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Progress in Physics (55)

Upgrading the TCV tokamak to get closer to fusion reactor conditions

Yves Martin, Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne

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Introduction

In a recent SPS paper [1], A. Fasoli succinctly presented challenges that physicists must solve to harness fusion as an energy source for the benefit of mankind.
Fusion is the energy that powers the stars. To reproduce the process on Earth, one needs to heat the Hydrogen isotopes, Deuterium and Tritium, to very high temperatures, around 10 - 20 keV (100 - 200 Million °C), to reach an efficient fusion reaction rate. At these temperatures, the 'fuel' is in the plasma state and can then be confined in a toroidal vessel via magnetic fields in such a way as to reduce the contacts with the walls to minimal values.
The major remaining challenges, following [1], are to overcome the breakeven condition and reach high fusion gains, to control burning plasmas, especially their fast ion population, to reduce the detrimental effect of turbulence on the energy and particle transport, to minimize the impact of energy and particle exhaust onto the walls, and to optimize the efficiency of the blanket modules and their ancillaries where the Tritium breeding occurs and the generated heat

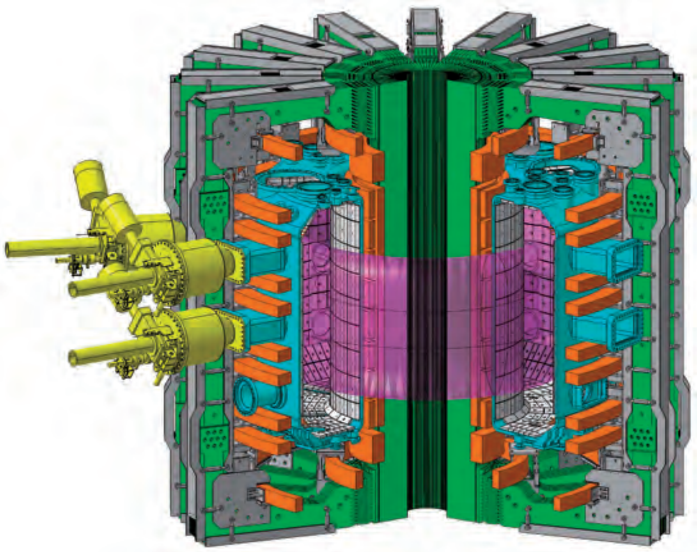

Figure 1: The TCV tokamak with its vacuum vessel (cyan), toroidal magnetic field coils (green), poloidal magnetic field coils: OH transformer and shaping coils (orange) and three ECH launchers (yellow).

is recovered for running the turbines that produce electricity. The TCV tokamak and its ongoing upgrades are conceived, built and operated to contribute to these challenges, in parallel with the construction and future operation of ITER [1] as well as the preparation of the next generation device, a demonstration power plant called DEMO.

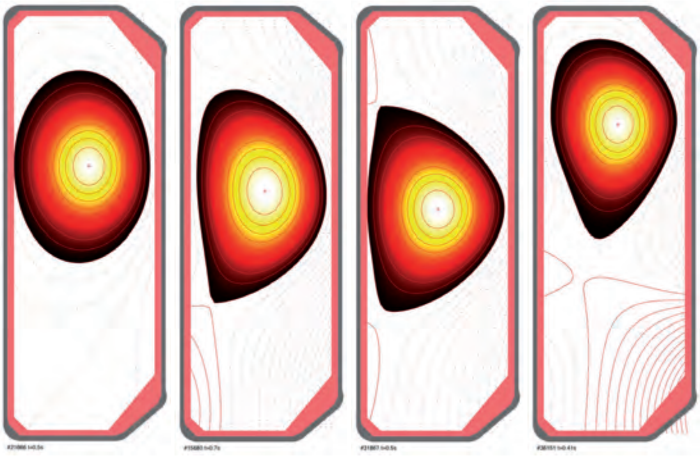

Figure 2: Plasma configurations obtained in TCV: limited, diverted with single null X-point, diverted with double null X-points, snowflake.

