with two 1 MW neutral beam injection (NBI) systems, two 0.75 MW gyrotrons for electron cyclotron resonance heating (ECRH) at the second harmonic (X2), and two 1 MW dual frequency (X2/X3) gyrotrons [4]. This heating upgrade will, in particular increase TCV's capability to heat high density discharges above the X2 cut-off from 1.25 MW to 5.25 MW. The higher heating power will not only increase the power that may be dissipated in the divertor, but also the plasma pressure in the scrape-off layer (SOL) and hence its opaqueness to neutrals.

This article provides the motivation for the various elements of the divertor upgrade and identifies the required steps towards a physical design. Placement, design solutions and first performance predictions for the gas baffle are presented in section 2. Enhancements to control the neutral and impurity density in the newly formed divertor chamber are discussed in section 3. The divertor coils are motivated in section 4. A list of diagnostic upgrades for control and better physics understanding is given in section 5 before presenting a summary of the planned TCV divertor upgrade in section 6.

2. The gas baffle

Dissipative divertors, as required in ITER and DEMO, rely on the transfer of energy and momentum from charged particles to neutral particles and should, therefore, operate with a high neutral density in the divertor region. In TCV the neutral density in the divertor is limited by excessive cooling of the SOL and core fuelling as the neutrals generated by recycling at the divertor targets easily escape from the extremely open divertor into the main chamber. The ratio of the neutral pressures measured in the vicinity of the strike line in the divertor, $p_{\mathrm{n}}^{\mathrm{div}}$, and at the outboard mid-plane, $p_{\mathrm{n}}^{\mathrm{omp}}$, in high density TCV discharges does not exceed values of 5-15, which is significantly lower than values observed in larger or higher density tokamaks, which can be 100 or more [3, 5]. As a means to increase the neutral compression in the diveror, it is proposed to insert a gas baffle that effectively separates the TCV vessel into a divertor and a main chamber.

2.1. Placement

The geometry of the baffles seeks 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 NBI heating, plasmas have to be located close to the mid-plane of the TCV vessel. With the ECRH launchers located in mid-plane and upper lateral ports as well as 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.

