Feasibility Studies of the Neutral Beam Heating System for the TCV Tokamak

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Introduction. The TCV tokamak (Ro≅0.88 m, a≤0.25 m, B_T≤1.54 T) contributes to the physics understanding of fusion plasmas, broadening the parameter range of reactor relevant regimes, by investigations based on an extensive use of the existing TCV main experimental tools: flexible shaping (elongation up to 2.8, positive and negative triangularity) and high-power (4.5 MW) real time-controllable second (X2) and third-harmonic (X3) electron-cyclotron heating and current drive (ECH-ECCD) systems. Unfortunately high power electron cyclotron heating (T_e up to 14 keV) in the present relatively low density plasmas does not allow operation at reactor relevant ratios of ion to electron temperatures (T_i/T_e~1). A possible installation of a heating neutral beam system (NBH) [1] with a total power up to 3 MW in combination with existing ECH would allow the extension of T_i/T_e present range (0.1-0.8) to beyond unity, depending on the mix of NBH/ECH and on the plasma density. Target plasmas could include ITER-like H-mode shapes together with advanced shapes, recently accessible only in Ohmic regimes [2]. The proposed NBH system would also provide TCV with an important tool for investigating fast ion and related MHD physics as well as the effects of plasma rotation for which TCV is already well diagnosed.

The feasibility studies (engineering aspects, modelling and supported experiments) for the NBH on the TCV presented in this paper, aimed to build the specification for the neutral beam injectors and their position on TCV.

Access for neutral beams. The TCV was not originally designed for neutral beam heating; however, several relatively wide midplane lateral ports were implemented for improving diagnostic flexibility. Plasma access for a few 1 MW NB injectors on the TCV is available through 15 cm diameter ports with near normal injection (Θ<15 deg., R_{tan}≤0.23 m). The geometry permits two NB injectors (aiming in co– and counter-current directions) on the same port (Fig.1-1&2). With proper power adjustment one could obtain scenarios with the balanced momentum transfer to the plasma. Shine through is satisfactory at the high densities typical of H-mode plasmas and X3-ECH targets. Neutral beams usage with near-normal injection at the low densities required for simultaneous X2 ECH-ECCD and NB heating is severely limited by excessive shine-through and high inner wall power loads. The maximal acceptable power load of 7.6 MW/m^2 for a 1 sec duration leads to temperature rise of graphite inner wall tiles of 1000 K corresponding to ~10% shine-through of the 1MW beam with the 15 cm aperture.

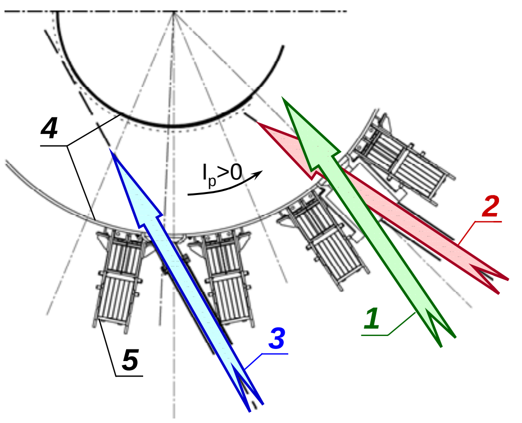

Fig.1: Possible injection arrangements. 1&2 – near-normal setups (1 – co-, 2 – counter-injection), 3 – near-tangential setup, 4 – inner and outer walls of the vacuum vessel, 5 – toroidal field coils.

A single fairly tangential injection port with of Ø10 cm aperture with the axis passing near the inner wall at R_{tan}≅0.65 m is also available for near-tangential NB injection (Fig.1-3). The inner wall would then intercept about half of injected power, and the second half pass for a second time through the plasma to the other wall. Because of shallow incidence of the beam on the inner wall heat load is significantly lower than for near-normal cases. This allows an operation at low densities, well below X2 ECH cut-off. The transmission of the high power (0.6-1.0 MW) NB through the narrow port demands high current density, low divergence neutral beam injector, reachable, up to date, only for the lower current diagnostic neutral beams.