TCV

The TCV tokamak [2], operated since 1992, is composed of a toroidal vacuum vessel with a vertical rectangular cross section surrounded by three sets of coils as shown in Fig. 1. A set of vertical coils produces the main magnetic toroidal field ($B_T \leq 1.5$ T). A toroidal coil set, located near the vertical axis of the machine, provides the magnetic flux, whose variation induces the plasma current ($I_P \leq 1$ MA) which is needed to stabilize the plasma via the poloidal magnetic field it generates. Finally, a set of 16 poloidal field coils, all powered independently, are used to generate the magnetic field configuration, which gives the plasma its shape.
Plasma configurations obtained in TCV include both limited as well as diverted plasmas. Limited plasmas lie against the vessel wall, as shown in Fig. 2. The separatrix is defined as the surface that separates the domain where the magnetic field lines are closed on themselves from the domain where they hit the vessel. Diverted plasmas have no direct contact with the vessel but are connected to it via 'separatrix legs' that extend from a null point in the poloidal magnetic field, called X-point, to the vessel. Most tokamaks presently produce single null (one X-point) or double null (two X-points, one at the top and one at the bottom of the plasma) configurations. See examples from TCV in Fig. 2. Snowflake configurations, with two coinciding X-points, that is with four separatrix legs, have been pioneered in TCV, see SPS communication [3]. Snowflakes and other diverted configurations such as super-X, are of great interest in the quest of solving the heat exhaust problem, to which a large fraction of the TCV upgrades is dedicated. Beside the variety of possible configurations, TCV and its 16 shaping coils allow control of plasmas in wide ranges of shape parameters. A great chapter of TCV history already covers the effect of the plasma shape on its properties, especially its energy confinement.

To reach the plasma temperature ranges required for fusion, ohmic heating is not sufficient. In the past, the TCV has opted for the electron cyclotron resonance heating (ECRH) method, since the millimeter wave beam can easily be directed and focused in different regions of interest in the plasma [4]. This approach is based on injecting an electromagnetic wave at a frequency corresponding to the electron gyrofrequency or one of its harmonics. The advantage of this heating method is that the wave penetrates into the plasma without interactions before reaching the resonance layer, which consists of a vertical plane passing through the plasma, therefore allowing localised heating, either at the plasma centre, mid-radius, or at the plasma edge, as shown in Fig. 3. The limitations of the current ECH system on TCV are a relatively low cut-off density ($4.2 \times 10^{19} m^{-3}$) for the second harmonic (X2 - 82.4 GHz), but which is fully absorbed at the first pass, and a lower absorption for the third harmonic (X3 - 118 GHz), which on the other hand has a higher cut-off density ($12 \times 10^{19} m^{-3}$). Lateral launchers with revolving and tilting mirrors allow localised injection of the microwaves at the 2nd harmonics, single pass, and have led to a large number of scientific achievements, including internal transport barriers, with the electronic temperature record of 17 keV, full sustainment of the plasma current (200 kA) by the EC microwaves via their current drive capabilities, used instead of the magnetic induction, and full sustainment of the plasma current via bootstrap current, a transport phenomenon resulting from the presence of a strong pressure gradient, which builds up when the plasma is heated locally. On the other hand, microwaves at the 3rd harmonic are launched from the top, along the resonance layer, to compensate the lower absorption rate with a longer path in the absorption region. Interesting results have also been obtained using the X3 system, especially in the high confinement regime, called H-mode, which builds up after a transport barrier develops at the plasma edge (the H-mode is the operational regime foreseen for ITER). However, since the 3rd harmonic microwave absorption increases with temperature, multi-step scenarios were developed to approach the high density and high temperature fusion reactor-relevant operational domain. A more direct access would be preferable. This would be possible by adding another heating scheme such as neutral beam injection.

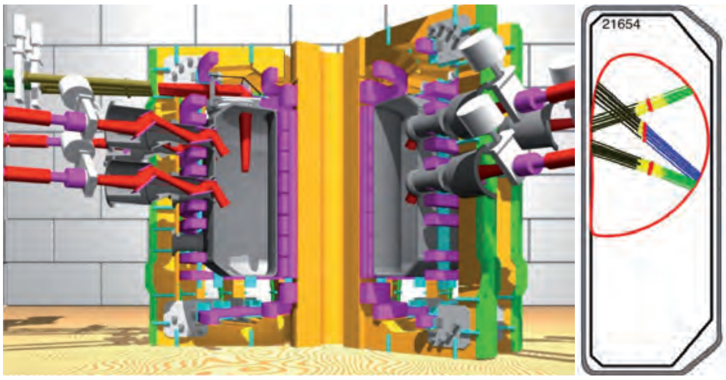

Figure 3: Left, schematic view of the ECH launching system. ECH beams, in red, are launched from six lateral ports and one top port. Right, simulation of the absorption of the ECH beams with different orientations in a plasma. The red zones indicate the resonance location.