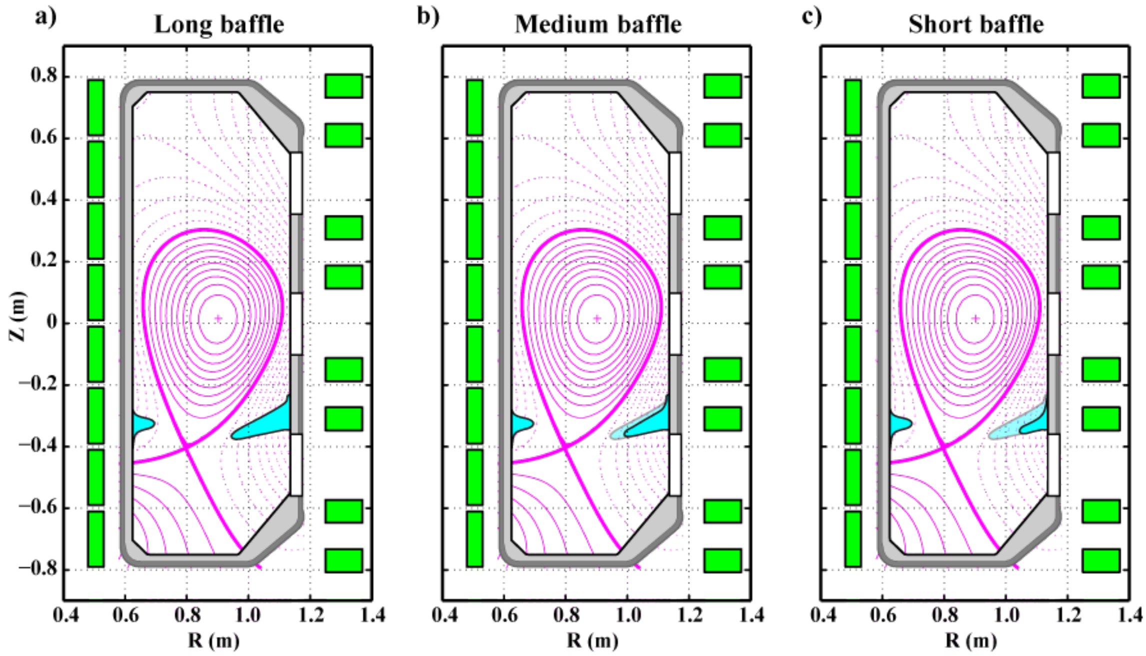

Figure 1: Baffles of varying divertor closure. Shown are baffles that limit the SOL at the flux surface with an outboard midplane separatrix separation, ρ_u^{baffle}, of approximately (a) 18 mm, (b) 30 mm and (c) 44 mm, when the X-point of a typical single null configuration is centred between the baffles.

The 'baffle closure' can be parameterised for a given equilibrium by the outboard midplane distance of the limiting SOL surface from the separatrix, ρ_u^{baffle}. The conductance of the gap between the plasma and the baffle for neutral particles is then determined by its relation to the characteristic power decay length, $\lambda_{q,u}$.

The proposed high-field side (HFS) baffle is sufficiently long to be effective in a large range of divertor configurations including the snowflake divertor (Fig. 2(a)), and the X divertor (Fig. 2(b)), but sufficiently short to keep the plasma in close proximity to the inner wall to provide sufficient passive stabilisation of its vertical position. In addition, the placement of the X-point at relatively small major radius allows also for large variations of the major radius along the outer leg, when the outer strike point is placed on the outer wall (Fig. 2(c)), which is 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 strikeline. This requires, in particular, additional protection of the leading edges of the lateral divertor ports.

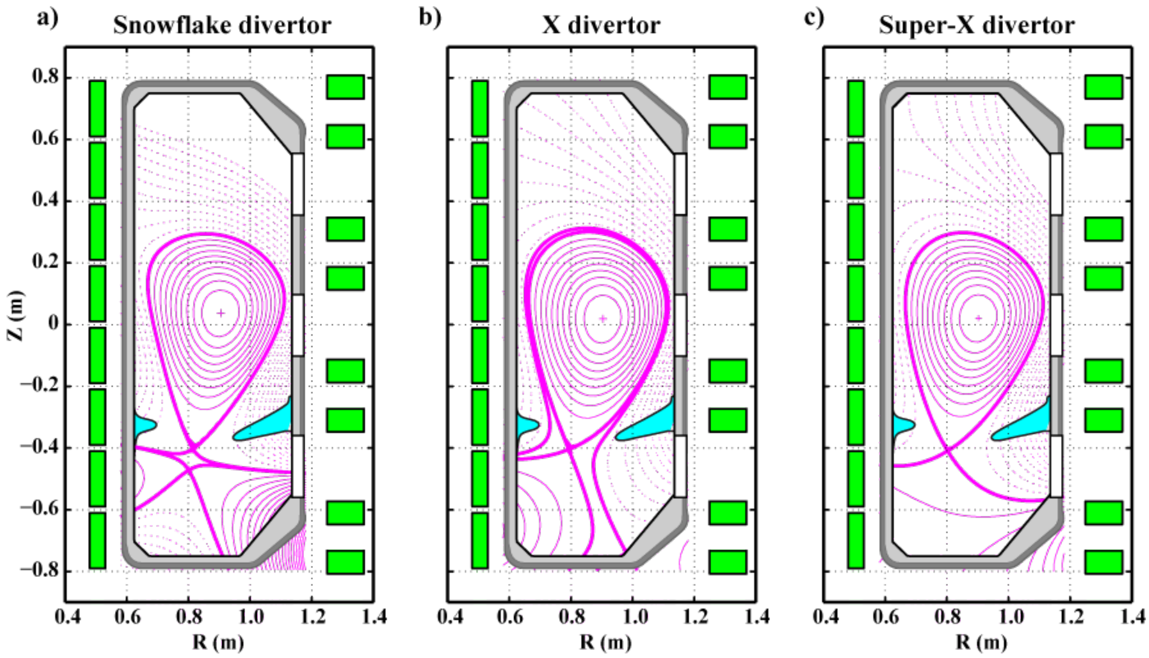

Figure 2: Compatibility of the 'long' baffle shown in Figure 1(a) with (a) a snowflake divertor, (b) a X divertor and (c) a Super-X divertor.