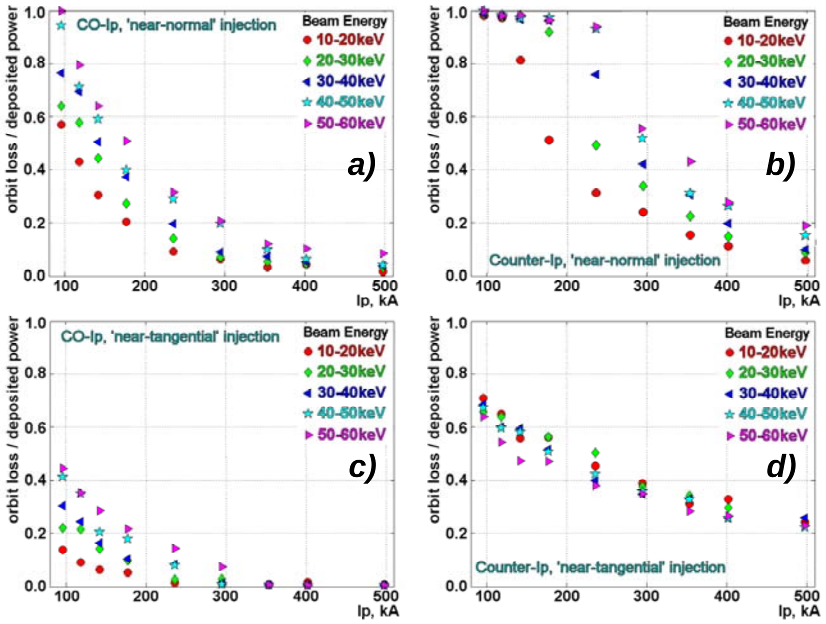

Fig.2: Relative orbit losses for co-(*a&c*) and counter-injection (*b&d*) for near-normal (*a&b*) and near-tangential (*c&d*) setups for deuterium ions with different energies for the intermediate plasma density ($5\times10^{19}m^{-3}$).

Modelling of the orbit losses. The near-normal NB injection leads to creation of substantial fraction of trapped ions, particularly for neutrals deposited near low field side of the plasma. The resulting fast ion population has a strong anisotropy with $E_{||}/E$~0.1 (~0.7 for near-tangential injection). At low plasma current, orbit losses becomes very important, constraining, together with shine-through losses at low density, the upper limit for the NB injection energy. Results of orbit diffusion, slowing down and angular scattering calculations are shown in Fig.2. For near normal beam injection large first and slowing-down losses of fast ions with energies above 20-40 keV at plasma current below ~350 kA become substantial for counter-injection. Orbit loses are significantly lower for co-injection (at ~200 kA). The fast ion orbit confinement for the near-tangential injection is significantly better, especially with co-injection.

Experimental studies of the ion confinement and orbit losses. A set of dedicated experiments with the Diagnostic Neutral Beam (DNB) was performed to validate the fast ion orbit losses modelling. A DNB injector [3] with the equivalent current of hydrogen neutrals of 1-2 eq.A mainly used on the TCV for the CXRS local measurements of plasma ion temperature, velocity and carbon impurity density. The DNB with an operational energy range of 20–55 keV injects H^O or D^O in bursts of 10–60 ms at a toroidal angle of 11.25^O in the Tokamak horizontal mid-plane (similarly to co-injection in Fig.1). The extracted and neutralized beam contains components with energies equal to full, half, 1/3 and ~1/18 of the accelerating voltage, typically [60; 8; 26; 6]% (in equivalent currents). Experiments with co-