In summary, TCV with its high plasma shaping and heating capability has proven to be a very valuable device to improve our knowledge of a variety of basic phenomena in

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[1] https://www.iter.org

fusion plasmas. The next step consists of merging these capabilities and findings in more relevant fusion reactor conditions. To do so, a series of upgrades to the TCV infrastructure are required [5]. Some have currently already been installed and other are planned for the coming years; all are described in the next sections.

TCV Upgrades

EC waves interact with, and transfer energy to electrons only. At low densities, for which ion-electron collision rates are low, the ion temperature actually decreases when the electron temperature increases, due to the further reduced ion-electron collision rate. At higher densities, the ion temperature slightly increases, but direct ion heating is necessary to reach ion temperatures in the range of 10 - 20 keV, as required for fusion reactions. Two 1 MW neutral beam heating systems will fulfill this requirement.

Reactor relevant conditions also include operation at higher plasma densities. It is therefore necessary to improve the EC capability at the 3rd harmonics. Two 1 MW gyrotrons working at two frequencies (126 GHZ - 3rd harmonic and 84 GHz – 2nd harmonic) will be installed.

Finally, to address the exhaust issues, and in particular to test new divertor concepts, different sets of baffles, equipped with measurement systems will be developed together with gas feeding and pumping capabilities. Additional shaping coils will complete the divertor improvements.

ECH system upgrades

The ECH system of TCV, in operation since 2000, is built on three independent, high voltage (80 kV), well regulated power supplies. The first two power supplies feed two clusters of three 500 kW gyrotrons each. These microwave sources, of maser type with a cavity of about 5 cm, produce beams at the frequency of 82.4 GHz, which corresponds to the 2nd harmonic of the electron cyclotron frequency in TCV. The microwave beams are then led to the tokamak in individual transmission lines (corrugated wave-guides), and launched in TCV from lateral ports via independent sets of revolving and tilting mirrors. The last power supply feeds another cluster of three 500 kW gyrotrons, producing microwaves at 118 GHz, which corresponds to the 3rd harmonic resonance in the plasma. Individual transmission lines carry the beams to the top of the tokamak where they converge on one tilting and radially adjustable mirror, as shown in Fig. 3.

The upgrade first consists of replacing three defective 82.7 GHz gyrotrons by two 750 kW units producing beams at the same frequency and being powered by one power supply. The beams are then launched into TCV through the lateral ports. The first of these two gyrotrons, provided by GYCOM, Russia, has just been installed, tested and accepted at the SPC.

The three surviving 82.4 GHz gyrotrons are now grouped in the other X2 cluster and their waves injected into TCV from the other set of lateral launchers. The 3rd harmonic, 118 GHz, cluster of three gyrotrons remains untouched but will be powered, in the future, by the same power supply as the remaining gyrotrons. The plan is to also modify the transmission lines to allow injection of the 118 GHz beams from top or lateral ports. For this, new segments of transmission line and three way switches will be installed.

In a second step (2017 - 2018), two dual frequencies, 84 GHz and 126 GHz, gyrotrons will be added. Their resonant cavity is designed to produce microwaves at these different frequencies. Moving from one frequency to the other only requires the operator to change the external magnetic field and the angle of the last mirror in the gyrotrons. The output power should reach 1 MW at both frequencies. The design of these gyrotrons has been performed in collaboration with KIT and Thalès, which will also build them. The microwaves produced by these new devices will be injected into TCV through existing top or lateral ports using another set of microwave switches. Fig. 4 shows the gyrotrons implementation and Table 1 summarises the possible schemes for using the different sources once the whole system will be installed.

Cluster	Power	Ports	Physics goals
Old 82.4 GHz gyrotrons (X2)	1.25 MW	Lateral	Localised heating or current drive of low density plasmas
New 84 GHz gyrotrons (X2)	1.5 MW		
Old 118 GHz gyrotrons (X3)	1.5 MW	Top or lateral	Bulk heating of high density low temperature plasmas Localised heating or current drive of high density high temperature plasmas
New 126 GHz gyrotrons (X3)	2 MW		

Table 1: Usage of the different gyrotron clusters.