2.2 Requirements

Any design solution for a baffle will allow for some neutral gas leakage from the divertor to the main chamber (e.g. to provide for diagnostics such as holes for the interferometer and the laser of the Thomson scattering system). As a first estimate, 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. These estimates will have to be confirmed by detailed modelling of the neutral densities and neutral fluxes.

Even though the baffle is not intended to act as a limiter or divertor target, accidental limiting or even a placement of the strikeline on the baffle cannot be excluded. Its power handling should, therefore, be similar to the high heat flux bearing center column, which are designed to handle the heat loads resulting from up to 3 MW of auxilliary heating for the duration of at least 1 s in a wide range of magnetic configurations while allowing for some misalignment of the tiles [6].

The baffles also have to withstand the electromagnetic forces that are expected to occur during disruptions. These forces may arise from halo currents, which may be a sizable fraction of the plasma current [7] and lead to vertical forces of the order of 50 kN/m^2 onto the baffles, as well from eddy currents with vertical displacement events leading to axisymmetric poloidal field changes of the order of dB_p/dt ~ 500 T/s.

The baffle design specifications and constraints discussed in this section are preliminary and will be revised following a detailed analysis of their mechanical feasibility (a first discussion is presented in section 2.3) and their effect on the divertor parameters (a first discussion is presented in section 2.4).

2.3. Design solution

Once established, it is desirable to control the neutral compression. This can be achieved by integrated bypasses in the baffle [8] or installing a mechanically extendible structure to modify the neutral conductance between the divertor and main chamber. Since moving mechanical solutions are complex, the possibility to design and install a set of easily replaceable baffles in a manned entry is presently being investigated as the baseline option. It consists of one set of 32 graphite tiles mounted on the high field side (HFS) wall and several sets of 64 tiles mounted on the low field side (LFS). The LFS sets vary in tile length to allow for a variation of the divertor closure.

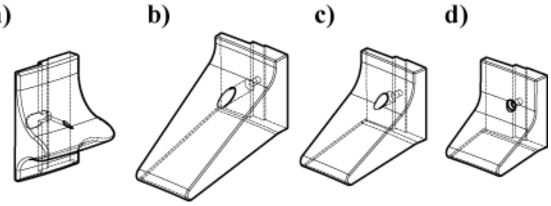

Figure 3: CAD drawings of graphite tiles for (a) the inner wall and the (b) long, (c) medium and (d) short outer wall baffle.

The tiles are made out of solid graphite, which is the standard material for TCV tiles. A preliminary design is shown in Fig. 3. The new baffle tiles will be fixed on the existing internal welded rails, which also hold the current tiles. The use of a structural material such as Inconel or stainless steel will be considered, if an analysis of the electromagnetic loads and thermal stresses shows that a design based on solid graphite tiles is inadequate. Such tiles will be able to withstand heat loads of ~30 MW/m^2 for one second before the surface temperature exceeds 2200 K and sublimation of the graphite surface commences [6]. Limiting peak heat loads to lower values requires chamfered tile edges, which will be optimised for low grazing angles of field lines typically encountered in limited plasmas and at the strike points of diverted plasmas with short divertor legs. It is foreseen to isolate tiles with 1.5 mm inter-tile gaps in order to suppress large-scale eddy currents while absorbing toroidal non-uniformities in the vacuum vessel itself. Studies are, however, needed to evaluate whether the inner baffle must be combined with a toroidally continuous conducting passive stabiliser to control the plasma position and divertor configuration. The foreseen gaps between the tiles would reduce the gas tightness of the baffle by approximately 1.4%. The conductance due to the gaps can be decreased by introducing an overlap between adjacent tiles. A further decrease of the tightness is caused by holes to pass diagnostic beams or lines-of-sight. The largest hole is an approximately 100 mm gap for the 14-chord interferometer leading to a decrease of the gas tightness by another 2%.

