Validation of RAPTOR simulations on the first NBI-heated L-mode TCV plasmas with Internal Transport Barriers

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Tokamak plasmas with Internal Transport Barriers (ITBs) can attain a high fraction of bootstrap current and improved confinement [1]. This scenario is attractive for the contemporary thermonuclear fusion research, whose main objective is the fully non-inductive operation of high performance plasmas. In this work we investigate for the first time on Tokamak à Configuration Variable (TCV) [3] the impact of the newly available 1MW Neutral Beam Injector (NBI) [2] on the performance and stability of the so-called Improved Central Electron Confinement (ICEC) scenario [5, 6]. In these L-mode plasmas an electron ITB is built up by injecting on-axis Electron Cyclotron Current Drive (ECCD) in the counter-Ip direction. The resulting hollow or very flat plasma current density profile is known to play a crucial role in the formation and sustainment of the transport barrier [4].

The plasmas that are analysed here are in limiter configuration with the magnetic axis aligned with the NB port in order to enable an on-axis power injection in the co-Ip direction. The NB energy injection is limited to 0.5MJ by provisional operational constraints. Within this limitation and in presence of a weak eITB, i.e. with the normalized temperature gradient R/L_{Te} being 2.5 times the corresponding value during the Ohmic phase, the NBI is observed to double the ion temperature, which remains half of the electron one, to slightly peak the electron density in the core, whose profile is not correlated with the electron temperature one [7], and to induce a noticeable toroidal torque in co-Ip direction. This evidence is documented in Fig. 1, which compares a) the electron temperature (T_e), b) the ion temperature (T_i), c) the electron density (n_e) and d) the toroidal rotation velocity profile of a plasma with Ip≈130kA, B_t≈1.4T, $n_{e,0}$≈1.7 10^{19}m^{-3} in three different heating phases: the Ohmic one (in blue), the on-axis injection of P_{EC}≈[1.6, 0.5]MW in the counter-Ip direction (in magenta and red) and the addition of P_{NB}≈0.5MW in the co-Ip direction (in green). The profiles are measured with a,c) the Thomson Scattering (TS) and b, d) the Charge Exchange Recombination Spectroscopy (CXRS) diagnostics, respectively.

The investigated plasmas do not suffer any disruptive MHD activity, nonetheless β_N collapses occur with high reproducibility when plasma triangularity exceeds a critical threshold ($\delta \gtrsim 0.3$). The on-axis co-Ip NBCD injection is also observed to have a detrimental effect on the sustainment of the eITB, since it tends to lower the core q-profile [8]. This evidence is confirmed by 1D transport simulations that are performed with RAPTOR [9], that is used here as a plasma profile simulator. This control-oriented code provides the time evolution of the plasma profiles, by solving two coupled partial differential equations for the poloidal flux and the electron temperature. The equilibrium reconstruction code LIUQE provides the magnetic equilibrium to RAPTOR. The ECH/CD deposition is calculated using the Toray-GA ray-tracing code, while the NBH/CD profiles are modelled as Gaussians with fixed current drive efficiency per unit power, which is tuned to match the time evolution of the measured loop voltage. Transport is modelled using a closed-form expression for the heat diffusivity χ_e [10], which includes an empirical term to simulate the decrease in thermal transport in low-shear regions in the core of the plasma, the bootstrap current with the Angioni-Sauter model [11] and the sawtooth instability with the Porcelli's model [12]. The time evolution of both n_e and T_i is obtained from the TS and the CXRS measurements, respectively. The results of a RAPTOR predictive simulation for a NBI-heated ICEC plasma, where we

