An upgraded TCV for tokamak physics in view of ITER and DEMO

A.Fasoli, S.Alberti, R.Chavan, B.P.Duval, A.Karpushov, Y.Martin, O.Sauter, M.Toussaint, H.Weisen and the TCV Team

Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas, Association Euratom-Confédération Suisse, CH-1015 Lausanne, Switzerland

1. Introduction

Improving understanding and control capabilities of burning plasmas is a major scientific challenge, which requires accessing plasma regimes and configurations with high normalised plasma pressure, a wide range of accessible temperature ratios, including T_e/T_i~1, significant populations of fast ions and relatively low collisionality [1]. It is possible to achieve these conditions on TCV by installing a neutral beam heating system (1MW) and by increasing the electron cyclotron plasma heating power at the third harmonic (2MW) [2]. These heating upgrades are being conducted together with some modifications of in-vessel components, necessary to make TCV shaping capabilities compatible with increased heating power.

2. X3 gyrotron power upgrade

High confinement modes are typically obtained in high density, highly elongated and high current plasmas. On TCV, these plasmas cannot be heated using the 82GHz EC system, which corresponds to the second electron cyclotron harmonic (X2), as the 82GHz waves cannot propagate in plasmas with density above $4\times10^{19}m^{-3}$, except in O-mode, where absorption is low and the operational window small. Additional heating at higher density, as required for H-modes, may be achieved by upgrading the existing third harmonic (X3) EC system, whose frequency, 118GHz, corresponds to a cut-off density of $1.2\times10^{20}m^{-3}$. As shown in Fig.1(left), which was obtained from an ASTRA simulation of a standard TCV configuration, to approach the ITER relevant range of β_N values, X3 power levels higher than the presently available 1.5MW are necessary. The proposed upgrade foresees the installation of two additional 1MW gyrotrons operating at 126 GHz for a pulse length of 2 seconds. These new gyrotrons could be based on the concept developed for the 1MW/170GHz ITER sources [3]. The microwave power will be launched from the top of the vessel, as for the three existing 118GHz sources. Absorption calculations using TORAY suggest that under typical H-mode conditions single pass absorption exceeding 80% can be achieved. The existing 118GHz gyrotrons would be connected via high-power microwave switches through the lateral low field side (LFS) launchers currently used for X2. Single pass absorption in excess of 70% can be achieved even in this configuration in plasmas pre-heated by top-launched X3. Bulk electron heating will then be ensured by the 2MW from the top launcher, while localised deposition necessary for MHD control will be possible with the 1.5MW launched from LFS. A large fraction of the infrastructure necessary for this development, including power supplies, wave-guides and beam steering mirrors, is already available.

