Experiments and gyrokinetic simulations of TCV plasmas with negative triangularity in view of DTT operations

A. Balestri[1], P. Mantica[2], A. Mariani[2], F. Bagnato[1], T. Bolzonella[3], J. Ball[1], S. Coda[1], M. Dunne[4], M. Faitsch[4], P. Innocente[3,5], P. Muscente[3,6], O. Sauter[1], M. Vallar[1], E. Viezzer[7,8], the TCV team[9] and the Eurofusion tokamak exploitation team[10]

[1] *Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), 1015 Lausanne, Switzerland*
[2] *Istituto per la Scienza e la Tecnologia dei Plasmi, CNR, 20125 Milan, Italy*
[3] *Consorzio RFX (CNR, ENEA, INFN, UNIPD, Acciaierie Venete SpA), Padova, Italy*
[4] *Max Planck Institute for Plasma Physics, Garching, Germany*
[5] *Istituto per la Scienza e Tecnologia dei Plasmi, CNR, Padova, Italy*
[6] *Centro di Ateneo "Centro Ricerca e Fusione", Padova University, Italy*
[7] *Dept. of Atomic, Molecular and Nuclear Physics, University of Seville, 41012 Seville, Spain*
[8] *Centro Nacional de Aceleradores CNA (Universidad de Sevilla, Junta de Andalucía, CSIC), 41092 Seville, Spain*
[9] *See H. Reimerdes et al 2022 Nucl. Fusion 62 042018.*
[10] *See E. Joffrin et al 2024 Nucl. Fusion.*

Introduction

In the past three decades, experiments on TCV [1] have shown that NT plasmas have a reduced level of turbulent transport which enables sustaining enhanced gradients at the same injected power of a Positive Triangularity (PT) L-mode (Low confinement mode). With more recent additional contributions from DIII-D [2] and ASDEX Upgrade [3], it has also been shown that NT plasmas have a higher power threshold for transitioning from L- to H-mode. These findings have been corroborated by many numerical simulations made possible by the rapidly increasing computational power available. This combination of features makes a NT plasma able to achieve H-mode-like core pressure levels with L-mode-like edge pressure profiles, guaranteeing an ELM-free scenario with high performance.

The Divertor Tokamak Test facility (DTT) [4], a novel superconducting tokamak under construction in Frascati (Italy), is designing a NT option already in the early phase of operation. Preliminary numerical modeling and experiments in presently working tokamaks are key to investigating the feasibility and performance of this scenario. The present work is performed within this framework and has two main goals. First, to replicate on TCV (Tokamak à Configuration Variable) plasmas with the PT and NT shapes (suitably rescaled) foreseen for DTT's operation and to heat them with different heating mixes to test the resilience of the beneficial effect of NT. Second, the experimental data have been used as input for integrated modeling performed with the codes ASTRA [5] and TGLF [6] and gyrokinetic simulations performed with GENE [7]. The main goals of this numerical effort were to to address the capabilities of these tools to correctly capture the impact of geometry, in order to validate them for DTT predictions and to understand better the physics underlying the beneficial effect of NT on confinement.

Experimental set-up and results

The unique plasma shaping capabilities of TCV make this tokamak one of the best environments to test the PT and NT shapes envisioned for DTT. Figure 1 shows the radial penetration of the upper triangularity (δ^{up}), lower triangularity (δ^{low}) and the average of the two (δ^{avg}). The elongation is kept fixed at a value of $\kappa = 1.6$. The values of triangularities show that NT is not up-down symmetric and has a slightly positive lower triangularity, making the absolute value of δ^{avg} lower than the PT counterpart. The motivation for this peculiar *teardrop* shape is the mechanical constraints imposed by DTT's vacuum vessel. Different heating mixes, namely Neutral Beam Injection (NBI), Electron Cyclotron Resonance Heating (ECRH)

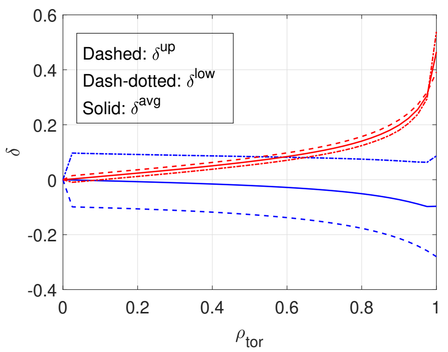

Fig. 1 Radial penetration of lower and upper triangularity for the NT (blue) and PT (red) shapes produced on TCV as functions of the normalized radial coordinate.

and NBI+ECRH have been applied. Moreover, to make a thorough comparison, within a fixed heating mix, three scenarios have been considered: a NT-PT L-mode pair with the same injected power and a higher power PT H-mode scenario.