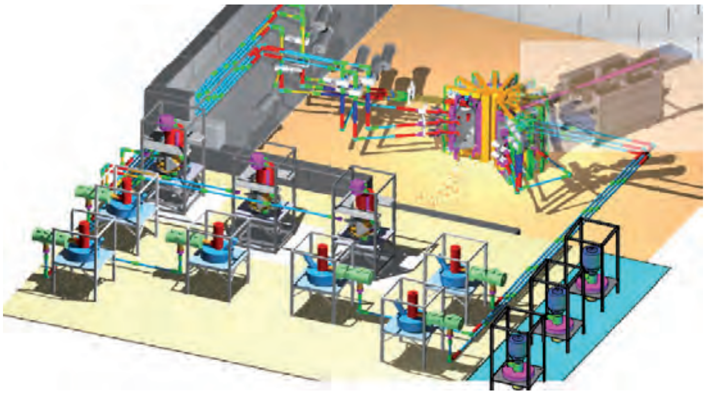

Figure 4: Implementation of all gyrotrons on the plateform next to TCV.

Neutral Beam Injection

Neutral Beam Injection consists in launching high energy neutral Hydrogen isotopes into the plasma. The reason to launch neutral particles, instead of charged particles, lies in the fact that charged particles would be deflected before entering the tokamak, due to the presence of the magnetic fields. Entering the plasma, these particles nonetheless get ionised and confined by the magnetic field and consequently can transfer their energy to the plasma particles through collisions. NBI has the advantage of directly heating the ions at the energies required for TCV.

A NBI system contains a plasma source that generates the charged particles, which are then accelerated in a series of high voltage grids, before entering a volume filled with neutral gas where charge exchange occurs. Fast neutrals then exit from this volume and fly in a straight line into the plasma. The remaining charged particles are deflected away. The SPC has purchased one 1 MW 35 keV beam from Budker INP, Russia. It is now installed on the TCV tokamak and the first results showed operation close to specifications and ion heating in accordance with the simulations.

To benefit from a longer beam/plasma interaction region, neutral beams are usually launched tangentially into tokamaks. Therefore, prior to the installation of the neutral beam, modifications of the TCV vacuum vessel have been performed to accommodate tangential injection, as shown in Fig. 5: two radial ports located on the equatorial plane of the machine have been replaced by tangential ports. This work has been performed by De Pretto technicians who directly modified the vessel from inside. The second new tangential port is planned to dock a second 1 MW beam, with slightly higher energy to study fast ion physics. It will also be provided by Budker, INP, likely in 2018.

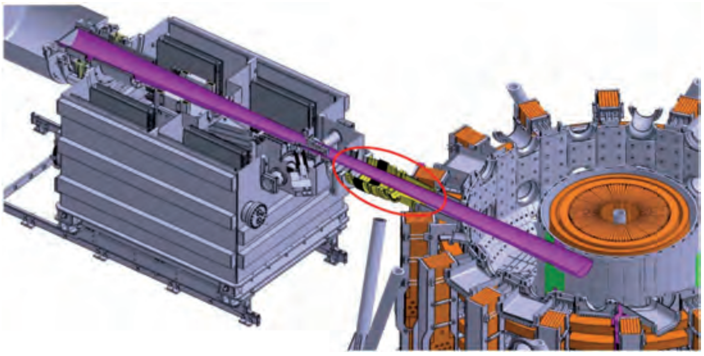

Figure 5: Horizontal cut of the neutral beam injection system (left) and TCV (right). From the top left corner, the plasma source, the neutralyser, the beam duct and the tangential port. The second tangential port is visible at the lower right corner.

Due to their tangential injection, neutral beams also inject toroidal momentum, thus inducing plasma rotation, which, in turn, strongly influences the plasma characteristics, especially the access to the high confinement regime, the so-called H-mode. The process is not yet fully understood, since, for instance, plasma rotation is also observed with radial injection of EC waves, which do not carry toroidal momentum. To contribute to the clarification of these observations, the new tangential ports have been oriented in opposite direction to allow neutral beam injection in the same direction of the plasma current or in the opposite direction, or in such a way as to compensate each other.

Neutral beam injection will then directly bring high density plasmas to high temperatures, i.e. provide more reactor relevant conditions. In particular, H-mode regimes should be easily obtained by NBI and the 3rd harmonic of ECH could then be used to act on the temperature profile, in order, for instance, to create an additional internal transport barrier, or to act on the edge transport barrier itself.

Finally, having two high power systems that independently heat the electrons and the ions allows studying plasmas with a wide range of different ion to electron temperature ratios. This is of prime importance, since different turbulent regimes seem to develop according to the different temperature ratios.

