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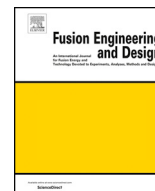
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Status, scientific results and technical improvements of the NBH on TCV tokamak

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ABSTRACT

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 1MW, 25 keV deuterium heating neutral beam (NB) has been installed in 2015 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 than 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 $T_e/T_i \sim 1$, 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 $\beta_N \sim 1.4$ –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).

1. Introduction

The Tokamak à Configuration Variable (TCV, $R_0 \cong 0.88$ m, $a \leq 0.25$ m, $B_T \leq 1.54$ 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 injector features an RF driven (< 40 kW @ 40 MHz) plasma source and 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 \times vertical divergence of 20×12 mrad (across \times along IOS slits)).

Neutral Beam Heating (NBH) has widened 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 large fast ion fraction to study wave-particle interaction phenomena of interest for burning plasmas.

2. NBI operation on TCV

The heating neutral beam was routinely used in TCV experiments:

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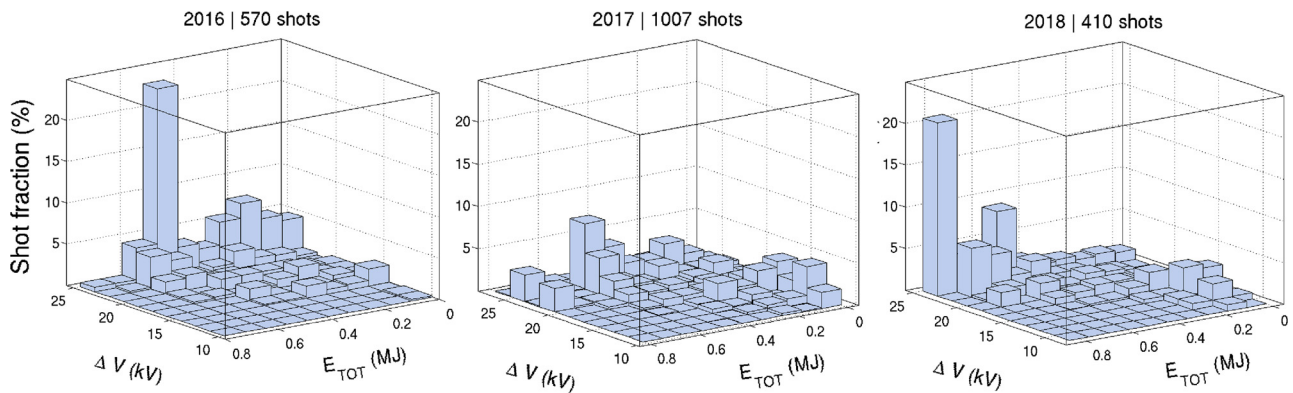


Fig. 1. NBH in TCV in the last 3 years: fraction of NB shots vs acceleration voltage ΔV (beam energy) and total injected energy E_{TOT} per shot.

about 30% of TCV discharges (> 2000 shots) used NB injection into plasma since NBI installation. Fig. 1 shows distributions of NBH shots in TCV, with different beam energy (particle energy) and total injected energy (integral of power over time) 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 (Fig. 2).

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 were experimentally adjusted by tuning the RF power to minimise the beam divergence (corresponding to a minimum of the beam width on the calorimeter – see Section 5). The voltage on the suppression (2nd) grid and the bending magnet current were also optimised at each power/energy level. The accurate and time consuming beam optimization in September 2017 made it possible to reduce beam power losses in the beam duct and increase the safe duration of 1 MW beam from 0.5 to 0.8 s per shot, see maxima in Fig. 1 for 2016 (0.5 MJ) and 2018 (0.8 MJ) both at 25 keV (and 1 MW). The losses in the duct sums up to 15%, being 2% re-ionization losses. A significant fraction of NBI shots at low energy/power has been dedicated to experimental studies of power dependences (e.g. L-H mode power threshold), plasma toroidal rotation vs external torque and correlations of fast ion turbulent transport and instabilities vs energy (fast ion velocity).