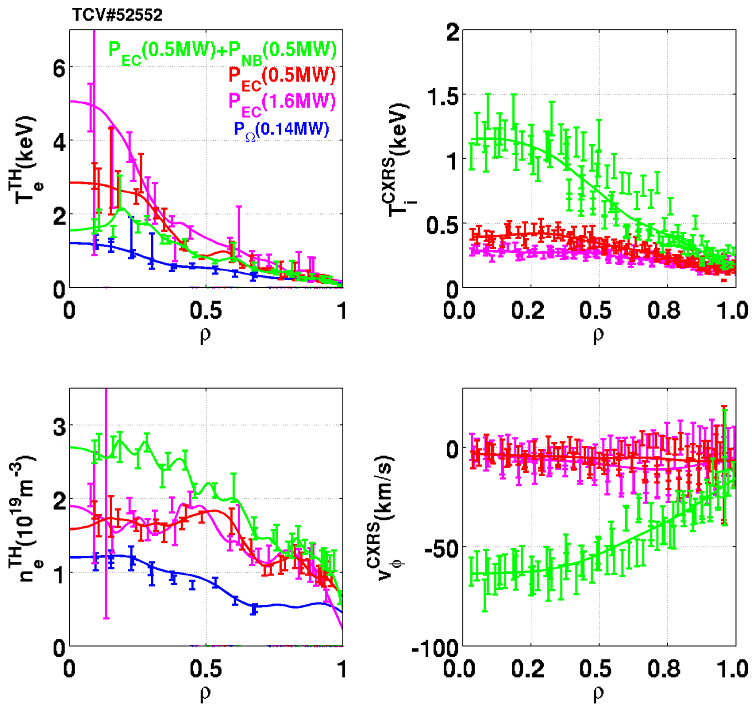

Fig.1 *Effect of the Neutral Beam Injection (NBI) on a) the electron temperature, b) the ion temperature, c) the electron density and d) the rotation velocity in the toroidal direction of a TCV plasma with Ip = 130kA, on-axis counter-Ip P_{EC}=[1.6, 0.5]MW and on-axis co-Ip P_{NB}=0.5MW. The profiles correspond to the following H/CD sequence: P_Ω (blue), P_{EC} (magneta and red) and $P_{EC}+P_{NB}$ (green).*

achieved the highest normalized beta ($\beta_N \gtrsim 1.5$), are summarized in Fig. 2. The frame on the left compares the simulated (red) and the experimental (blue) time evolution of a) the plasma current, b) the auxiliary powers ($P_{EC}\approx$1.7MW (red) and $P_{NB}\approx$1MW (green)), c) the loop voltage, d) T_e, e) βN and f) the electron energy confinement time. On the right, we report g) the q-profile at t≈0.9s that is simulated by RAPTOR (black solid line) and the one reconstructed by LIUQE (empty black circles), using magnetic measurements and the diamagnetic loop to constrain the total energy. The slightly reversed q-profile simulated by RAPTOR results from the combination of the different current density components, i.e. Ohmic (magenta), EC (red), NB (green) and the bootstrap current (blue)), which sum up to a total hollow current density profile (dash-dotted black line). The corresponding simulated (red) and measured (blue) electron pressure profile is reported in h) together with the heat diffusivity, which is in good agreement with the one given in [5].

