Evolution of ELMy H-mode performance in presence of core radiation on ASDEX Upgrade

R. Ochoukov[1], V. Bobkov[1], C. Angioni[1], M. Bernert[1], M. Dunne[1], R. Dux[1], R. Neu[1,2], J.-M. Noterdaeme[1,3], T. Odstrčil[1,2], T. Pütterich[1], F. Reimold[1], the AUG Team, and the EUROfusion MST1 Team

[1]*Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany*

[2]*Technische Universität München, Boltzmannstr. 15, 85748 Garching, Germany*

[3]*UGent, Applied Physics Department, 9000 Gent, Belgium*

1. Introduction

High performance, high temperature tokamak plasmas require that a large fraction of the thermal power that crosses the separatrix from the core (P_{sep}) is radiated away in the form of photons to mitigate heat loads on and erosion of plasma facing components (PFCs). It is common to use nitrogen and/or noble gases, such as neon, argon, or krypton, as a radiating species to transfer the plasma thermal energy into electromagnetic radiation. However, in case of a low-Z number of the radiating species, relatively high concentrations of the radiator must be used, which can impact the fusion reaction rate of the plasma core through dilution. High-Z radiators, on the other hand, are capable of radiating a large fraction of the plasma thermal power, while being present in low (~10^{-5}-10^{-4}) concentrations in the plasma core. But, unlike low-Z radiators, it is crucial to maintain control over the core radiation profile to prevent central radiation peaking and subsequent degradation of the plasma performance and the discharge stability. The goal of the study is to determine the feasibility of using controlled core radiation to reduce P_{sep}, and hence, heat loads on PFCs, while maintaining high plasma performance in a stable discharge.

The early results on ASDEX Upgrade show that the core plasma performance parameters – the stored plasma energy (W_{MHD}) and the confinement factor (H98) – remain robust (Fig. 1 (a) and (b)) as the core radiating power fraction is increased (with tungsten (W) being the dominant radiating impurity). We remind that the radiated power is not included in the definition of H98. While the radial electron temperature (T_e) profiles show a slight drop inside ρ_{tor} <0.5 in the high radiation case, the plasma density (n_e) profile is little changed in the same region resulting in the plasma stored energy ($W_{MHD} \sim n_eT_e$) approximately

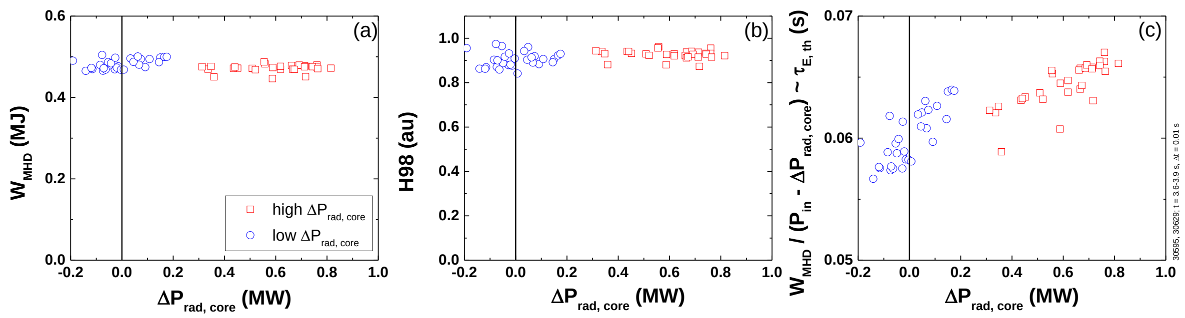

Figure 1: Changes in (a) the plasma stored energy W_{MHD}, (b) the confinement factor H98, and (c) the thermal energy confinement time $\tau_{E, th}$ as a function of the radiated power from the plasma core $\Delta P_{rad, core}$. The "base" P_{rad} value (when $\Delta P_{rad, core}$ = 0 MW) was 3.5 MW.