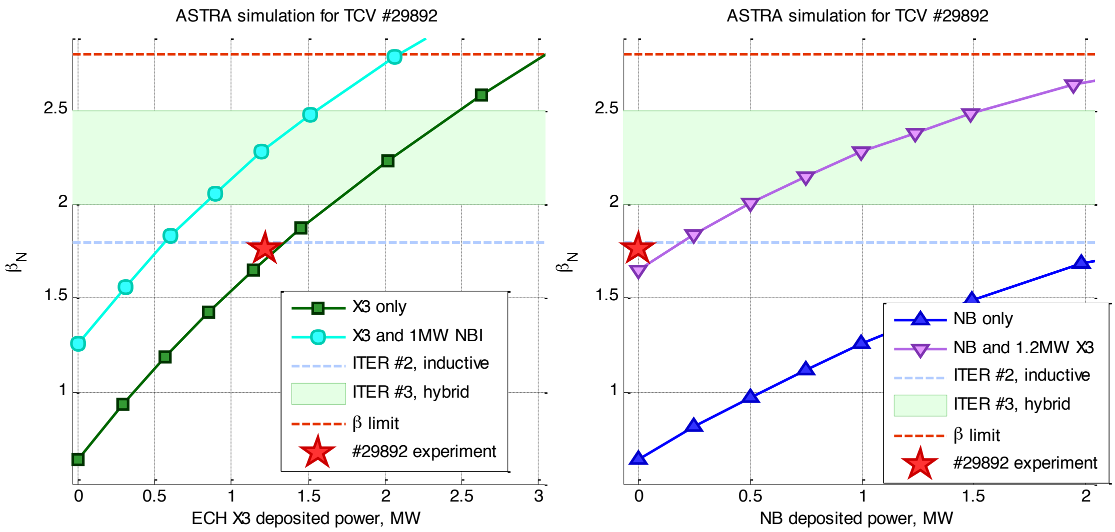

***Fig. 1** Astra simulation of the TCV plasma performance as a function of ECH X3 power (left), and NB power (right), based on an actual scenario (H-mode discharge 29892, with I_p=410kA, B_T=1.44T, Z_{eff}=2.6, $n_e(0)=6.5\times10^{19}m^{-3}$, $T_e(0)$=2.8keV, $T_i(0)$ = 0.9keV, q_{95}=2.5; the shaping parameters are κ_{95}=1.68 and δ_{95}=0.36). Here and in the following figures an NBI D-beam of 30keV is considered, together with the ITER H98 confinement scaling, with $\chi_i=\chi_e/2$.*

However, Fig. 2(left) shows that, even with injection of additional X3 EC power, TCV plasmas would have T_e/T_i in the range 2-5, outside the ITER and reactor relevant domain. This is due to the naturally weak electron-ion coupling in small devices such as TCV, where electron-ion collision times are substantially longer than energy confinement times.

3. Neutral beam heating on TCV

As illustrated by Fig. 2, for $T_e/T_i\sim1$, the ions must be heated directly using NBI [4]. In such conditions, the turbulence is dominated by other modes than those observed to date (mixed ITG-TEM). The resulting change in characteristics for heat, particle and momentum transport give rise to important open questions for the core of burning plasmas. Combined with the upgraded X3 ECH system, a new NBI system on TCV could bring the plasma at the β limit in H-mode (β_N~2.8), of great interest for ITER and DEMO [5], provide variations in the momentum input to the plasma, and generate fast ions that can be used to study wave-particle interaction phenomena of interest for burning plasmas. Fig. 2 shows that in TCV plasmas of similar shape to ITER, the condition T_e/T_i~1 is met for about 1MW of NB power absorbed in discharges together with about 1MW of X3 ECH. With a combination of an NBI up to 1MW and up to 1.3MW of X3 ECH, T_e/T_i is foreseen to range between 0.5 and 3.0.

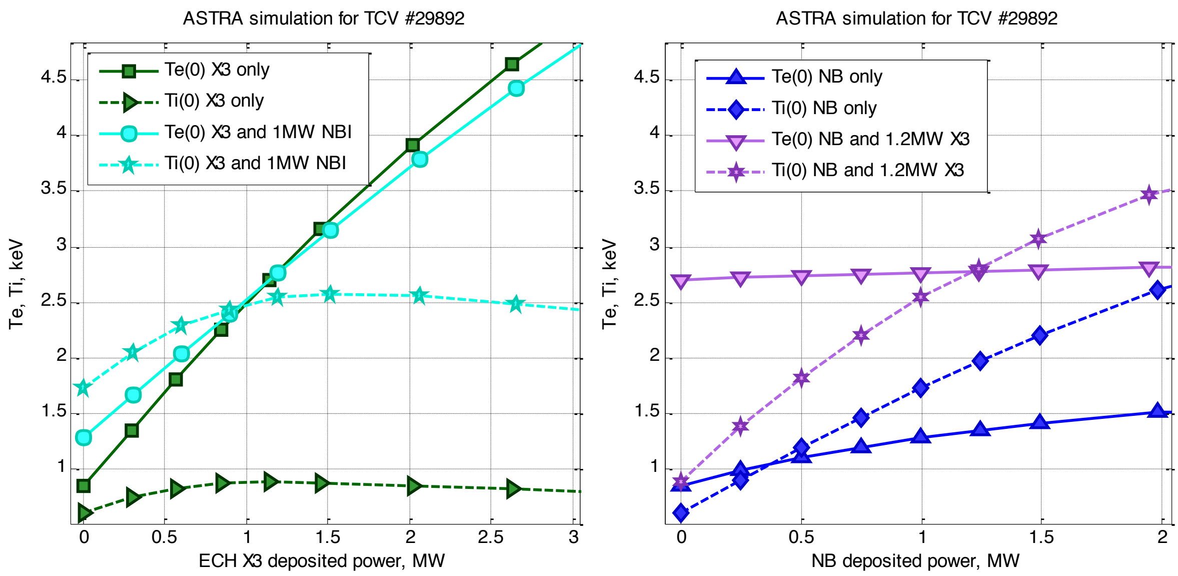

Fig. 2 *Variation of the electron and ion on-axis temperatures as a function of EC X3 power (left) and NB power (right) from Astra simulations, for the same cases shown in Fig. 1.*