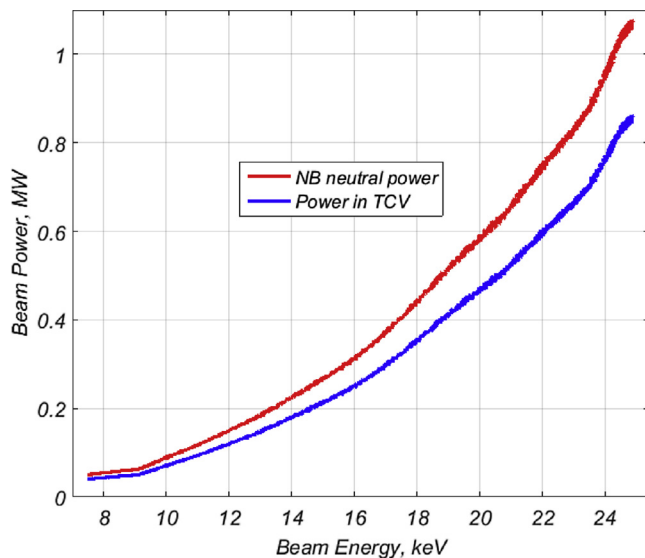


Fig. 2. NBI calibration curve: optimal neutral beam power and power in TCV vessel vs energy.

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

The NB injection on TCV allows more flexibility in entering H mode plasmas and providing access to ITER-relevant scenarios. A specific TCV experimental mission was devoted to establishing a reliable H-mode with Edge

Localized Modes (ELMs), high density, the maximum attainable P_{sep} (power flowing through the separatrix) and possibly divertor 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 a back transition occurs 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]. The targets of AT scenarios are fully non-inductive plasmas with high β_N , which are obtained by optimizing the heating and current drive deposition from the auxiliary heating systems. Fig. 4 shows one of the most successful plasmas with these features obtained in the MST1 campaign. Zero loop voltage (V_{loop}) confirms that the current is fully non-inductive. In the AT plasma performed in TCV, according to NUBEAM and ASTRA simulation the beam does not contribute much (< 50 kA) to the current (V_{loop} doesn't change significantly 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 the 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 58,832: the plasma where NBH is used must be carefully designed to optimize the beam absorption, even if charge exchange losses seem to be a general issue for NBI on TCV also in other conditions [6]; Fig. 5(b) shows the power deposition onto the wall (orbit loss of the fast ions, which are born in

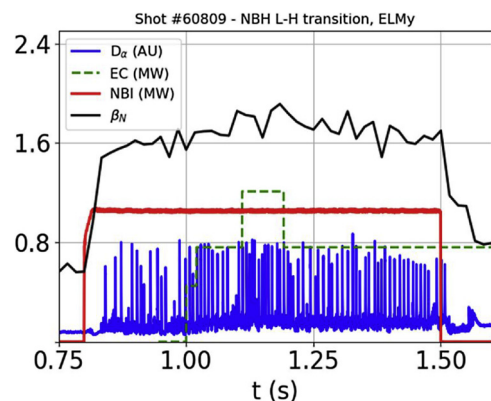


Fig. 3. ELMy H-mode plasma with $\beta \approx 1.8$.

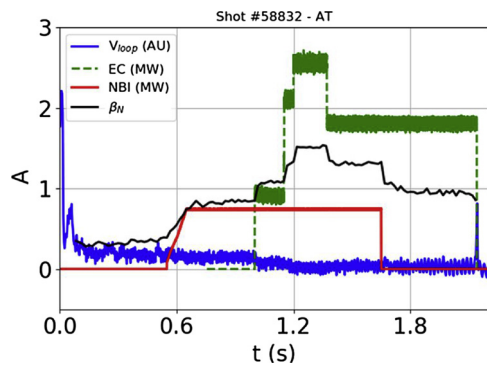


Fig. 4. AT scenario development shot.