In summary, the combination of NBI and ECH opens wide new fields of investigations of high relevance to fusion research.

Closed divertor

In diverted configurations, charged particles that exit the plasma by crossing the separatrix, find themselves on open magnetic field lines, and thus flow towards the vessel walls until they hit it near the separatrix strike points, i.e. where the separatrix legs connect to the vessel. Most escaping particles thus hit the walls in two bands that fully expand toroidally but have a very narrow expansion poloidally.

The power density deposited onto the walls at the vicinity of the strike points of a large fusion device will be extremely large, up to 10 - 20 MW/m^2, leading to material surface damage. Measures must therefore be taken to reduce it. The first idea, already tested in JET for instance, is to tilt the divertor plates in order to obtain a wider wetted area. An alternative consists of moving back and forth the strike points in an oscillating motion to also increase the time-averaged wetted area. Furthermore, the strike points can be displaced towards a larger major radius to increase the length of the interaction region in the toroidal direction, in the so-called super-X configuration. Another possibility consists of merging two X-points together, which results in a configuration counting four separatrix legs, called the snowflake divertor. Variants of these configurations, which include different flux expansion and X-point locations, provide a continuum of shapes that can be addressed in TCV.

A completely different but complementary approach consists of radiating a large fraction of the power before it hits the vessel walls. The idea is to inject neutral gas (Deuterium, Nitrogen, Neon or Argon) in the divertor volume, which is the region that expands from the X-point to the strike points. The radiated power is then distributed over a much larger surface area and strongly reduces the heat load near the strike point. To implement this idea, a clear separation between the main plasma volume and the divertor volume

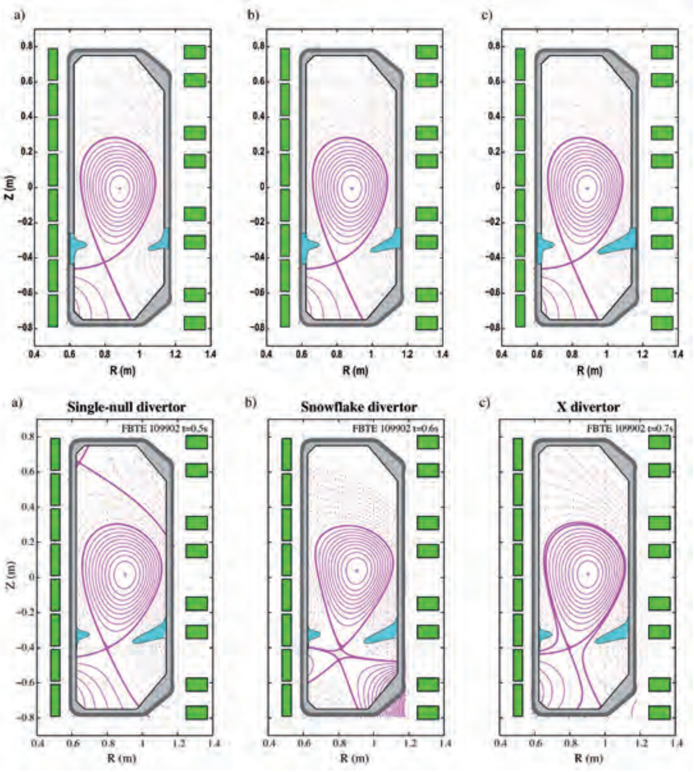

Figure 6: 1st row: implementation of baffles with different lengths. 2nd row: simulations of different plasma configurations showing the compatibility with the most closed baffles.

is then necessary to maintain control of the pressure in the two different regions.

The TCV vessel cross section is by design almost rectangular, to accommodate the largest variety of plasma configurations and shapes. This proved to be very useful to develop new configurations and to explore the influence of shape parameters over very wide ranges but requires significant modifications if one wants to explore closed divertor physics, especially while keeping the high plasma shaping and divertor configuration capability of TCV.

It has therefore been proposed to install a gas baffle structure in the lower part of the TCV vessel. This device consists of a ring of graphite tiles attached to the inner wall on the high field side together with a set of three different exchangeable rings, made of graphite tiles as well but with different lengths in order to vary the closure of the divertor region, mounted alternately against the outer wall (low field side), as shown in Fig. 6. A solution that does not require human access inside the torus to switch from one to the other sets is currently under investigation. These baffles will be equipped with thermocouples to monitor their temperature and with Langmuir probes to measure the characteristics (density, temperature and floating potential) of the plasma close to the tile surface. Additional IR cameras will complement the characterisation of the interaction between the plasma and these baffles.