The design choices made for the NBI installation on TCV were based on several considerations, including beam access, for which significant modifications of the vacuum vessel are required, shine through and orbit losses [6]. An energy range of 15-35keV, a tunable power up to 1MW (at 30keV), and 1-2s duration are foreseen for the D-beam. Detailed studies confirmed the feasibility of inserting a port with an aperture of 170×220 mm^2 and of injecting tangentially through it a 1.0MW beam. Two such apertures are being created in the existing vacuum vessel, as shown in Fig. 3. In a first phase, one NBI system is envisaged, with the port on the opposite side dedicated to diagnostic use. With this geometry, one NBI system can drive a significant fraction of the plasma current in low-current, low-density regimes and provide a contribution to the plasma rotation similar to that observed in the absence of external torque, corresponding to about 1% of the Alfvén frequency. Operation with an H-beam at higher energies, with reduced power, is also anticipated in order to explore wave-particle interaction phenomena with super-Alfvénic ions, with $\beta_{N,fast}$~1/4$\beta_{N,thermal}$.

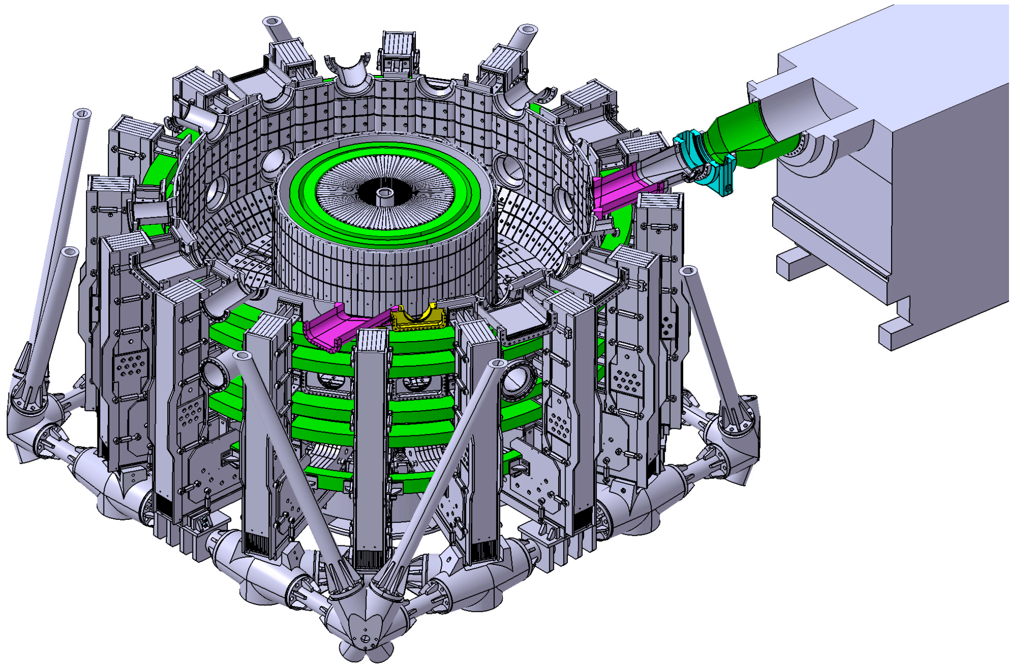

Fig. 3 *View of the two new tangential ports installed on TCV for the NBI injector.*

4. Conclusion

The on going heating upgrades (1MW NBI and 2MW of additional X3 EC) will enable TCV to access β_N 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 assessments, ELM control, transport and shape studies, and to disentangle effects of electron-ion coupling, rotation, current density profile, edge density control and shape, in ITER and reactor relevant ELMy H-mode with dominant electron heating. Various plasma configurations will be tested, from JET and ITER like conventional shapes to plasmas with high elongation (so far produced in TCV only in Ohmic discharges), snowflake divertors, and diverted plasmas with negative triangularity, which have lower β limits but improved confinement over positive triangularity.

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