Topic: EX-C

Non-inductive high-performance discharges on TCV on the path to steady state

S. Coda[1], C. Piron[2,3], F. Auriemma[3], I. Voitsekhovitch[4], L. Cordaro[3], M. Podestà[1], M. Agostini[3], S. Garavaglia[5], A. Jardin[6], M. La Matina[3], D. Mazon[7], A. Moro[5], A. Pau[1], O. Sauter[1], M. Ugoletti[3], the TCV team[8], and the EUROfusion Tokamak Exploitation team[9]

[1]Ecole Polytechnique Fédérale de Lausanne, Swiss Plasma Center (EPFL-SPC), 1015 Lausanne, Switzerland
[2]ENEA, Fusion and Nuclear Safety Department, C. R. Frascati, Via E. Fermi 45, 00044 Frascati (Roma), Italy
[3]Consorzio RFX – ISTP CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA, I-35131 Padova, Italy
[4]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, United Kingdom
[5]ISTP-CNR, via R. Cozzi 53, 20125 Milano, Italy
[6]Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN), PL-31-342, Krakow, Poland
[7]CEA, IRFM, F-13108 Saint Paul Lez Durance, France
[8]See author list of B.P. Duval et al 2024 Nucl. Fusion **64** 112023
[9]See author list of E. Joffrin et al 2024 Nucl. Fusion **64** 112019

E-mail: stefano.coda@epfl.ch

An extended experimental effort is underway on the TCV tokamak to develop scenarios compatible with long-pulse operation, featuring mostly non-inductively driven current – preferably with a large fraction of bootstrap current. A closely related goal is to achieve good plasma performance, typically measured through the normalized beta β_N. This paper reports on the remarkable progress achieved in the last campaign, featuring an extensive set of discharges sustained over multiple current redistribution times with zero flux contribution from the central solenoid (CS), and approaching stationary conditions with β_N~2 and ion temperature (T_i) of the same order of magnitude as the electron temperature (T_e). With increased heating being added in 2025, there is now a realistic prospect of a fully stationary, high-β_N, fully non-inductive NBI-heated scenario.

This work is part of a broader endeavor involving several European tokamaks, and aimed in part at preparing advanced scenarios for the new JT-60SA tokamak [1], which is the largest such device ever operated and has these scenarios at the core of its mission.

TCV is a conventional-aspect-ratio, mid-sized (R/a=0.88/0.23 m) tokamak, equipped at present with three electron-cyclotron resonance heating (ECRH) sources, one delivering 0.7 MW in the 2nd harmonic X-mode (X2), and two delivering up to 0.95 MW each in either X2 or X3, through three separate launchers. TCV has an extensive history of steady-state, fully non-inductive discharges with the current driven by X2 electron-cyclotron current drive (ECCD) and bootstrap current. A subset of these shots featured electron internal-transport barriers (eITBs), featuring a reverse-shear profile with a non-monotonic safety factor. This family of discharges relied entirely on electron heating before TCV was equipped with ion heating in the form of neutral beam injectors (NBI) and therefore T_e was invariably much larger than T_i [2].

The addition of NBI to TCV (now two counter-directed beams of up to 1.3 MW each) has opened up a sizable research avenue involving directly reactor-relevant H-mode scenarios with comparable ion and electron temperatures. These NBI-heated scenarios run the gamut from literal ITER-baseline scenarios [3] to more exploratory ones and are the higher-performance extension of a sprawling earlier research line on Ohmic H-modes.

Merging T_e~T_i with non-inductive conditions has been seen as a quest to merge the two scenarios described above, which has accordingly been alternately pursued by starting from one or the other, with the expectation of a unified eventual asymptote. The examination of earlier partial successes has resulted in an increased emphasis on the non-inductive element.

Earlier attempts had highlighted a peculiar difficulty inherently caused by the TCV constitutive parameters, namely, that a narrow range is available to advanced tokamak scenarios – in particular in density (if too high, as often caused by NBI fueling, ECRH-X2 is cut off; if too low, both NBI coupling and equipartition are weakened, driving T_e well above T_i). A significant component of this experimental endeavor was then achieving good density control, as well as adjusting the timing of the different heating sources – a related task, as this also strongly affects density. Helpful guidance was given by interpretative and predictive transport modeling, primarily with the ASTRA and TRANSP codes, in particular to avoid the establishment of a current hole in the plasma core.