constant before and during the high core radiation discharges. A combination of a constant W_{MHD} and an increase of the core radiating power fraction suggests that the thermal energy confinement time ($\tau_{E,\ th} \sim W_{MHD}/(P_{in} - \Delta P_{rad,\ core})$), where P_{in} is the total incident heating power, constant for these discharges) increases in the high core radiation discharge (Fig. 1 (c)). Data analysis using a time-dependent tokamak transport code TRANSP reveals that the electron heat diffusivity (χ_e) decreases across the plasma core during the high radiation regime, consistent with the observed improvement in $\tau_{E,\ th}$. Note, that the high radiation regime remains stable for ~1 s (equal to the duration of the Ion Cyclotron Range-of Frequencies (ICRF) power pulse in non-standard phasing [1]). The radial tungsten concentration (c_W) profile across the core remains uniform without central peaking. Overall, the early results show a promising (robust) plasma performance in ELMy H-modes on AUG with a high core radiating fraction warrantying further study of this scenario either on its own or in combination with other high-Z radiators such as krypton [2].

2. Experimental Method

The discharge parameters for this study were: the toroidal magnetic field $B_T = -2.5$ T and the plasma current $I_p = 0.8$ MA. The edge safety factor q_{95} was 5.4. The main ion species was deuterium and the core radiating impurity was tungsten, "seeded" from the active ICRF antenna limiters by operating antennas in non-standard phasing [1], while maintaining a constant ICRF power of 1.5 MW. The plasma shape was a lower single null. The H-mode was maintained by 4.9 MW of neutral beam power. Additionally, 1.4 MW of core electron cyclotron resonance heating (ECRH) was used to prevent tungsten concentration (c_W) from centrally peaking. P_{in} (including ohmic heating) was ~8 MW. Core radiation was monitored with poloidal arrays of soft x-ray (SXR) detectors, sensitive to photons with energies >1.8 keV [3]. The c_W radial profiles were reconstructed from the SXR emissivity (ε_{SXR}) profiles, assuming that the dominant radiating species in the core was W [4]. The data from these discharges were subsequently analysed using TRANSP to determine the effect of core radiation on electron and ion thermal diffusivities (χ_e and χ_i) across the plasma core.

3. Experimental Results and Discussion

As a result of central ECRH heating, the discharges showed large sawtooth (ST) oscillations with $\Delta T_e \sim 1$ keV. In order to account for the observed ST oscillations in these discharges, the plasma profiles were examined just before the ST crash and just after the ST crash. The radial T_e profiles inside the q = 1 region showed the largest modulation during an ST cycle (Fig. 2 (a)), while the sawtooth induced variations in T_i and n_e profiles were small (Fig. 2 (b) and (c)). In the discharges with high core radiation, the T_e profile was slightly reduced for ρ_{tor} <0.5, with the ST amplitude also being reduced (Fig. 2 (a)). The reduction of T_i was observed further in, inside the ST inversion radius at ρ_{tor} <0.31 (Fig. 2 (b)). The n_e profile showed a minimal change across the plasma core in the high radiation regime (Fig. 2 (c)). The overall plasma stored energy ($W_{MHD} \sim n_eT_e$), which is a volume-integrated quantity,

