New heating and divertor capabilities for TCV

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Introduction

The TCV tokamak, with its high plasma shaping capability [1] and its localised, high power electron cyclotron (EC) wave heating [2], has already provided a wide collection of significant results. In the area of plasma exhaust, for example, TCV was the first device to demonstrate the feasibility of the snowflake configuration [3]. Its shaping capability has also been used to vary the flux expansion at the vicinity of the separatrix strike points to address the issue of the heat load into the divertor [4]. Its many independent EC wave sources and launchers allowed intensive studies of electron cyclotron resonance heating (ECRH) and current drive (ECCD) [5]. In order to pursue these investigations in more fusion reactor relevant conditions, a series of major upgrades have been undertaken [6]. These mainly consist in increasing the electron heating power, adding ion heating power and installing a divertor structure with variable closure, equipped with gas valves, pumping units, magnetic field coils and diagnostics.

Rationale for TCV upgrades

Fusion reactors will operate at high beta, that is at high density and high temperature. In TCV, the most flexible part of the EC apparatus is the X2 system, which consists of the 82.4GHz gyrotrons and the lateral launchers, since the wave is fully absorbed at its first path in the plasma. However, the cut-off density of the X2 waves of 4.2 x $10^{19}m^{-3}$ is rather low, which only allows edge heating in the case of dense plasmas. The third harmonic, X3 at 118GHz, has a higher cut-off density of 12 x $10^{19}m^{-3}$, but is less well absorbed, at least at low electron temperature. The X3 wave is, therefore, injected from the top, which does not provide highly localised heating. We have then considered the installation of NBH to heat high density plasmas, which should lead to conditions that allow launching the X3 waves from lateral ports, since the absorption improves with the temperature, in order to maintain the benefits of the localised heating by EC waves. In addition, since a large fraction of the low energy NBH directly heats the ions, the influence of the temperature ratio T_i/T_e on the nature of the turbulence (ITG/TEM) can be investigated.

The downside of operating a reactor at high beta plasmas is the large heat flux that flows in the SOL and reaches the divertor plates. To maintain the flux below the levels materials can tolerate under stationary conditions in a reactor, which is currently thought to be of the order of 10MW/m^2, different solutions to spread the power over a wide surface area are being explored worldwide. A radiative divertor can be combined with alternative plasma configurations such as snowflakes and/or flux expansion, but would be more efficient if the divertor were closed enough to avoid neutrals from the divertor including impurities to reach and contaminate the main plasma. We consider installing a divertor structure with variable closure in TCV. The preliminary design studies led to a solution, presented here, which provides a closed divertor while keeping the plasma configuration flexibility of TCV.

TCV Upgrades – Phase I

The first phase of the upgrades is almost completed. The first 1MW neutral beam is being commissioned while already delivering its first results. Two 750kW gyrotrons, also in commissioning, will soon replace old, defective tubes. The 25keV neutral deuterium beam provides up to 1MW power. It is injected into TCV through a recently machined tangential port with an aperture of 22x17cm. The first experiments (Fig.1) demonstrate that the core plasma ion temperature in L-mode increases from about 600-800eV, the typical values in TCV high density Ohmic plasmas, to about 2keV, in agreement with the values predicted by the ASTRA code [7]. In the mean time, the plasma rotation with NBH reaches a velocity of 150-180 km/s, while it rotates in the opposite direction at less than 20km/s without it. These encouraging preliminary results led to an already frequent use in the frame of the currently ongoing EUROfusion campaign, although the available beam energy has been limited due to non-optimal angular characteristics of the beam compared to the size of the beam duct and the subsequent damages that it provoked.

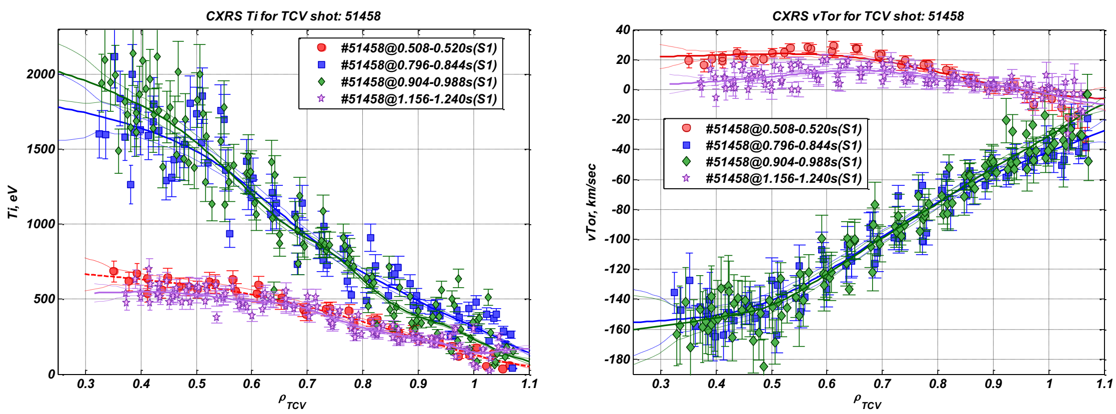

Figure 1, left: Ion temperature profiles with and without NBH; right: Effect of NBH on the plasma toroidal rotation.