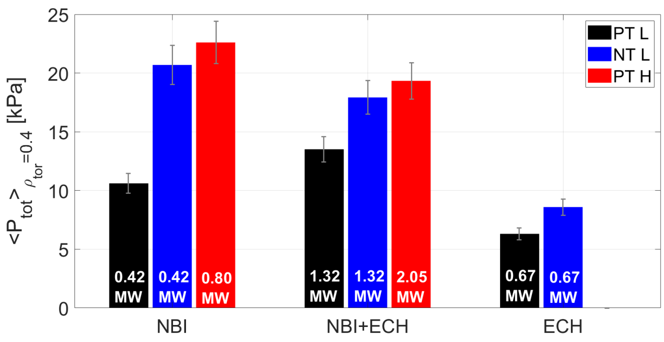

Fig. 2 Volume averaged core total plasma pressure for different heating mixes. NT in blue, PT L-mode in black and PT H-mode in red. The white writings at the bottom are the injected power for each scenario.

The comparison between L-modes is very useful to isolate and observe by what amount confinement and kinetic profiles are improved by a reduction of turbulent transport. On the other hand, the comparison of NT with PT H-mode is the most relevant one for a reactor. Indeed, the target of a NT reactor is producing an ELM-free plasma with the same fusion gain of an H-mode plasma, i.e. with the same central values of plasma pressure. Figure 2 shows the ratio of the volume-averaged total plasma pressure in the core (i.e. $\rho_{tor} = [0, 0.4]$) between NT and PT L-mode or NT and PT H-mode. Regardless of the heating mix, we observe that NT can recover the same value of central plasma pressure of the PT H-mode cases without any pedestal and largely overcome the one of the PT L-mode cases. The reasons why NT can reach the same core values of pressure of the PT H-mode cases can be found by comparing the kinetic profiles of NT with respect to the PT L-mode counterparts. We identify two main factors. First of all, the better confinement with respect to the PT L-mode counterpart allows NT to sustain logarithmic gradients that are on average 1.2 times larger then PT L-mode ones in the edge region (i.e. between $\rho_{tor} = [0.85 - 1.0]$). Additionally, we observe larger values of electron density and temperature at the separatrix because steeper gradients in the Scrape-Off Layer (SOL).

Gyrokinetic simulations

In this section, we present the results of flux tube gradient-driven gyrokinetic simulations performed with GENE. The available computational resources allowed us to simulate only the NBI-only NT L-mode and PT L-mode cases. To correctly model the up-down asymmetric NT DTT shape, we used the numerical reconstruction made by tracer-efit and we performed all the simulations at $\rho_{tor} = 0.95$. We chose this radial location because here the strength of triangularity is still large and because at this location we still have a significant difference in the gradients between NT and PT. All the simulations tried to achieve a high level of realism retaining the effect of collisions modeled with a linearized Landau operator, carbon as the main impurity and electromagnetic effects. To isolate the impact of geometry, we performed additional modeling by keeping the kinetic parameters fixed and changing the geometry, i.e. swapping NT and PT shapes.

With linear simulations, we identified temperature-driven Trapped Electron Mode (TEM) turbulence as the dominant type of turbulence. With nonlinear simulations, we investigated transport stiffness (i.e. the quantity that

