H-mode operation in Helium plasmas on TCV: access, confinement and pedestal properties

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Introduction – In ITER, not only will fusion operation be performed in mixed deuterium-tritium (D-T) plasmas, but also the pre-fusion power operation will be performed in helium (He) plasmas. Therefore, it is important to understand both the dependence of the H-mode power threshold, P_{L-H}, for Helium plasmas and the pedestal properties for type-I ELMy H-modes. On JET-C, a series of helium-4 H-mode experiments were performed with pure helium-4 NBI auxiliary heating. Compared with deuterium plasmas, Type I ELMy H-mode confinement was seen to be 28% poorer in helium-4 plasmas and the L-H power threshold about 40% larger [1].

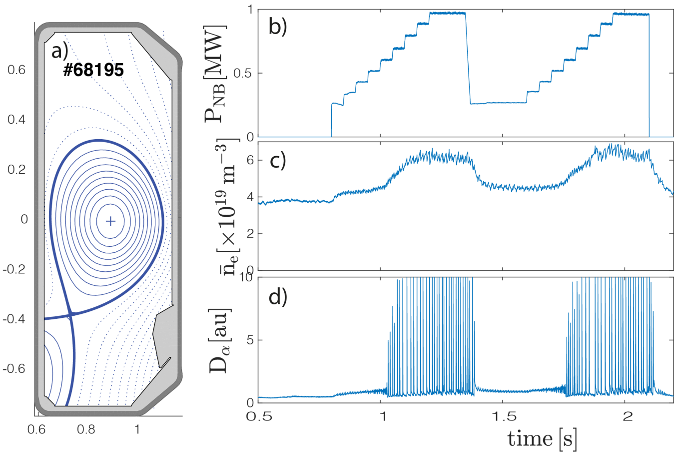

Figure 1: *Experimental scenario with a) plasma shape, b) neutral beam heating power, c) line averaged density and d) D_α emission.*

On AUG, experiments have been carried out to compare H-mode power threshold and confinement time in helium and deuterium. A scan in magnetic field and a wide density variation indicate that the threshold power is very similar for both gases $P^{D}_{L-H} \sim P^{^4He}_{L-H}$. The density dependence of the threshold exhibits a clear minimum. In line with JET-C, confinement in helium is about 30% lower than in deuterium and a reduction of the ion density in helium was conjectured as the reason for the reduced confinement [2]. In this contribution, we report on H-mode plasmas with Type-I ELMs in Helium which have been observed for the first time in TCV.

Experimental setup – A series of dedicated experiments have been perfomed in TCV primiraly to determine the power for the L-H transition with neutral beam heating. As shown in Fig.1a), the plasma configuration is a lower single null plasma with open divertor (no baffles), fav. ∇B drift, κ=1.6, δ=0.4, I_p=240 kA and $B_T = 1.4$ T ($q_{95} \simeq 3.2$). All these parameters were kept unchanged. To assess the density dependence of P_{L-H}, a fuelling scan was done. Moreover,

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*See author list of "H. Reimerdes et al 2022 Nucl. Fusion **62** 042018"* these helium plasmas were heated with power ramps from the neutral beam either operated in D or in H. On Fig1b-d), typical traces for the neutral beam power, the line averaged density and the D_α emission are plotted. The confinement and pedestal properties have been estimated during the last power step of each neutral beam power ramp, lasting 150 ms which is about four times longer than the energy confinement time. For comparison, deuterium ELMy H-mode plasmas with the same parameters were also done.

L-H power threshold – To estimate the power threshold, the net power has been evaluated 20 ms before the drop in the D_α signal, signature of the L-H transition. The net power is defined as $\mathrm{P_{net} = P_{Ohm} + P_{heat} - dW/dt}$ where P_{Ohm} is the residual Ohmic power, P_{heat} the absorbed auxiliary heating power and W is the stored plasma energy. No correction from bulk radiation and anisotropy of fast (NB) ion velocity distribution was applied. The dependence of P_{net} with plasma line averaged density is shown in Fig.2b).