2.4. Performance predictions

The capability of baffles to increase the neutral compression in TCV is evaluated through preliminary simulations using the EMC3-Eirene code [9] (Fig. 4). The calculations use a computational mesh that was developed for a previous numerical study of the snowflake divertor [10]. The equilibrium (I_P = 260 kA, B_0 = 1.44 T) is topologically a SF+, but has a large separation of the X-points (σ = 1.0, corresponding to ρ_{pol}^{X2} = 0.988). Schematic baffles with various degrees of closure and a gas-tight "floor" are added to approximate the proposed baffled TCV divertor. The calculations assume that 1.2 MW 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 outside the separatrix through nitrogen radiation (due to nitrogen seeding or as a proxy for ubiquitous carbon in TCV). The outboard mid-plane density on the separatrix is fixed at $n_{e,sep} = 2\text{x}10^{19}\ \text{m}^{-3}$. The assumed effective cross-field diffusivities ($D_\perp$ =0.5m^2/s, $\chi_\perp$ = 1.5 m^2/s) result in an outboard mid-plane power fall off length $\lambda_{q,u}$ of 4 mm (corresponding to ρ_{pol} = 1.012), which is consistent with measurements in single-null TCV plasmas with the magnetic axis at z = 0, albeit at low power [11]. The simulations neglect any pumping and assume full recycling of ions impinging the wall. The resulting neutral pressure in the main chamber in the case without a baffle is 5-10x higher than measured values at comparable densities and plasma currents.

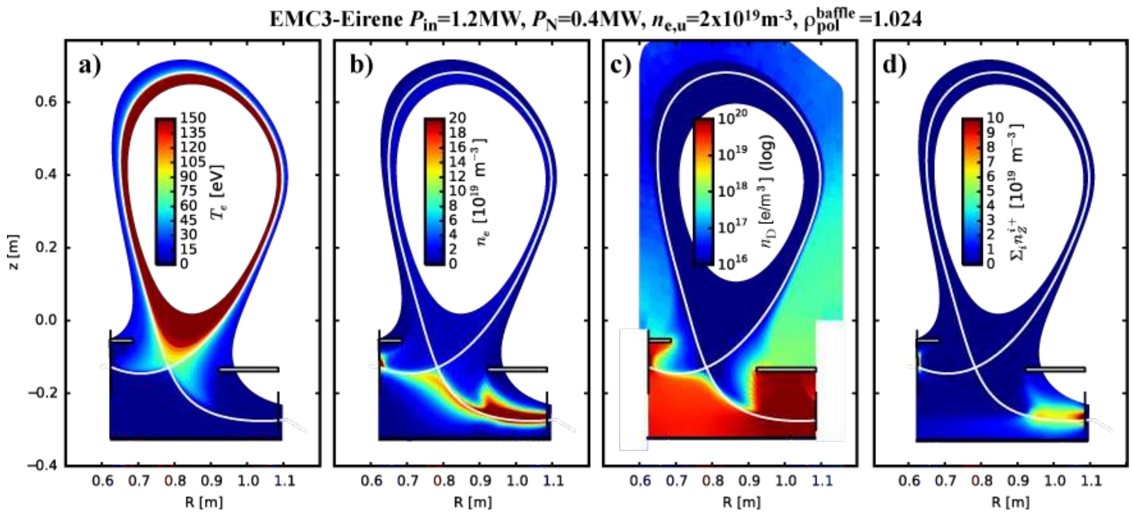

Figure 4: Simulated distribution of the (a) electron temperature, T_e, (b) electron density, n_e, (c) neutral density, n_D, and (d) seeded nitrogen impurity density, n_Z, including all charge states.

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}. The simulations show a substantial increase of n_D^{div}, Fig. 5(a), a decrease of n_D^{omp} , Fig. 5(b) with increasing baffle closure. For ρ_{pol}^{baffle} = 1.048, which corresponds to ρ_u^{baffle} = 16mm or ~4 λ_q and is, therefore effectively ~10% tighter than the tightest baffle shown in Fig. 1(a), the simulations predict an increase of the neutral compression $C_D \approx n_D^{div} / n_D^{omp}$ by a factor of ~10 with respect to the no-baffle case, Fig. 5(c).