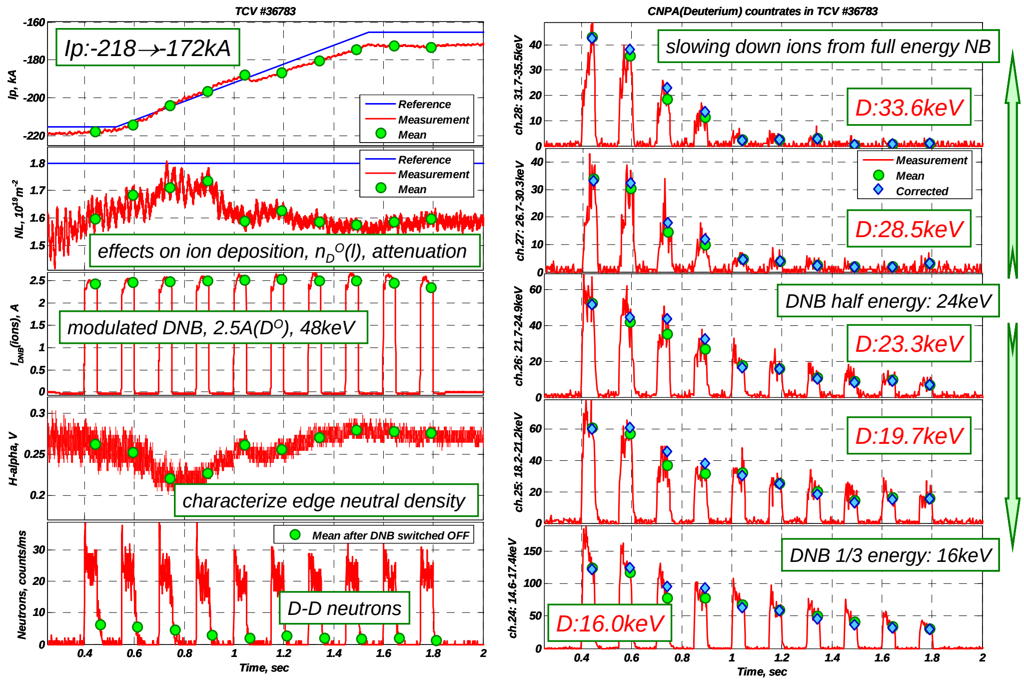

Fig.3: TCV discharge with plasma current ramp-down, counter-Ip deuterium DNB injection: Ip, line integrated electron density, beam ion current, H-alpha emission, neutron countrates and countrates (counts/2.5 ms) in high energy deuterium channels of the CNPA.

and counter-current configurations were performed together with changes of the sign of the plasma current. The behavior of the fast ion population was monitored using a 28-channel Compact Neutral Particle Analyzer (CNPA) [4]. The CNPA is an E||B spectrometer with mass and energy separations and simultaneously detects two mass species (hydrogen: 11 channels, 0.644–50.0 keV and deuterium: 18 channels, 0.565–33.6 keV) with an energy resolution of 60–10% and a time resolution of 0.5–4.0 ms. In experiments, described herein, the CNPA line of sight was placed along the TCV major radius on an equatorial port shifted toroidally on 270 degree from the DNB entrance into torus. The D-D neutrons emission in experiments with the deuterium beam was measured by the He^3 neutron detector.

Figure 3 presents typical time traces from the TCV discharge with plasma current ramp-down and injection of the 48 keV deuterium beam. The TCV real-time feedback control minimized the density variation during change of the plasma current. The strong decrease of the count-rates in high energy deuterium channels of the CNPA correlated with decrease of the |Ip| is a clear indication of a degradation of the fast ion confinement

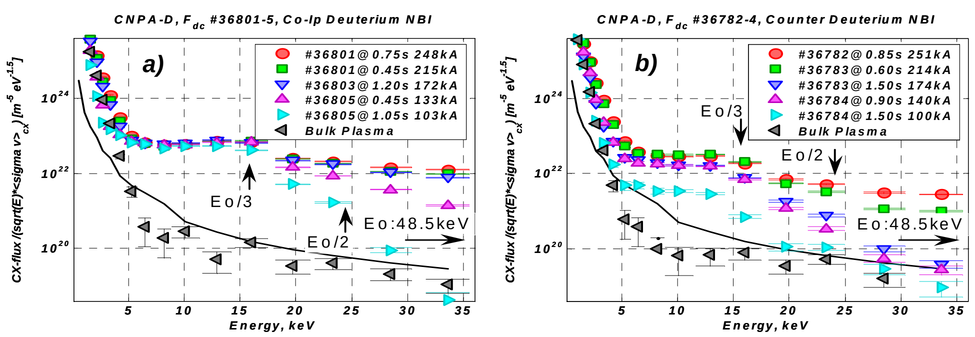

Fig.4: Deuterium CX spectres for co- and counter-Ip deuterium NB injection for different plasma current.