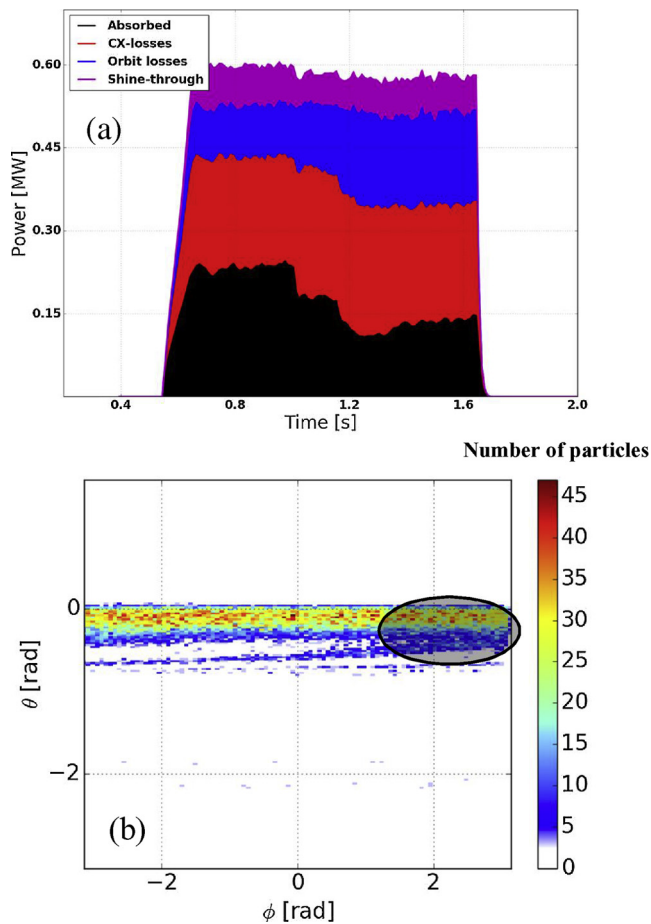


Fig. 5. Power balance computed with TRANSP (a) and ASCOT simulation of particles lost to the wall (b).

shaded area from NBI): the losses are focused on the outer midplane.

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 were then calculated and uploaded in the FPGA memory of PCIe cards. Following trigger reception, the beam pulse control sequence was executed, and analog and digital control waveforms were transmitted to the NBI power supplies.

Power modulation at constant energy [4] is not possible in TCV because the minimum in modulation period is much longer than the fast ions' confinement time ($\tau \approx 10\text{ms}$). This can be done modifying the extracted current at constant voltage, but this modifies as well the beam optics. If the acceleration voltage (consequently the energy) is modified as well, the beam perveance can be kept to optimal conditions.

The NB control system was modified in 2017 to implement 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-the-fly” in FPGA according to the table stored in the FPGA-host shared memory with relations between DAC output 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 $100\ \mu\text{s}$ time resolution. In Fig. 6 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. This test had some problems in the control algorithm (not related to the beam control), but further experiments are ongoing.

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 the TCV vacuum vessel were predicted to be ≤ 40 kW for which most of the internal surfaces of the port were expected to remain $\leq 100^\circ\text{C}$. The predicted power density profile is shown in Fig. 7. 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 $\sim 500^\circ\text{C}$ per 1 MW 2 s 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. This device featured a 4 mm actively cooled tungsten (W) tile inclined 45° with respect to the 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 the duct entry are shown in Fig. 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 design values: the horizontal dimension of the beam is much greater than planned and this causes the unexpected power losses on the beam duct walls, thus the limitation for maximal beam duration. The measured power distribution corresponds to a beam divergence 36×8 mrad.

The high beam divergence in the 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, to allow extending the duration of 1 MW beam up to nominal 2 s (2 MJ).

6. Conclusions

The experimental capability and flexibility of TCV have been significantly extended with the installation of a neutral beam injector.