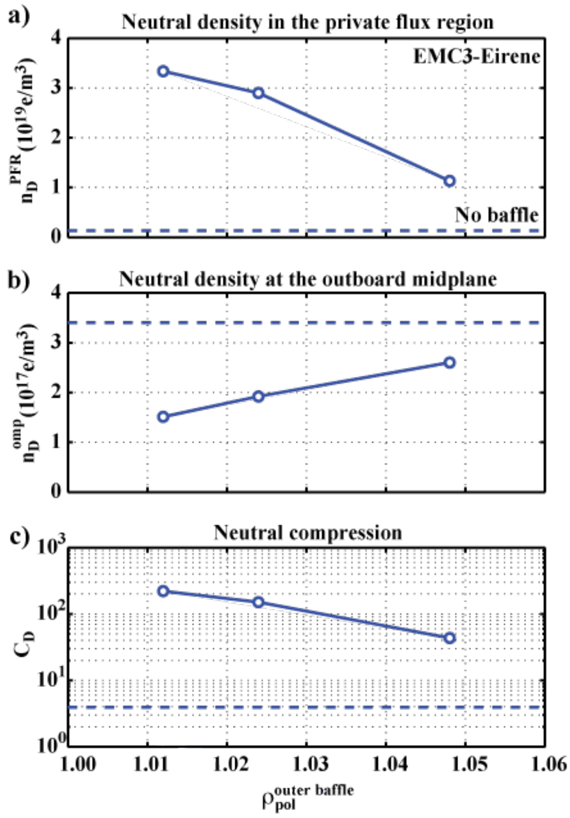

Figure 5: EMC3-Eirene predictions of the dependence of (a) the neutral density in the divertor (averaged over the entire private flux region), (b) the neutral density at the outboard mid plane and (c) the corresponding neutral compression on the closure of the outer baffle. The values are compared to predictions without a baffle (dashed line).

3. 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 as well as control of the seed impurity and He compression in the divertor requires an upgrade of the existing gas-valve system and of the pumping capacity.

3.1. Gas valves

Currently three gas valves are 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 region will be a necessity, together with impurity seeding at different poloidal locations in the divertor. As toroidally localised seeding can lead to significant toroidal asymmetries in the detachment, the capability to inject gas through toroidally distributed valves may be needed. The possibility to operate such valves individually will allow for a study of toroidal asymmetries even without the need for measurements at different toroidal locations.

3.2. High capacity pump

For studies of the effect of neutral and impurity compression on the divertor performance, for example by using a "puff-and-pump" technique [12], the pump must have a sufficiently high pumping speed to affect the neutral density in the divertor. A first estimate of the pumping specification is obtained from the initial EMC3-EIRENE simulations, section 2.4. These predict that for a high power, high density discharge in detached condition, a baffle corresponding approximately to the longest considered baffle results in a neutral compression factor in the divertor of the order of 100 (Fig. 5(c)). With typical measured main chamber neutral pressures in the current open TCV divertor of the order of 10 mPa, a total volume of the planned divertor chamber of 1 m^3 and a typical discharge duration of 1 s the required pumping throughput is of the order of 1 Pa m^3/s. Admitting for some conductance losses between the pump and the divertor chamber, a preliminary pumping speed between 5000 and 10000 l/s is considered.

Given the preliminary specifications of the pumping speed, cryogenic pumps are suggested because of the required velocity and their efficiency for light gases. The proposed TCV modification has been conceived in order to guarantee the maximum flexibility so that divertor baffles can be replaced, or even removed to allow for the investigation of a wide divertor parameter space. Among investigated solutions is the installation of a false-floor on the bottom of the machine under which the cryogenic system could be accommodated. Carbon tiles on this floor would provide the needed screening for the heat load, whereas a specially designed tile arrangement will be used to optimise the amount of neutral particles reaching the cryogenic surfaces. A first version of a possible solution is based on the successful design of the DIII-D cryo-condensation pumps [13]. Its helium cooled surface as well as the nitrogen-cooled shell and radiation particle shielding are shown in Fig. 6. The usable surface area of the actively helium cooled surface will be approximately 0.32 m^2 and 0.45 m^2 for the inner and outer loops, respectively. The assessment of the pumping solutions, including the choice of cryopump, is, however, still work in progress.