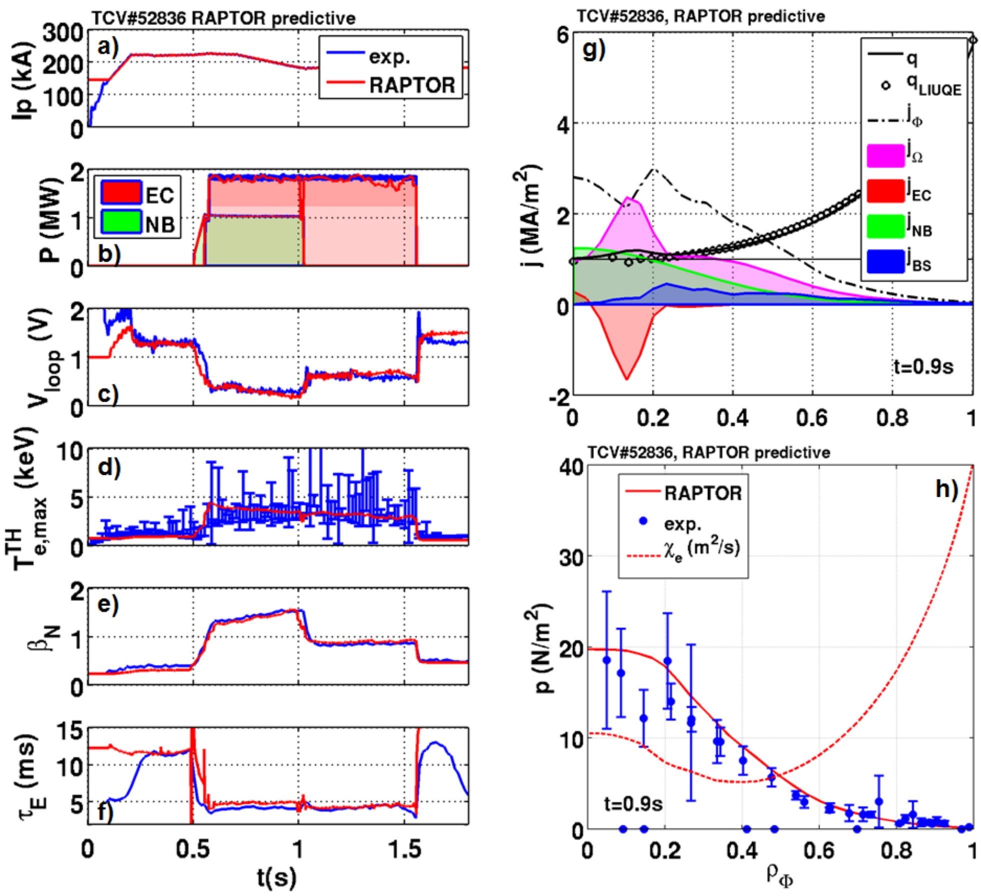

Fig.2 *Validation of a predictive RAPTOR simulation (red) of a TCV NBI-heated L-mode plasma (experimental data in blue). On the left, time evolution of a) the plasma current, b) the PEC=1.7MW (red) and PNB=1MW(green), c) the loop voltage, d) the electron temperature, e) the normalized beta and f) the electron energy confinement time. On the right, g) Ohmic (magenta), EC (red), NB (green), bootstrap (blue) and total (dash-dotted black line) current density profiles and the resulting reversed q-profile (solid black line) simulated by RAPTOR at t=0.9s. The q-profile is compared with LIUQE one (black circle). h) Experimental (blue) and RAPTOR (solid red line) electron pressure profile at t=0.9s and the corresponding* χ_e *profile (dashed red line).*

In this work we also apply for the first time the RAPTOR code to predictive transport simulations for DEMO1 (2015) plasmas, which are designed to be heated by ≈50 times higher EC and NB power compared to typical TCV plasmas. In Fig.3 the a) T_e and b) q-profile at t=500s simulated by RAPTOR predictive (red) are compared to METIS [13] (blue) and ASTRA [14] (green). The results of the first two codes are in relative better agreement than with the ASTRA results, for which a more systematic investigation is required for a complete benchmark. As future developments of this work, we plan to extend the benchmark of RAPTOR predictive with ASTRA both for the TCV plasmas that are presented here and for the latest DEMO1 scenario, whose design is being currently updated. Predictive RAPTOR simulations are also foreseen in view of the 2017 MST1 campaign in support of the development of fully non-inductive scenarios on TCV towards higher $\beta_N \gtrsim 2.5$ and/or stationary or quasi-stationary operation.

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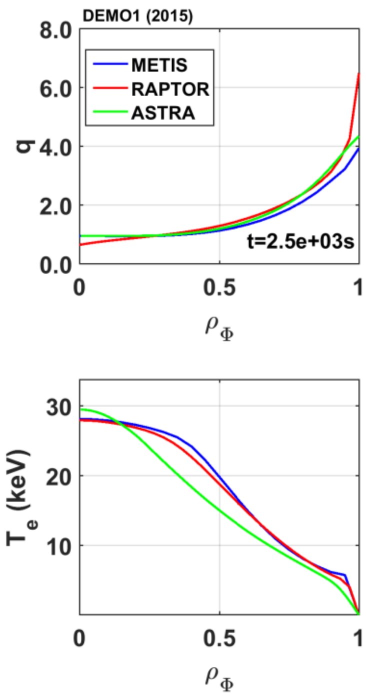

Fig.3 *Benchmark of the a) electron temperature and b) the q-profile of a DEMO1(2015) plasma simulated by METIS (blue), RAPTOR (red) and ASTRA (green).*

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