Status, scientific results and technical improvements of the NBH on TCV tokamak

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The TCV tokamak contributes to physics understanding in fusion reactor research by a wide set of experimental tools, like flexible shaping and high power ECRH. A 1 MW, 25 keV deuterium heating neutral beam (NB) has been installed in 2015 [3] and it was operated from 2016 in SPC-TCV domestic and EUROfusion MST1 experimental campaigns (~50/50%). The rate of failures of the beam is less 5%.

Ion temperatures up to 3.5 keV have been achieved in ELMy H-mode, with a good agreement with ASTRA predictive simulations. The NB enables TCV to access ITER-like β_N values (1.8) and T_e/T_i ~1, allowing investigations of innovative plasma features in ITER relevant ELMy H-mode. The advanced Tokamak route was also pursued, with stationary, fully non-inductive discharges sustained by ECCD and NBCD reaching β_N~1.4-1.7.

Real-time control of the NB power has been implemented in 2018 and presented together with the statistics of NB operation on the TCV. During commissioning, the NB showed unacceptable heating of the TCV beam duct, indicating a higher power deposition than expected on duct walls. A high beam divergence has been found by dedicated measurement of 3-D beam power density distribution with an expressly designed device (IR measurement on tungsten target).

Keywords: TCV tokamak, Neutral Beam Heating, Real-time control, NB modeling

1. Introduction

The Tokamak à Configuration Variable (TCV, R_O≅0.88 m, a≤0.25 m, B_T≤1.54 T) contributes to physics understanding in fusion reactor research by a wide set of experimental tools including: flexible shaping and high power real time-controllable electron cyclotron heating (ECH) system. Plasma regimes with high plasma pressure, a wider range of T_i/T_e ratios and significant fast-ion population are now attainable with the TCV heating system upgrade [1,2].

A 1 MW, 25 keV deuterium heating neutral beam (NB) has been installed in 2015 [3] and operated from 2016 in SPC-TCV domestic and EUROfusion experimental campaigns (~50/50%). The beam features RF driven (<40 kW @ 40 MHz) plasma source whose positive ions are accelerated through a three-electrode multi-aperture ion optical system (IOS). The beam full energy fraction in power is greater than 70% at nominal power. The IOS is designed to provide the beam with elliptical shape (horizontal×vertical divergence of 20×12 mrad (across×along IOS slits)).

NBH allows to widen the operational scenario of TCV reaching T_i/T_e>1 with record T_i of 3.7 keV [4] in H-mode), providing direct momentum input to the plasma and generating a high fast ion fraction for studying wave-particle interaction phenomena of interest for burning plasmas.

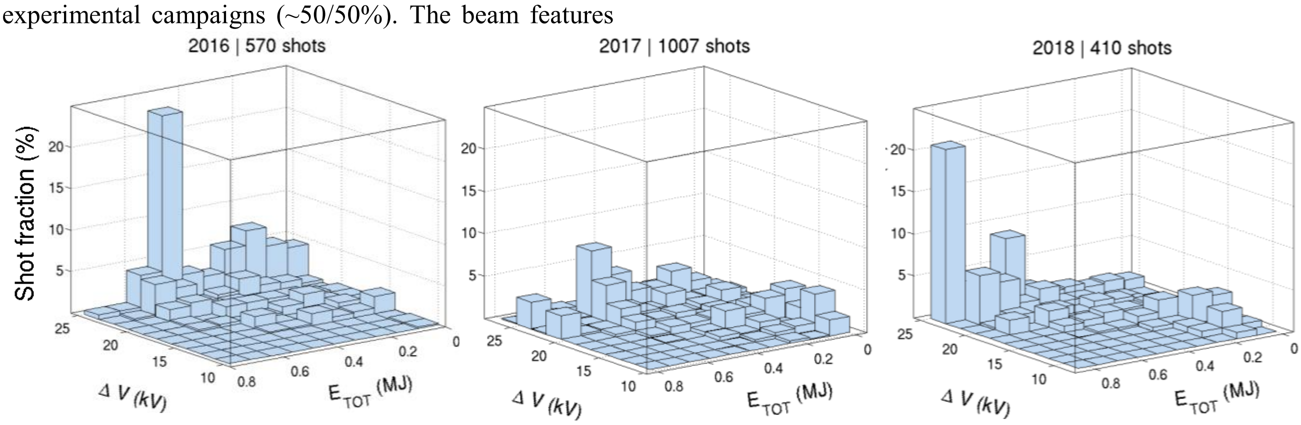

Figure 1 NBH in TCV in the last 3 years: fraction of NB shots vs acceleration voltage ΔV (beam energy) and total energy injected E_{TOT} per shot

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2. NBI operation on TCV

The heating neutral beam was routinely used in TCV experiments, about 30% of TCV discharges (>2000 shots) used NB injection into plasma from the date on NBI installation. Figure 1 shows distributions of NBH shots in TCV, with different beam energy and total injected energy for 3 years of operation.