4. 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 (PF) coils on the high field side (E-coils) and eight PF coils on the low field side (F-coils), 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 will be required for the planned closed divertor configurations, E- and F-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 (primary) X-point and, consequently, long connection lengths. To investigate the effect of the connection length on the divertor physics, it is desirable to extend the range of attainable connection lengths also to lower values. This can be achieved with a more conventional divertor coil located below the X-point. One or more coils below the divertor chamber would also extend the range of flux expansions at the strike points to lower values and improve the ability to control their location. Such improved control is desirable for diagnostics as well as for power handling that will gain greater importance with the upgrades of the heating power. The combined current in the new divertor coils has to be a large fraction of the plasma current, which in the planned divertor configurations and a safety factor of $q_{95} \approx 3$ is approximately 300 kA.

The new coils may be located in the space between the vacuum vessel and the toroidal field coils (Fig. 6). Numerous ports on the floor of the TCV vessel result in a minimum distance between vessel and coils. Alternatively, the possibility to locate the coils inside the vessel will be evaluated.

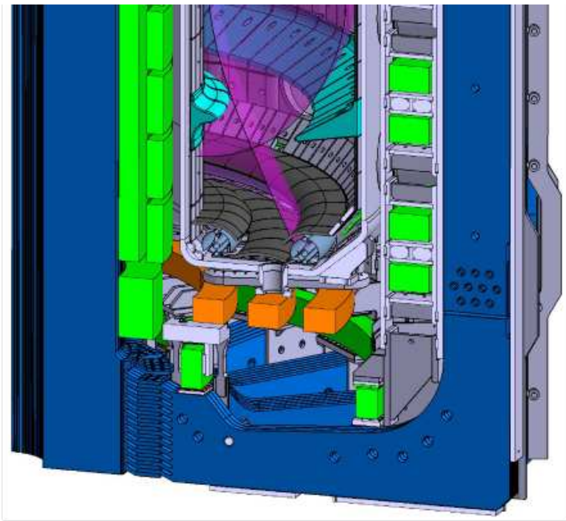

Figure 6: Drawing of the TCV divertor upgrade including the baffles (cyan), cryo-pumps (light blue) and possible divertor coils outside the vacuum vessel (orange).

As a step towards the demonstration of a potential long-term key technology for magnetic fusion, the use of High Temperature Superconductors (HTS) is considered. Possible advantages are the larger current density compared to a conventional water-cooled copper coil, and the high flexibility of HTS coated conductor tapes, necessary for the required in-situ winding procedure. The type of superconducting material and the operating temperature are still under investigation and depend on the exact location of the coils and a possible synergy with the cryopumps.

Systematic equilibrium calculations will be used to investigate to which extent additional divertor coils located inside or outside the TCV vessel can increase the range of divertor configurations. This study will, thereby, identify the optimum number of new divertor coils and their locations and yield the specifications for the required total current in each coil.

5. Diagnostics upgrade

The diagnostic array of TCV will require modifications to be compatible with the baffle installation. In addition, extensions of diagnostic systems are proposed to correctly diagnose the divertor performance. The main approach is to fully equip the divertor region to estimate power and particle deposition at and around all divertor strike points and measure the characteristics of the divertor plasma itself to monitor detachment for a wide range of divertor plasma configurations. Some of this diagnostic information may have to be provided in real time for use in active divertor performance control.

Pressure gauges: For detailed monitoring of the neutral pressure in the divertor and the main chamber, a set of miniature, high-pressure, Penning ionisation gauges developed and tested on Alcator C-Mod [14] will be installed at several poloidal and toroidal locations in TCV. These pressure gauges, with a dynamic range between 10^{-4} Pa and 10 Pa and a ~millisecond time resolution, will be absolutely calibrated against existing magnetically shielded Baratron gauges.