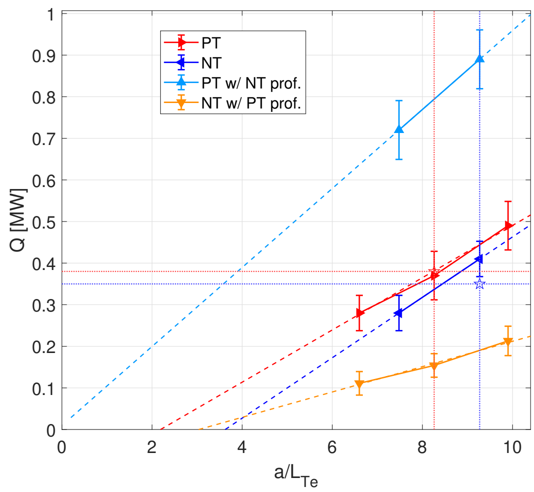

Fig. 3 Electron heat flux as a function of the logarithmic electron temperature gradient a/L_{Te}. The dashed lines are extensions of the solid lines to find the intercept with the x-axis. The dotted blue and red horizontal lines are the experimental heat fluxes, while the vertical ones are the experimental gradients of PT (red) and NT (blue). The stars represent the points where the vertical and horizontal lines meet.

describes how much a variation in the gradients affects the heat flux). Given that all the scenarios are TEM-dominated, we carry this study out by changing the electron temperature gradient. Studying the stiffness of transport is extremely important if we want to identify the trend that links the heat flux to the gradients. Figure 3 shows the results of this exercise. First, we can compare NT (blue line) with PT (red line). We can see that the two lines have similar slopes, but different critical gradients (i.e. the value of gradient for which turbulence starts to be destabilized and the heat flux is nonzero). Indeed, as observed in experiments, we can see that for a given value of heat flux, the electron temperature gradient will be increased by 12% in NT. This behaviour reflects the stabilizing effect of NT. Once again, since many parameters are changing between the NT and PT *self-consistent* cases, we can compare the blue line (NT) with the light blue line (PT with NT profiles), and the red line (PT) with the orange line (NT with PT profiles). The slopes of the two curves are equal and only the critical gradients are increased going from PT to NT. Therefore, if we were able to perform a perfect match of all the parameters between NT and PT, we would be able to produce a NT plasma that has an electron gradient increased by 56% with respect to a PT plasma produced with the same heating power. Similar observations can be made if we compare the red and orange lines. We conclude that the effect of NT geometry is stabilizing on turbulent transport and allows a NT plasma to achieve larger gradients, and, thus, better performance than PT.

Integrated modelling

In this section, we show the results of integrated modeling performed with the transport code ASTRA coupled with the quasilinear model TGLF-SAT2 to predict particle and heat turbulent fluxes.

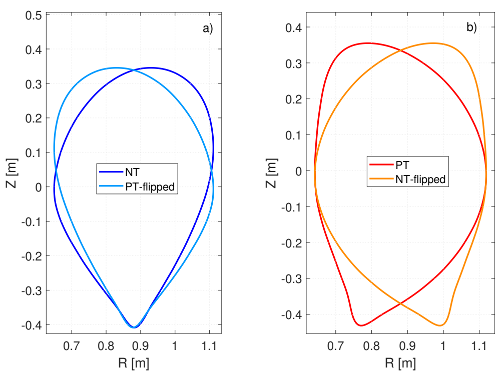

Fig. 4 Shapes of the LCFSs seen by ASTRA. In blue and red are the NT and PT realistic cases respectively, in light blue and orange the artificially mirrored versions.

As we did with GENE, we simulated the NT and PT L-mode NBI-only cases. Moreover, to isolate the effect of shaping seen by ASTRA-TGLF we ran two additional simulations where boundary conditions (i.e. values of T_e, T_i and n_e at the separatrix) and the heat and particle sources were kept fixed, while only the shape of the LCFS was mirrored along the vertical axis to flip the sign of triangularity. The case with a shape flipped from NT up-down asymmetric shape will be called PT-flipped. The one with the flipped shape from PT up-down symmetric shape will be called NT-flipped. The LCFSs are pictured in figure 4. Figure 5 shows the total plasma pressure predicted by ASTRA-TGLF for the four scenarios. We observe that ASTRA-TGLF can predict quite well the pressure of the PT case (red) and underestimates the pressure of the NT one (blue), thus underestimating the beneficial effect of NT. We can understand this behaviour by comparing the pairs PT/NT-flipped and NT/PT-flipped. Although the flipped shape, NT (blue) and PT-flipped (light blue) have no difference in the total pressure. On the contrary, if we compare PT (red) with NT-flipped (orange), we can notice a large increase of total pressure across the whole plasma radius in the NT-flipped case.