In most of the discharges discussed in this paper, the CS was clamped to a constant current soon after the beginning of the designed flat top, i.e., after all the heating sources were applied. Any remaining loop voltage would then be small, supplied by whatever non-stationarity remains, i.e., from the time variation of the plasma current and of the currents in the poloidal-field coils involved in the vertical and radial real-time control. Empirically, we have established that good performance and good non-inductive current sustainment require the three existing ECRH beams to be employed for off-axis co-ECCD. Repurposing one beam to heat the center invariably causes an excessive loss in driven current, negating the advantage provided by injecting heat in the highest-confinement region.

One line of inquiry sought to establish the non-inductive conditions early on, with reverse central shear, and adding NBI later. With one ECRH source directed to central heating, this resulted in electron temperatures in excess of 10 keV in some cases, accompanied by β_N values of order 2, but only in the ECRH-only phase. With NBI, a progressive degradation of confinement and performance is observed over time, reducing β_N to ~1. These are, essentially, revisitations of the eITB scenario, failing to lift the ion temperature and maintain the transport barrier at the same time.

A more balanced application of NBI and ECRH yielded far more promising results in the cases in which density could be controlled within the narrow useful range. Empirically, it was found that, all other factors being equal, beam 2 (NBI-2) at 50-60 keV, injected in the counter-current direction, was better than co-current NBI-1 (20-25 keV) in sustaining high β_N with less virulent MHD activity. This result is not readily understood and is a current object of theoretical investigation. In practice, best results were obtained by injecting both NBI-1 and NBI-2, with an asymptotic, semi-stationary β_N=2 reached during a density rise driven by beam fueling, accompanied by a slow plasma-current descent (Fig. 1). Neither the density nor the temperature profile features a strong barrier, although local increases in gradient are observed both at mid-radius and near the plasma boundary. Consequently, the bootstrap current fraction remains modest, at below 30%. Also, while T_i/T_e rises during the NBI phase, is still does not exceed ~30%.

This is where this campaign had to stop, but the result points to the possibility of making the scenario more stationary by engineering a slightly higher earlier density by gas puffing, which is then gradually replaced by beam fueling. Even more significantly, the fact that the available ECRH power is entirely devoted to scenario sustainment through off-axis co-ECCD strongly suggests a great potential in adding a fourth ECRH source to heat the center of the high-confinement region – which could increase β_N significantly without an excessive increase in T_e/T_i. Such a fourth source will become available on TCV in the latter part of 2025. The MHD stability of such a scenario, of course, remains to be determined, as does the possibility of producing steeper gradients and a larger bootstrap component. The option of using X3 heating remains unexplored. Modeling is expected to be instrumental in suggesting optimized discharge trajectories.

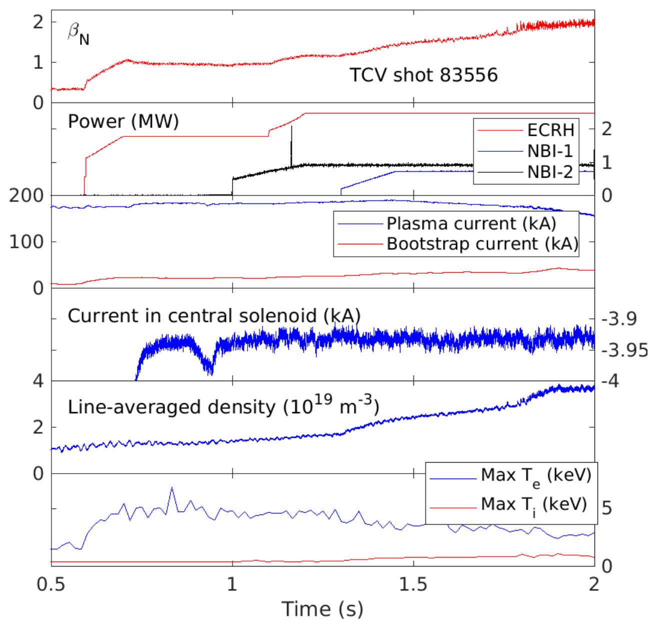

Figure 1. Time traces of relevant quantities for TCV shot 83556.

[1] G. Giruzzi et al, Plasma Phys. Control. Fusion **62**, 014009 (2020).
[2] S. Coda et al, Phys. Plasmas **12**, 056124 (2005).
[3] B. Labit et al, Plasma Phys. Control. Fusion **66**, 025016 (2024).