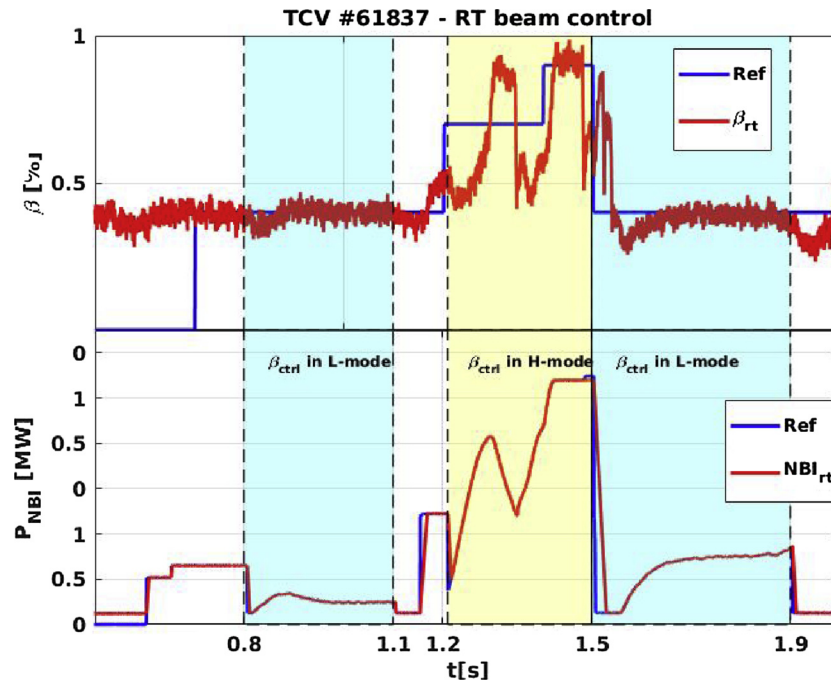


Fig. 6. Example of RT control of beam power.

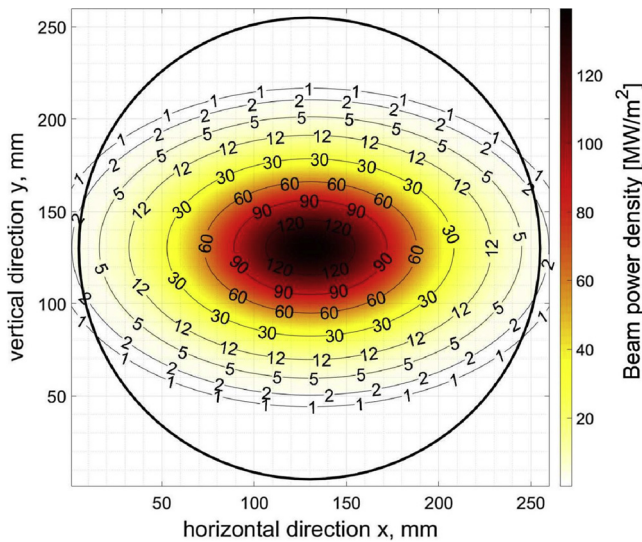


Fig. 7. Expected beam power density at duct entrance.

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 $\beta_N \approx 1.8$ has been achieved on the TCV with NBH, providing a reference scenario that could widen the studies of 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 attempted and H-mode advanced tokamak scenarios will be obtained in next experimental campaign. 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. Measurements of 3D power deposition profiles from the beam have been shown. The duct overheating was suspected to be caused by defective beam optics and this has been

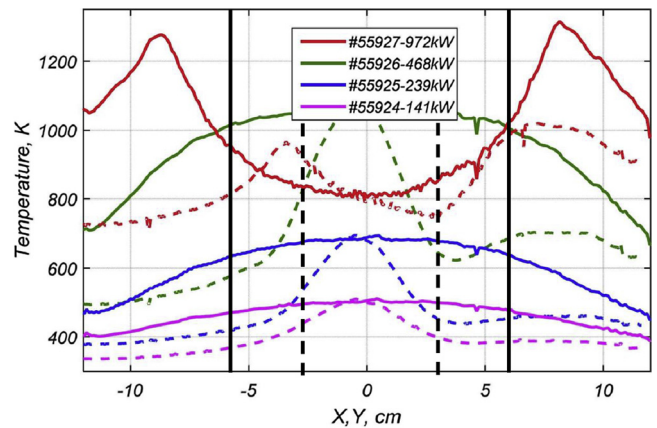


Fig. 8. Temperature measurements on W calorimeter at optimum perveance along X (solid) and Y (dashed) direction.

confirmed using an 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 cause of the defective bad optics is imprecise manufacturing of the acceleration grids.

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