To better comprehend these results, clarification is needed about the parametrization of the magnetic equilibrium in ASTRA and TGLF. In ASTRA the LCFS shape is specified numerically by the user and all the other flux surfaces are computed consistently by solving Grad-Shafranov and current diffusion equations. Therefore, the equilibrium is very close to the realistic one. By contrast, TGLF uses the local Miller equilibrium analytical model to specify the geometry, which exploits a Mercier-Luc formalism to perform a radial expansion of a given flux surface and assumes up-down symmetry.

Therefore, an up-down asymmetric shape like the highly up-down asymmetric DTT NT shape will be badly parametrized by Miller local equilibrium and the effective triangularity greatly decreased. On the contrary, since PT is up-down symmetric, the parametrization is satisfactory and the actual shape is preserved. We can draw the following conclusions. First, ASTRA-TGLF is able to catch the effect of geometry and can predict a beneficial effect coming from NT. However, this effect is caught only when triangularity is sufficiently large, which is the case for the NT-flipped scenario. Instead, ASTRA-TGLF is not able to predict a difference between NT and PT-flipped because the parametrization of geometry is poor in TGLF and the effect of shaping is greatly reduced. Second, we can conclude that the mild beneficial effect that ASTRA-TGLF was able to capture in the *self-consistent* cases was only due to different boundary conditions (i.e. larger values of temperature and density at the LCFS in the NT scenario) and different heating profiles used as inputs.

Conclusions

In this work, we carried out an experimental and numerical investigation of different scenarios foreseen for the DTT tokamak. On TCV, we produced pulses with the rescaled shapes foreseen for the PT and NT full-power operations of DTT and we heated them with different heating mixes. In all the experiments we saw a net beneficial effect arising from NT geometry. NT discharges were able to reach the same values of total plasma pressure of the PT H-mode scenarios in the core (between $0 \leq \rho_{tor} \leq 0.4$) *without any ELMs and half the injected power* and greatly overcome the ones of PT L-mode counterparts. This is due to increased temperature and density gradients at the edge of the plasma and to larger values of temperature and density at the LCFS due to larger gradients in the SOL.

GENE local nonlinear GK simulations at $\rho_{tor} = 0.95$ were able to reproduce the experimental results. Studying the stiffness, we observed a 10% increase in the critical temperature gradient, which leads, in agreement with experiments, to enhanced plasma performance. This behaviour is due to a reduction of TEM turbulence. Moreover, by artificially swapping the PT and NT shapes while keeping the kinetic parameters fixed, we saw that part of the improvement is just due to geometry. Integrated modeling performed with ASTRA-TGLF reproduced reasonably well NBI-only PT L-mode scenario and was not able to accurately model the experimental kinetic profiles of the NT case, underestimating the beneficial effect of NT on transport. Producing artificial cases where only the LCFS is flipped along the vertical axis, we find that the main culprit is a bad parametrization of the NT up-down asymmetric magnetic equilibrium made in TGLF by the local Miller model. This model forces up-down symmetry of the flux surfaces and reduces the effective triangularity of the DTT NT scenario. Hence, unless the equilibrium reconstruction method is changed in TGLF, the predictive capabilities of ASTRA-TGLF for the DTT NT scenario will underestimate the performance of this scenario.

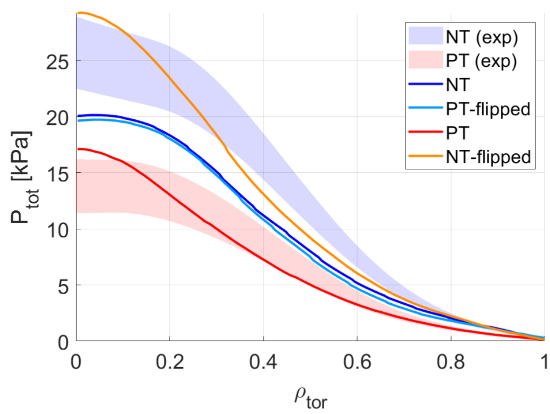

Fig. 5 Total plasma pressure predicted by ASTRA-TGLF for NT (blue), PT-flipped (light blue), PT (red) and NT-flipped (orange). The shaded blue and red areas are the experimental values of pressure for NT and PT

Acknowledgments

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