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H-mode physics studies on TCV supported by the EUROfusion pedestal database

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Introduction – The H-mode confinement regime will be the main operational scenario on ITER and also the current foreseen scenario for fusion reactors. A continuous effort towards better predictive capabilities of H-mode confinement is being pursued on both experimental and theoretical fronts. The H-mode is characterised by the formation of a pedestal near the plasma edge and as the fusion power scales as p_{ped}^2, it is advantageous to maintain a high pedestal pressure. This goal is challenged by the need to mitigate H-mode characteristic Type-I ELMs either by creating a highly radiating divertor using impurity injection [1] or via ELM-free or small ELMs regimes [2]. With a pedestal database, the H-mode physics studies performed on TCV are reviewed with emphasis on the comparison between the historically ECRH dominated scenario and the NBH H-mode regime explored more recently.

Pedestal database – The TCV pedestal database is one of several databases promoted by EUROfusion to stimulate the multi-machine comparisons, (JET, AUG, MAST-U and TCV), with common parameter definitions [3] and a common platform (IMAS: ITER integrated modelling and analysis suite). The pedestal structure is determined from the pre-ELM temperature and density profiles (75-99% of the ELM cycle) using TCV's Thomson Scattering [4]. Pedestal parameters are obtained using a mtanh fitting function [5]. To reduce uncertainties in the equilibrium reconstructions, temperature and density profiles were systematically shifted such that $T_{e,sep} = 50$ eV, estimated by using the two point model for the power balance at the separatrix. To enhance the overall pedestal data quality, entries were selected according to following rules: steady state intervals over at least 0.4s (~$10\tau_E$) and a reduced R^2 for the fit in the region 0.8<ψ_N<1.05 larger than 0.75. A new plasma equilibrium is computed using the CHEASE code from the fitted pedestal, accounting for the bootstrap current and, only then, is the pedestal stability analysed [6]. The TCV pedestal database currently contains $\sim$350 entries for about 100 implemented parameters. For TCV's heating methods, (Ohmic, ECRH and NBH), the normalised average lost energy as a function of the ELM frequency is shown Fig.1-left with the pedestal temperature plotted against the pedestal density, Fig.1-right. The plasma shaping capabilities of TCV have been exploited in the range of parameters: 1.3<κ<1.8, 0.2<δ_b<0.8 and -0.3<δ_u<0.8. For similar H-mode plasmas except the top triangularity (δ_u $\sim$-0.2 vs δ_u $\sim$0.2), the pedestal width is increased by 25% while its top pressure is reduced by a factor of 2 for the negative triangularity cases, in line with EPED predictions [6].

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ECRH ELMy H-modes – H-mode plasmas with Type-III ELMs are achieved in TCV with Ohmic heating only for q_{95}<3 (Fig.1 blue points). The central plasma density is too high for 2nd harmonic ECR heating, but central heating at third harmonic (X3) is possible. As the injected X3 power is increased (0<P_{X3}<0.5 MW), the type-III ELM frequency decreases to f_{ELM} $\sim$ 50 Hz. Additional X3 power doesn't change the ELM frequency but increases significantly the normalised lost energy ($\Delta W/W$ $\sim$17%). This is explained by some coupling of the ELM instability with the core MHD (m/n=1/1) that propagates the ELM crash to the plasma core region. Finally, for P_{X3}>0.8 MW, the ELM frequency increases, signifying a Type-I ELM regime, with a decrease in the normalised ELM losses [7-8]. Typical pedestal values for an ELMy H-mode heated with 1 MW of ECRH are $T_{e,ped}$ $\sim$0.8 keV, $n_{e,ped} \sim 3 \times 10^{19}$ m^{-3}, $n_{e,sep} \sim 0.2 n_{e,ped}$ and $T_e(0)/T_i(0)$ $\sim$6. Such hot plasmas at low densities for ψ_N>0.8, including the pedestal, is still accessible to X2 heating and it was demonstrated that the ELM frequency can be controlled by ECRH modulation [9]. Interestingly, a steady state ELM free regime has been reached with 1.2 MW of X3 power with unfavourable ∇B configurations [10]. In today's tokamaks, pedestal collisionalities relevant for ITER ($\nu_{\star,ped} \sim$ 0.1) might be achievable with an ECRH H-mode operational regime but conditions for partial detachment, $n_{e,sep}/n_G \sim$ 0.4 at the separatrix, are impossible.

NBH ELMy H-modes – The H-mode operational space extension towards high pedestal and larger separatrix densities has become possible with TCV's neutral beam injector (1MW, 30keV), in operation since 2015. Moreover, ELMy H-mode can be achieved at lower plasma current (q_{95}>3) allowing the development of an ITER baseline scenario on TCV (q_{95} $\sim$3-3.6, κ=1.7, δ=0.4) [11]. A scenario at q_{95} $\sim$4.5, δ=1.5 is well established with accompanying Type-I ELMs (f_{ELM} $\sim$ 100 Hz, $\Delta W/W$ $\sim$ 10%) and typical pedestal parameters $T_{e,ped}$ $\sim$

0.2 keV and $n_{e,ped} \sim 4 \times 10^{19}$ m^{-3}. The effects of D_2 fuelling and N_2 seeding on the pedestal stability and plasma confinement were investigated. Both induces an outward shift of the pedestal density relative to the pedestal temperature with a corresponding outward shift of the pedestal pressure that, in turn, reduces the peeling-ballooning stability, degrades the pedestal confinement and reduces the pedestal width [12], in line with AUG and JET results [13]. A small ELM regime with high confinement was achieved if, and only if, the separatrix plasma density was large enough ($n_{e,sep}/n_G$ ~0.3) and the magnetic configuration was close to a double null (δ>0.4) [14]. The extension of the regime to q_{95}<4 was recently achieved. A second neutral beam (1MW, 50keV), planned by the end of 2020, will open new possibilities, not only for H-mode physics at large β_N, but also for fast particle physics.

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Country or International Organization

Switzerland

Affiliation

Ecole Polytechnique Fédérale de Lausanne

Author: LABIT, BENOIT (Swiss Plasma Center (SPC) EPFL SWITZERLAND)

Co-authors: CODA, Stefano (CRPP-EPFL); DUVAL, Basil (Ecole Polytechnique Fédérale de Lausanne –Swiss Plasma Center (SPC)); MERLE, Antoine (Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas (CRPP), CH-1015 Lausanne, Switzerland); PORTE, Laurie (CRPP-EPFL); SAUTER, Olivier; SHEIKH, Umar; DUNNE, Mike (IPP-Garching); FRASSINETTI, Lorenzo (KTH, Royal Institute of Technology); SCANNELL, Rory (Association CCFE/Euratom)

Presenter: LABIT, BENOIT (Swiss Plasma Center (SPC) EPFL SWITZERLAND)

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