Two 750kW gyrotrons have been purchased to replace three old, defective 500kW microwaves sources. These new gyrotrons, also producing 82.4GHz waves, have been installed in the existing magnets and are connected to the TCV via the same waveguides and lateral launchers as the previous ones.

TCV Upgrades – Phase II

It is foreseen to install a second 1MW neutral beam with higher energy (50-60keV) for plasma heating at higher density, especially in H-mode, and for fast ion studies. The TCV vessel was already modified in phase I to accommodate two beams oriented in the opposite direction.

Two, 1MW, bi-frequency, 84 & 126GHz, gyrotrons will be installed in 2017-2018 on TCV. Microwave switches will be installed between the gyrotrons and the launchers to give the opportunity to launch the X3 or X2 waves either from the upper or from the lateral ports. It will then be possible to use the X3 system for ECCD. Table 1 summarises the future status of the ECH system on TCV.

Gyrotrons	**Mode**	**Power**
3 existing 82.4GHz	X2	1.25MW
2 new 84GHz	X2	1.5MW
3 existing 118GHz	X3	1.5MW
2 new 84GHz and 126GHz	X2 & X3	2MW

Table 1: Frequency, operational mode and power of the gyrotrons that will be available in 2018 on TCV.

In parallel, a mechanical structure will be installed in TCV to divide the vessel into a core plasma and a divertor region. Different preliminary designs of variable closure systems, which also have to maintain the plasma configuration capability, have been investigated. All consist of a fixed ring of protuberant tiles fixed against the central column and a second ring of variable length fixed against the outer wall between the lower and equatorial ports, as shown in Fig.2, to allow neutral beam heating from the equatorial port and divertor diagnostic from the lower port. The best solution found so far would consist of manufacturing three sets of interchangeable tiles of different lengths, its drawback being the necessity of a manual action, requiring entering the TCV vessel, to replace one set by another.

In order to increase and control the neutral pressure in the divertor region, a series of toroidally distributed gas valves will be installed. In addition, a high capacity cryogenic pumping system will take place in the divertor region to help controlling the neutral density. The favourite solution designed so far consists of a dual ring of cryo-pumps located under a false floor in the lowest part of the TCV vessel. Pressure gauges will monitor the pressure in both core plasma chamber and divertor region.

A series of diagnostics will be either modified, improved or added to monitor the divertor. Several Langmuir probes and thermocouples will line the new divertor protuberant tiles to characterise the plasma and its impact near and on the tiles. Some optical systems such as bolometers and spectrometers, will provide information on the radiated power and plasma parameters with increased spatial resolution in the divertor. The Thomson scattering system will be expanded into the divertor region and adapted for divertor plasmas to measure the variation of the electron temperature and density in the X-point region.

Finally, a set of up to three independently driven coils should take place under the TCV vessel to increase the range of configurations and improve the capability of controlling the magnetic configuration of the divertor. It is foreseen to use high temperature superconductors to demonstrate the feasibility of this promising technology for fusion reactors.

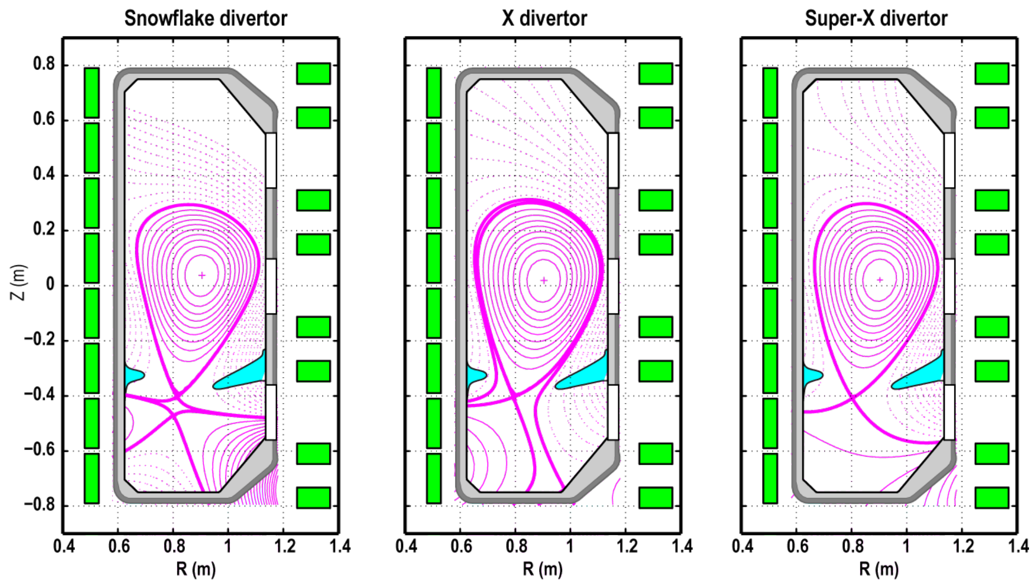

Figure 2: The preliminary design of a mechanical structure that divides the TCV vessel in a core plasma and a divertor regions. The closed divertor will still allow the realisation of the different plasma configurations.

Acknowledgements

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