A neutral power variation in the range of 50 kW…1.05 MW has been implemented on TCV by simultaneous variation of RF power (plasma density in the source) and extraction voltage keeping a minimal beam divergence (Figure 2).

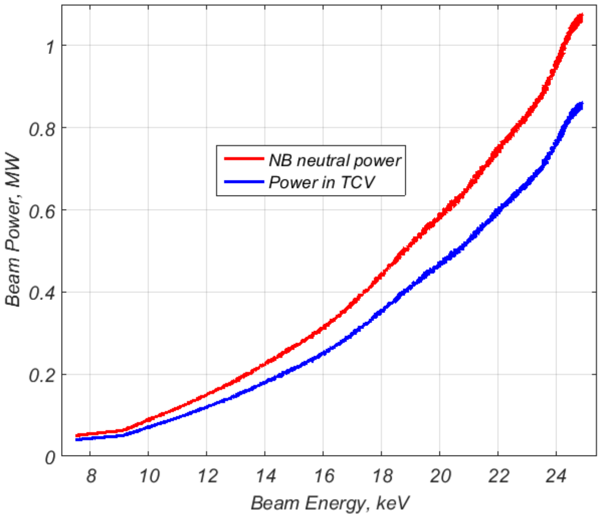

Figure 2 NBI calibration curve: optimal neutral and power in TCV vessel vs energy

The optimisation procedure for the TCV NBI was periodically (1-2 times per year) performed at several (5-8) extraction energies; the optimal beam currents (RF power) were experimentally adjusted to minimise the beam divergence (corresponds a minimum of the beam width on the calorimeter). The voltage on the suppression (2nd) grid and the bending magnet current were also optimised at each power/energy level.

The accurate and time consumptive beam optimization in September 2017 allows to reduce beam power losses in the beam duct and increase duration of 1 MW beam from 0.5 to 0.8 sec per shot, see maximums in Figure 1 for 2016 (0.5 MJ) and 2018 (0.8 MJ) both at 25 keV (and 1 MW).

Significant fraction of NBI shots at low energy/power dedicates to experimental study of power dependences (e.g. L-H mode power threshold), plasma toroidal rotation vs external torque, correlations of fast ion turbulent transport and instabilities vs energy (fast ion velocity), etc.

3. Scenarios with NBH: ELMy H-mode and Advanced Tokamak

The NB injection on TCV allows more flexibility in entering H mode plasmas and provide access to study ITER-relevant scenarios. Specific TCV experimental mission was devoted to establishing a reliable H-mode with Edge Localized Modes (ELM), high density, the maximum attainable P_{sep} and possibly divertor

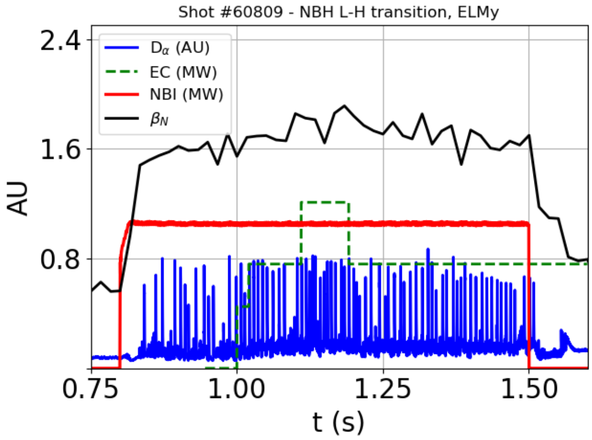

Figure 3 ELMy H-mode plasma with β≈1.8

detachment. H-mode plasmas with $\beta_N \approx 1.8$ were obtained in TCV (see fig. 3). In the shot shown here, NBI results in the L-H transition without using ECRH and the transition back happens only when the beam is turned off.