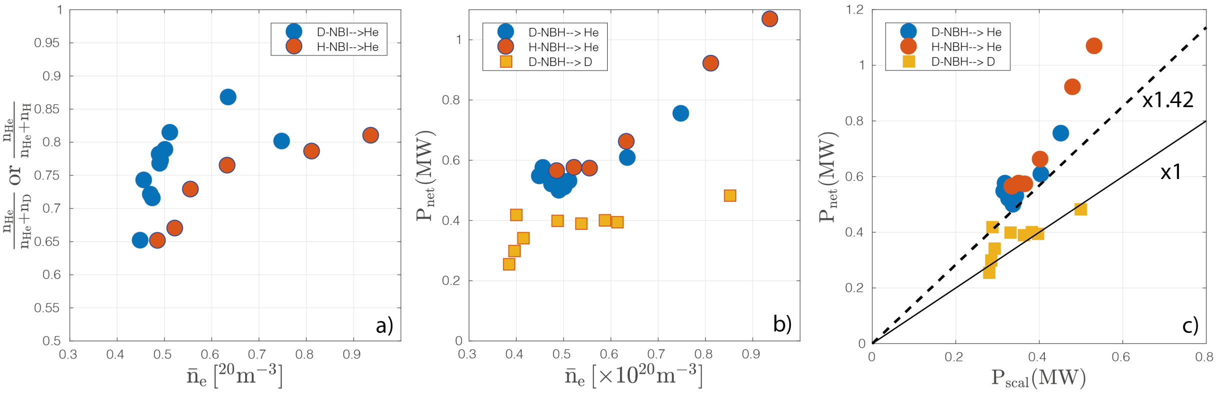

Figure 2: *Overview of the dataset for the L-H transition studies: a) Helium plasma purity vs line averaged density; b) Threshold power vs line averaged density; c) Experimental threshold power vs ITPA scaling.*

It is clear that the power threshold is larger for Helium plasmas compared to Deuterium. This is in agreement with JET-C results but also with previous TCV data obtained with ohmic heating only [3]. It has to be noted also that a critical density at which the required power is minimum was not observed, conversely to recent JET-ILW experiments where $\bar{n}_{e,min}(He) = 0.6n_{GW}$ has been reported and being significantly larger compared to D [5]. More of a concern, from the TCV dataset, is that the scaling with density for ^4He seems to be stronger w.r.t to the ITPA scaling [4] which reads for D, in MW: $P_{scal} = 0.049B_T^{0.80}n_{20}^{0.72}S^{0.94}$ where B_T [T], n_{20} $[10^{20}\mathrm{m}^{-3}]$ and $S\,[\mathrm{m}^2]$ are respectively the magnetic field, the line-averaged density and the plasma surface area. This is clearly illustrated in Fig.2c) where P_{net} is plotted against P_{scal}. The dashed black line indicates the expected trend derived from JET-C and which reads: $P_{L-H}^{4He} = M^{-1.1}Z^{1.6}P_{scal}$. The deviation from the ITPA scaling cannot be attributed to a Helium plasma dilution from the H-NBI since the purity is about 80% at large densities (Fig2a)). Only fast ions population (from ASTRA interpretative modelling) have been accounted for the estimate of n_H and n_D, neglecting recycling from the walls. The TCV dataset suggests a linear dependence of P_{L-H}^{4He} with line averaged density: $P_{L-H}^{4He} \propto \bar{n}_e$:

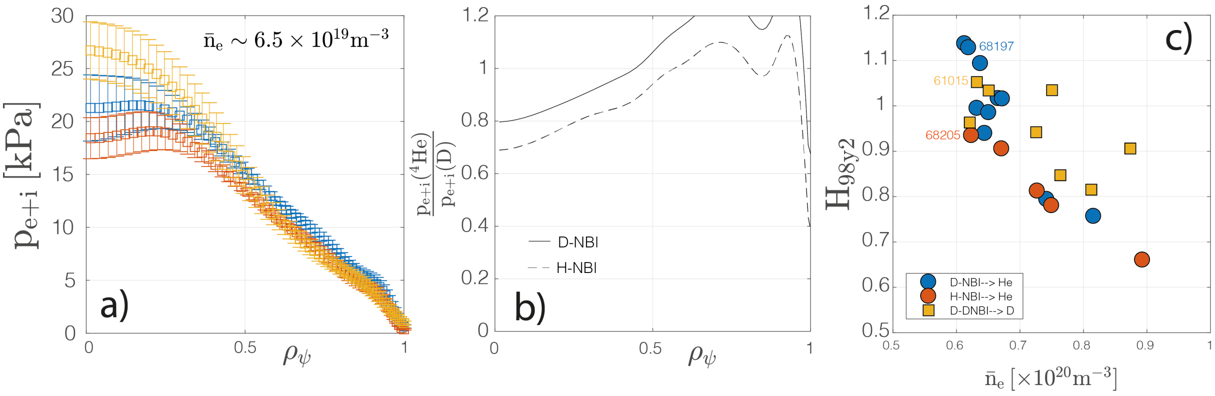

Figure 3: *a) Total pressure profiles for Helium and Deuterium plasmas at 1 MW beam power; b) Ratio between pressure profiles; c) Confinement factor H_{98y2} vs line avaraged density for 3 datasets.*