Langmuir probes: Langmuir probes are routinely used to measure particle and heat loads at the divertor targets for all divertor configurations. To complete the coverage of target surfaces, ~50 probes have to be added to the existing set of 114 graphite Langmuir probes. Coverage will include the main chamber facing sides of the baffles. Various tip shapes including roof-top and domed tips are envisaged to adapt to varying incidence angles of the field lines at the divertor targets.

Infrared thermography: Infrared (IR) thermography yields an accurate measurement of power loads on material surfaces. It is, therefore, foreseen to image the entire divertor and the top of the baffles with fast IR cameras. While the present horizontal IR system (HIR) will remain adequate to measure power loads on the inner wall, the present vertical IR system (VIR) will image the main plasma facing side of the baffle and only have a restricted view of the divertor floor. To diagnose the outer part of the floor and the outer wall, a third, tangential IR system will be added. This system will either use a tangential lower lateral port or a standard lower lateral port with a periscope. The IR thermography measurement will be crosschecked with tile calorimetry using an extensive set of existing and new thermocouples.

Bolometry: An accurate and well-resolved bolometric system is critical in the diagnosis of divertor performance. An upgrade of the current bolometric array is proposed consisting of two additional foil bolometric cameras, modification to an existing camera and carbon coatings on all installed bolometers [15]. The additional cameras will increase the spatial resolution in the divertor and near the null point, providing a significantly improved radiation emission location measurement, critical to detachment related experiments.

Divertor spectrometer: The Divertor Spectrometer System (DSS) is used to track plasma constituents and their plasma/neutral state as a function of divertor position by measuring the emitted spectrum of the plasma in the near-UV/visible range using multiple spectroscopic chords [16]. The proposed upgrade of the DSS improves the spatial coverage (both horizontally and vertically) in the divertor region. The upgrade includes the installation of a re-entrant port in order to optimise the coverage of the existing and the addition of a third upward view using a floor port. This increases the present number of chords of the DSS from 62 to 93.

Multi-spectral imaging diagnostics: TCV's MultiCam system consisting of four cameras that observe the same plasma volume at up to four wavelengths selected by appropriate interference filters will be replaced with a new version employing techniques developed for MSE and Thomson diagnostics. It will provide up to eight simultaneous spectral views of the divertor volume with significantly increased signal intensity and spatial and temporal resolution than the existing system.

Divertor Thomson scattering systems: To provide local electron temperature, T_e, and density, n_e, measurements in the divertor chamber, an upgrade of the Thomson scattering (TS) diagnostic is proposed. In a first phase, a new TS system dedicated to the divertor chamber measurements with a vertical path that intersects the null point region will be developed and installed. In a second phase, the coverage of the existing core TS system will be extended into the divertor. Both systems will be equipped with new 4-channel spectrometers with interference filters that are optimised for T_e measurements from ~1 eV to ~500 eV. The divertor TS systems will provide a powerful means of characterising local electron kinetic parameters in the divertor leg and in the X-point region.

Magnetic probes: A new set of four to six magnetic pick-up coils will be added on several of the new divertor baffle tiles. These sensors will improve the detection and control of the divertor configuration and also directly measure electro-magnetic turbulence in the vicinity of the X-point. It is foreseen to use the Low-Temperature Co-fired Ceramic (LTCC) technology [17], since the small LTCC sensors can be fitted within the new baffle tiles and their simultaneous measurements along several axis can diagnose the large variations of the poloidal field magnitude and direction expected in the X-point region.

6. Summary

The planned divertor upgrade seeks to enhance TCV's capabilities to study detachment in conventional and alternative configurations. It 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 systems 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. The use of High Temperature Superconductors (HTS) for the divertor coils would provide a practical step towards the demonstration of a potential long-term key technology for magnetic fusion. 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.

Acknowledgements

This work was supported in part by the Swiss National Science Foundation. The authors would also like to thank Dr. C. Hollenstein for his advice and help in developing this proposal.

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