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High density, high confinement, power exhaust compatible H-mode regime in TCV and ASDEX Upgrade

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Introduction – Power exhaust solutions for a next step device must be compatible with good plasma performance. To reach sufficiently low divertor power loading impurity seeding is necessary. The amount of injected impurities required depends critically on both the maximum achievable separatrix density and the scrape-off layer width. Transient power loads due to type-I edge localised modes (ELMs) are expected to reduce the life time of the first wall in ITER and have to be avoided completely for reactor-sized devices.
Recent optimisation of ASDEX Upgrade and TCV scenarios [Ref.1,Ref.2] has led to a regime highly suitable for power exhaust. This promising regime combines a high plasma core performance ($H_{98,\mathrm{y2}} \simeq 0.9 - 1.0$, $n_{\mathrm{e,core}} \simeq 0.9\, n_{\mathrm{GW}}$) with a high separatrix density ($n_{\mathrm{e,sep}} \simeq 0.4\, n_{\mathrm{GW}}$) at high triangularity, close-to-double-null. The most critical power exhaust parameter, the power fall-off length measured from divertor heat flux profiles in ASDEX Upgrade, is shown to widen up to a factor of four w.r.t. the ITPA-multi-machine (*Eich*) scaling of four whilst no type-I ELMs are present.

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Edge characterisation – The edge plasma reaches a ballooning parameter close to the ideal-MHD limit. HELENA calculations show that a small region just inside the separatrix is infinite-n ballooning unstable. Ballooning modes, which are generally driven by strong MHD-normalised pressure gradients and stabilised by magnetic shear, are destabilised in these discharges by the strong pressure gradient at the separatrix and the reduced local magnetic shear due to the close-to-double-null configuration. The onset of ballooning modes cause increased radial transport importantly at the pedestal foot and narrow the radial extent of the region with a steep pedestal pressure gradient. Peeling-ballooning stability calculations for these reduced pedestal widths show that type-I ELMs are avoided under these conditions.

Divertor characterisation – Fuelling and seeding variations in dedicated experiments allow at ASDEX Upgrade to change the divertor state from high recycling to partial detachment, as foreseen for ITER {\em Q=10} operation. Fuelling from main chamber valves leaves the divertor attached, while detaching with divertor fuelling not changing the confinement properties.
In 2019, TCV has explored operation with a baffled divertor [Ref.3], separating the neutral pressure in the main chamber from the divertor neutral pressure. Under these conditions, the here mentioned regime can be recovered only if the fuelling from the divertor is increased by a factor ~3. The operational window for the regime has been successfully extended down to q_{95} values around 3.7.
For ASDEX Upgrade, we report in detail on the divertor target power load profiles. They are measured by high resolution infrared thermography. The flexibility to vary between an attached high recycling and detached divertor state allows to measure directly the scrape-off layer power fall-off length. Fig.1 shows outer divertor target heat flux profiles for phases with lowest fuelling (red, type-I ELMs present) and two levels of elevated fuelling (blue and green, no type-I ELMs present). Most importantly, a broadening of the power fall-off length is measured, up to a factor of four compared to the ITPA-multi-machine scaling [Ref.4]. These observations are consistent with the increased radial transport at the pedestal foot. The ballooning instabilities lead to a radial convection of filaments carrying the heat much further into the scrape-off layer and may give rise to the formation of a density shoulder [Ref.5]. Direct evidence stems from thermal helium beam analysis [Ref.6] for the scrape-off layer showing both an increased filament frequency and amplitude.

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Integrated scenario – A plasma start-up into a high confinement, partially detached H-mode without any type-I ELM is realised for the first time at ASDEX Upgrade. Fig.2 shows time traces for ASDEX Upgrade discharge # 37164. The H-mode is initiated at high β_{pol} allowing easier access to a type-I ELM free regime. A ramp-up in plasma current after achieving the final close-to-double-null shape is performed eventually reaching T_{div}. Additionally, for the first time, a double feedback controlled discharge is achieved using neutral beam injection to control $q_{95} = 7.8$ and nitrogen seeding to control the divertor electron temperature of $q_{95} = 4.6$ (3-5s) and later of $\beta_{\mathrm{pol}} = 1.3$ (5-7s).

References

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