Advanced tokamak (AT) scenarios on the TCV have been improved in performance thanks to the additional power from the beam [5]. AT looks for fully non-inductive plasmas with high β_N, obtained by optimizing the bootstrap current and the induced current from the additional heating systems. Fig. 4 shows one of the most successful plasmas with these features obtained in MST1

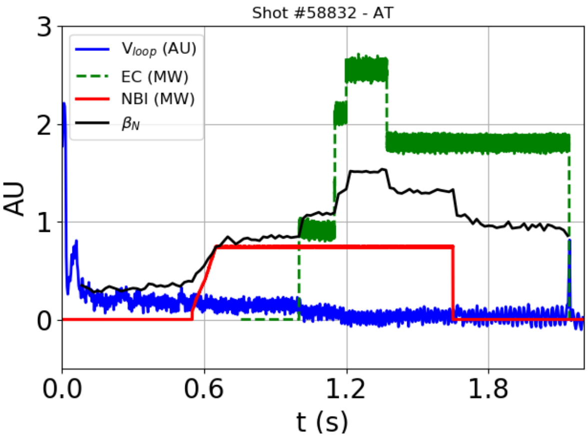

Figure 4 AT scenario with low V_{loop} and high β_N

campaign. Loop voltage (V_{loop}) close to 0 confirms that the current is fully non-inductive. In the AT plasma performed in TCV, according to NUBEAM and ASTRA simulation the beam doesn't contribute much (<50 kA) to the current (V_{loop} doesn't change much when using the beam) but the fast particles contribution to β is clear: at 0.6 s (beam turns on) β almost doubles while it decreases roughly 20% when beam turns off (but ECRH is still on).

Interpretative modelling has been used to understand the behavior of NBI fast particles in TCV [6, 7]. NUBEAM and ASCOT codes have been implemented for TCV with realistic NBI geometry: fig. 5(a) shows the power balance computed with TRANSP for shot 58832 while fig. 5(b) shows the power deposition to the wall (orbit loss of fast ions born in shaded area).

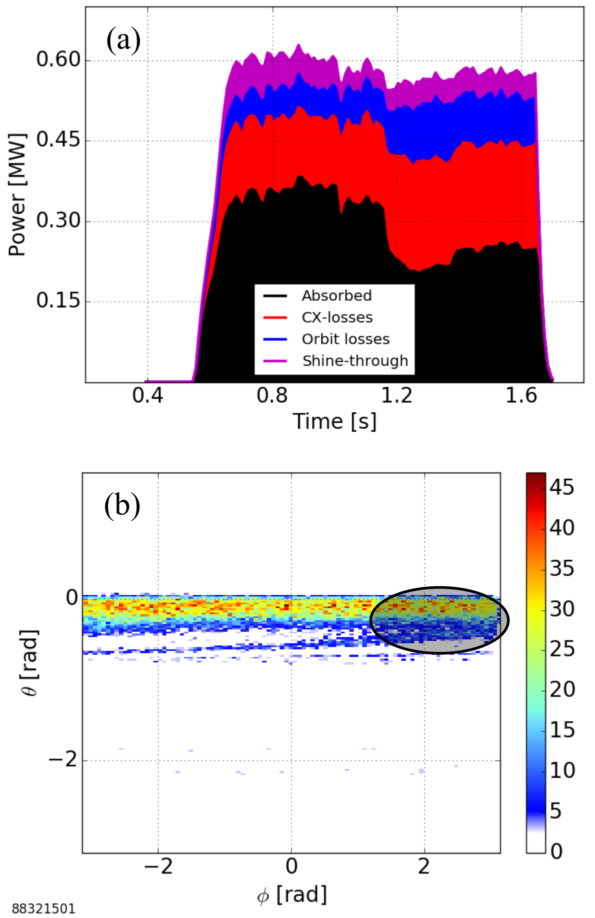

Figure 5 Power balance computed with TRANSP(a) and ASCOT simulation of particles lost to the wall (b)

4. Real-time control of beam power

The neutral beam operation is controlled by an instrumental computer with PCIe National Instruments cards, controlled via LabView. Originally, the binary beam ON/OFF, beam energy, neutral and ion currents time traces were calculated accounting for their dependencies on the desired neutral beam power vs time waveform designed in Matlab; the digital and analog (DACs) control waveforms calculated and uploaded in the FPGA memory of PCIe cards. Following trigger reception, the beam pulse control sequence is executed, and analog and digital control waveforms are transmitted to NBI power supplies.