Confinement – In Fig.3a), the total pressure for ^{4}He plasmas is compared with a D case at $\bar{\mathrm{n}}_\mathrm{e} \sim 6.5 \times 10^{20}\mathrm{m}^{-3}$. The core pressure in ^{4}He is lower than that in D by about 25%, as also shown in Fig.3b) by the ratio of the pressure in the two gases. This effect is mainly due to $Z = 2$ of the helium ions leading to a reduced ion density compared to D, while the temperature profiles were similar for both gases with $\mathrm{T_e} \simeq \mathrm{T_i}$. Nevertheless, the pedestal pressure being slightly larger for ^{4}He with D-NBI (#68197) at this line averaged density, the confinement factor H_{98y2} is a little larger compared to D (#61015). The normalized confinement factors H_{98y2}, in helium for D-NBI or H-NBI are summarized in Fig3c) versus density and compared with D cases with similar power level and plasma current. For the three datasets, H_{98y2} decreases with density with different scalings. The difference between D-NBI and H-NBI may be attributed to the influence of helium purity (Fig.2a), supported by the fact that both datasets converge at high density.

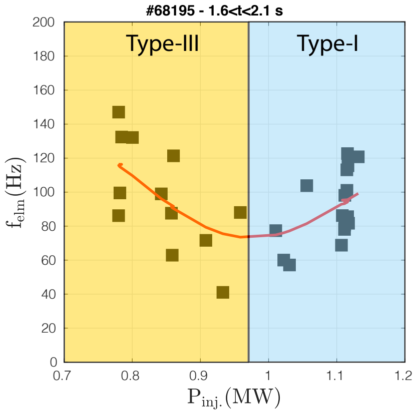

Figure 4: *ELM frequency as a function of injected power for #68195 (D-NBI→^{4}He) illustrating the transition from Type-III to Type-I ELMs.*

Pedestal characterisation – Type-I ELMs have been identifed from the increase of the ELM frequency as a function of the injected power (Fig.4). Pedestal profiles have been fitted and their stability was analysed with the workflow presented in [6]. In Fig.5a-b), density and temperature pedestals are compared between ^{4}He and D. While almost no noticable difference is visible on the density, the top pedestal temperature is larger for the Helium case with D-NBI heating. The stability analysis (Fig.5c) seems to indicate that the pedestal current density is larger for Helium compared to D. In any case, all pedestals are close to the peeling-ballooning limit with most unstable modes around $n = 40$ for helium and $n = 80$ for deuterium.

Outlook – Dedicated experiments in TCV are needed to better understand the confinement of Helium plasmas in particular with dominant electron heating and mixed heating. Turbulence diagnostics like reflectometry or phase-contrast imaging will be used to quantify core density fluctuations. Finally, the exhaust properties have to be characterized and alternatives to Type-I H-mode regime, like the QCE regime [7] have to be demonstrated. In the coming months, an extensive Helium campaign in JET-ILW will take place, together with experiments on AUG. One of the goal is to develop and characterise robust type-I ELMy H-mode plasmas and pave the way for the Pre-Fusion Power Operation of ITER.

Acknowledgements – This work was supported in part by the Swiss National Science Foundation.

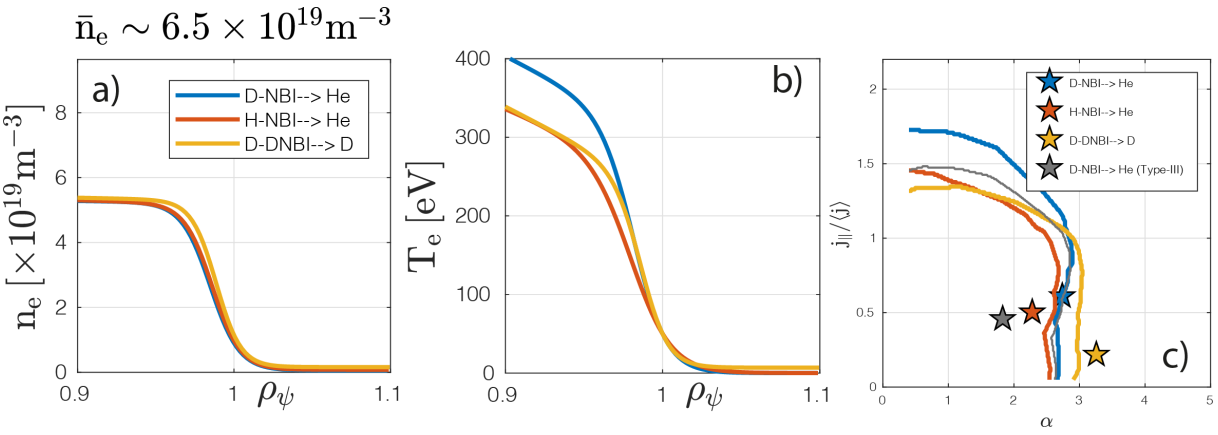

Figure 5: *a) Density pedestal; b) Temperature pedestal; c) Peeling-ballooning stability diagram for Helium and Deuterium H-mode plasmas with 1 MW injected beam power.*

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