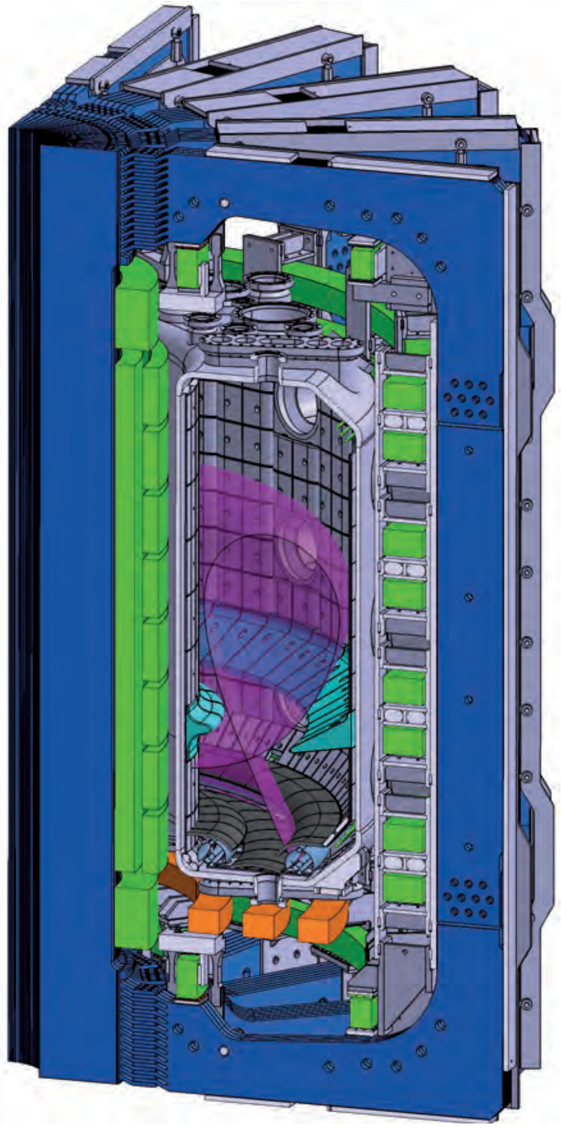

Figure 7: Schematic view of the divertor upgrades: baffles (cyan), superconducting coils (orange) and cryogenic pumps (blue-grey in the bottom of the vessel).

Gas valves and pressure gauges will be implemented in the walls surrounding the two regions to separately control, if closure permits, the neutral pressure in the plasma region and in the divertor region. A high capacity pumping system consisting of two rings of cryogenic panels will be installed under a ‘false floor’ in the bottom part of the vessel to help control the neutral density in this region when strong gas puffing will be used to increase the radiated power.

Several plasma diagnostics will need to be upgraded to accommodate measurements in the two regions. In particular, the divertor region will be equipped with a series of additional channels for the Thomson scattering system in order to collect precise temperature measurements of the plasma flowing in the divertor. It will also be mandatory to equip the divertor region with bolometric cameras to measure the radiation emissivity, in 2D, of the divertor plasma, in order to qualify the performance of the closed divertor in terms of radiated power. Divertor spectrometry will complement the information of the bolometers arrays by estimating the impurity content of the plasma.

Finally, a series of up to three poloidal field coils will be installed in the space between the vacuum vessel floor and the toroidal field coils, as shown in Fig. 7, to improve the control capability of advanced divertor configurations especially for snowflake divertors, but also for super-X divertors or other variants. High temperature superconductors are foreseen for this since they can sustain a much higher current density than conventional conductors and thus strongly reduce the impact of these coils in a region already occupied by several measurement systems.

The detailed design of the different components of the closed divertor, i.e. the baffles, the diagnostics, the cryopumps and the coils, will be initiated at the end of 2016. Procurements, fabrication and installation are planned for 2018 and 2019. All actions to upgrade the TCV tokamak should be completed by 2020.

The TCV team will then continue to significantly contribute to its chosen fields with a still very flexible device while approaching reactor-relevant plasma conditions.

The Swiss Plasma Center wants to express its sincere gratitude to all Swiss and European institutions that provide funding for these upgrades as well as for the research activities that are pursued in the mean time.

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