Power modulation at constant energy [4] is not possible in TCV because the limit in modulation frequency is much higher than the fast ions confinement time (τ≈10ms).

NB control system has been modified in 2017 to implement the possibility of the NB power real time (RT) control from the TCV distributed RT system. Instead of using the pre-calculated analog and digital wave-forms for power supplies they are calculated "on-fly" in FPGA according to the table stored in the FPGA-host shared memory with relations between output DAC signals and selected reference NB power signal. The selection of reference power signal between preprogrammed waveform stored in shared memory (FF) and the reference from the TCV RT system (DAC input) is controlled by logical signal from TCV RT CS.

Furthermore, additional constraints on max/min beam power, slope of power rise/fall (dP/dt) and maximal energy per shot are evaluated in FPGA with 100 µs time resolution.

In figure 5 an example of β real-time control using the beam is shown. The beam reacts to the requested waveforms, and the achieved β is controlled correctly, in particular in L-mode phases.

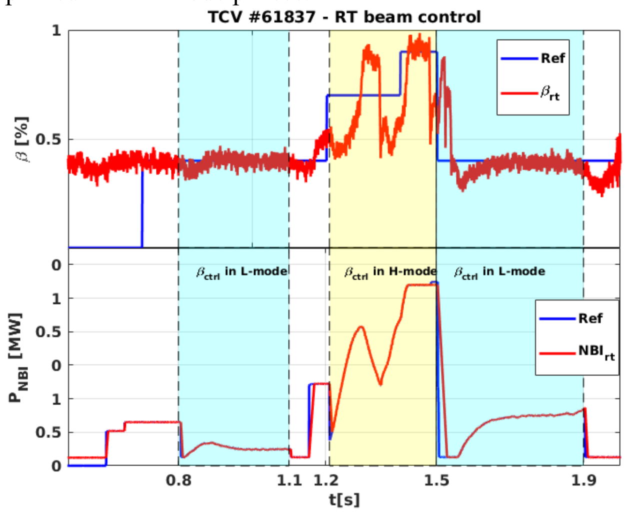

Figure 5 Example of RT control of beam power

5. Beam profile measurement on W target

The NB IOS was designed to extract the beam with divergence ≤20 mrad across and ≤12 mrad along slits with geometrical focusing at 3.6 m. The power losses in the beam duct between exit from injector tank and entering in the TCV vacuum vessel were estimated ≤40 kW for which most of the internal surfaces of the port were expected to remain ≤100^{O}C. The predicted power density profile is shown in fig. 6. However, the commissioning of the NBI showed high overheating of the duct. Thermocouples measurements showed that maximal temperature estimated on the inner surfaces of the duct was ~500°C per 1 MW 2 sec NB shot.

Related to this observation, an in-house built device to assess the 3D power density distribution of the beam in the duct region has been installed (fig. 7). This device featured a 4 mm actively cooled tungsten (W) tile

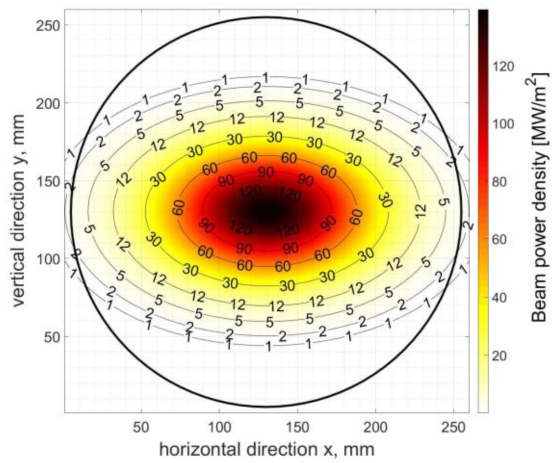

Figure 6 Expected beam power density at duct entrance

inclined 45° with respect to beam to reduce the thermal impact of the power density. An IR camera records the surface temperature. The device could be moved along the beam axis (z) ranging all over the duct.

Measurements on duct entry are shown in figure 8 for different power levels. At maximum power (red line) the profile is perturbed by sputtering of the target. The simulated dimensions are represented by the vertical black lines. The beam profiles radii and aspect ratios are clearly different from the ones foreseen: horizontal dimension of the beam is much greater than the designed one and this causes the unexpected power losses on the beam duct walls, thus the limitation for maximal beam duration. Measured power distribution corresponds to beam divergence 36×8 mrad.