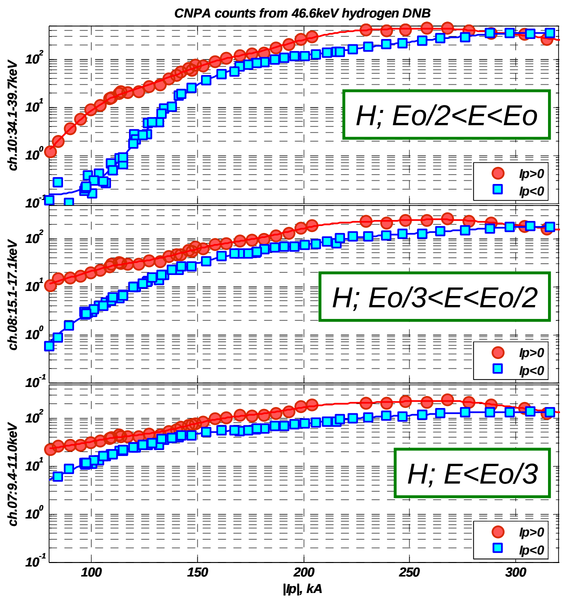

Fig.5: CNPA hydrogen countrates vs plasma current.

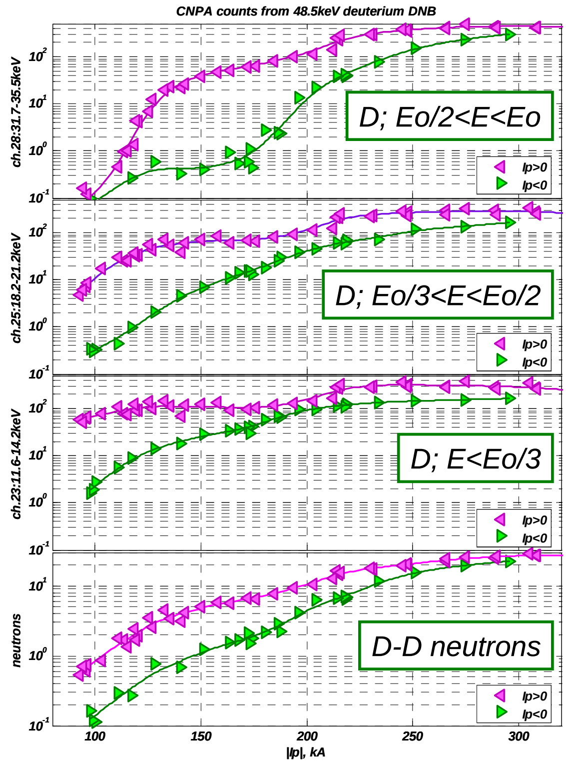

Fig.6: CNPA deuterium and D-D neutrons countrates vs. Ip.

interpreted as increase of the orbit losses. During the DNB injection, the measured neutron flux is dominated by beam-wall interaction. For analysis of the ion confinement we use the averaging on the 10-15ms of the neutron emission just after beam switch-off (for each beam pulse). Charge-exchange (CX) energy spectres from the CNPA measurements for different plasma currents and deuterium beam are shown in Fig.4. A strong confinement degradation of 48 keV deuterons was observed at ~130kA for co-Ip injection, 16 keV particles are mostly confined. For the counter-Ip case: the degradation starts at significantly higher current (~200 kA for 48 keV), the orbit losses of 16 keV ($E_O/3$) D^+ becomes well pronounced below 150 kA. In the experiments with injection of the 46.6 keV H^O (Fig.5), the degradation of the confinement for the ions originated from the deposition of the full energy beam fraction has been observed at 30-50 kA lower plasma current than for D^O-beam (Fig.6). CNPA measurements in experiments with H^O and D^O near-normal beam injection confirmed orbit calculation with, in particular, a rapid drop in confinement at 150-250 kA.

Conclusion. For the NB heating proposes, low energy beams are best suited to TCV. For the high density plasma (>3-5×10^{19}m^{-3}) with near-tangential injection the long duration NB heating will be restricted by overheating of the inner vessel tiles.

Hydrogen has better orbit confinement for the given energy (good agreement between simulation and experiment); however, due to reduced shine through and better ion neutralization, deuterium beams are better overall.

1. A.Fasoli 22nd IAEA Fusion Energy Conference, Geneva, (2008), paper OV/1-1
2. A.Pochelon et al,. 22nd IAEA Fusion Energy Conference, Geneva, (2008), paper EX/P5-15
3. A.N.Karpushov et al., Fusion Engineering and Design, 84, pp.993-997 (2009)
4. A.N.Karpushov et al., Rev. Sci. Instrum. 77(3), 033504 (2006)

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