The high beam divergence in horizontal direction is caused by two critical inaccuracies in machining of ion optical system (grids):

- machining inaccuracies of the plasma electrode emission slits;
- discrepancy between the accelerating gap and plasma density profile in the plasma box.

The re-fabrication of IOS is ongoing with the hope to install new grids this year, this allows to extend the duration of 1 MW beam up to nominal 2 sec (2MJ).

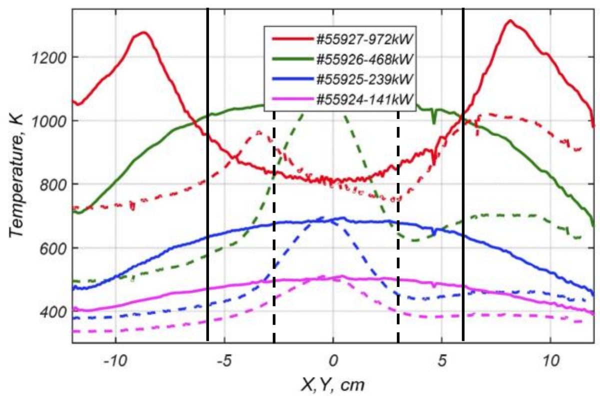

Figure 8 measurements on W tile at maximum perveance on X (solid) and Y (dashed) direction.

5. Conclusions

Experimental capability and flexibility of TCV are significantly extended with installation of neutral beam injector. Further progress of the NBH on the TCV strongly depends on resolving the problem with beam divergence and overheating of the beam duct.

ITER-relevant ELMy H-mode with β_N≈1.8 have been achieved on the TCV with NBH, providing a reference scenario that could widen the studies with high-confinement plasmas. Advanced tokamak scenarios are under study, since NBI allows a higher fraction of non-inductive current and higher β_N values. Plasmas with V_{loop} close to 0 and β_N up to 1.5 have been achieved and H-mode advanced tokamak scenarios will be obtained in next experimental campaign. Nevertheless, modelling tools such as NUBEAM and ASCOT are being interfaced with TCV data for interpretative modelling.

Successful control of β has been achieved with RT control of the beam power. This has been achieved by modifying the beam control system and the agreement between the requested power waveform and the injected power is excellent.

The measurements of 3D power deposition profiles from the beam have been shown. The duct overheating was suspected to be caused by a wrong beam optic and this has been confirmed using in-house built device. It consists of an IR camera looking at a W tile intercepting the beam and measuring its temperature. Using this device, the horizontal size of the beam has been measured to be larger than expected. This limits the maximum energy for NB heating. The reasons below this bad optic lie in a bad manufacture of the acceleration grids, with harmful results for the beam duct.

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References

[1] A. Fasoli for the TCV Team; *TCV heating and in-vessel upgrades for addressing DEMO physics issues*; Nucl. Fusion 55 (2015) 043006

[2] A.N. Karpushov, et al.; *A scoping study of the application of neutral beam heating on the TCV tokamak*; Fusion Engineering and Design, 86 (2011) 868–871

[3] A. N. Karpushov, et al.; *Upgrade of the TCV tokamak, first phase: Neutral beam heating system*; Fusion Engineering and Design 96–97 (2015) 493–497;

[4] A. N. Karpushov, et al.; *Neutral beam heating on the TCV tokamak*; Fusion Engineering and Design 123 (2017) 468–472

[5] C. Piron et al., *Extension of the operating space of high-β_N fully non-inductive scenarios on TCV using Neutral Beam Injection*, submitted for to 27th IAEA Fusion Energy Conference, October 2018, Ahmedabad, India.

[6] B. Geiger, et al.; *Fast-ion transport in low density L-mode plasmas at TCV using FIDA spectroscopy and the TRANSP code*, Plasma Phys. Control. Fusion 59 (2017) 115002

[7] M. Vallar, et al.; *Nonlinear contribution of neutral beam injection in TCV EC-heated advanced tokamak scenarios*, 45th EPS conference on plasma physics, July 2-6, 2018, Prague, Czech Republic; P2.1068

[8] M. Toussaint, et al.; *Estimation of the 3D power density distribution of the 1 MW neutral beam of TCV*; 13th International Symposium on Fusion Nuclear Technology (ISFNT-13), September 25-29, 2017, Kyoto, Japan; P3-026 (PDF)