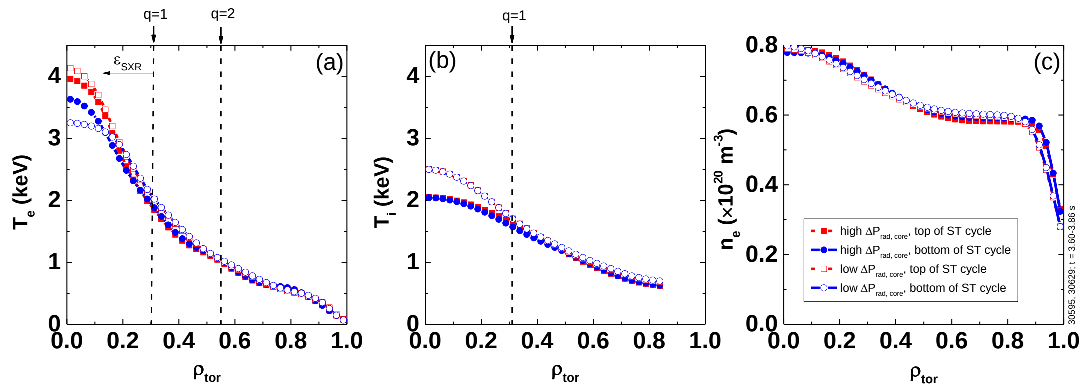

Figure 2: The radial profiles of (a) the electron temperature (T_e), (b) the ion temperature (T_i), and (c) the plasma density (n_e) before and during the discharges with high core radiation. The data is shown for the top and the bottom of a sawtooth (ST) cycle. The radial locations of q = 1 and q = 2 rational surfaces are shown. The radial location of the soft X-ray emission region (ε_{SXR}) is also shown.

remained approximately unchanged before and during the discharges with high core radiation (Fig. 1 (a)), as the observed T_e and T_i changes occurred over a small plasma volume.

The SXR diagnostic on ASDEX Upgrade is sensitive to photons typically in the energy range of >1.8 keV [3], which happened to coincide with the T_e and T_i values inside the ST inversion radius (Figs. 2 (a) and (b)). The ε_{SXR} profiles showed that the radiation increase in these discharges originated from the plasma core and was influenced by the phase of the ST cycle (Fig. 3 (a)). Note, that the data is shown for four consecutive ST cycles and the c_W profiles, averaged over a ST cycle, remained uniform across the plasma core without evidence for peaking (Fig. 3 (b)). The modulation of c_W during an ST cycle was "in-phase" with the T_e modulation (Fig. 3 (b)). In all cases the levels of c_W remained $\leq 10^{-3}$ in the core.

The lack of a drop in the plasma performance with the increase in the core radiated power (Fig. 1 (a) and (b)) indicates that the transport of thermal energy across the plasma drops (and, hence, improves) with core radiation. Such trend is observed in the thermal energy transport coefficients for the electrons (Fig. 4 (a)) and, to some degree, for the main ions (Fig. 4 (b)), as estimated by TRANSP. The radial χ_e values are reduced across the entire confined plasma profile (Fig. 4 (a)), while the χ_i values are enhanced inside the sawtooth inversion

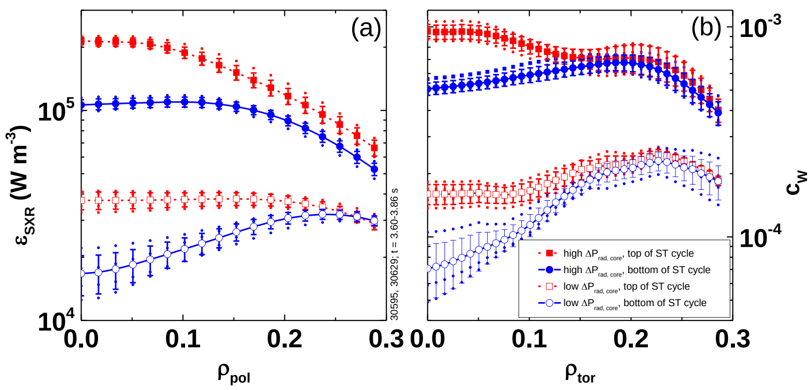

Figure 3: The radial profiles of (a) the measured soft X-ray emissivity (ε_{SXR}) and (b) reconstructed tungsten concentration (c_W) inside the sawtooth (ST) inversion radius ρ_{tor} = 0.31. The data is shown for four consecutive sawtooth cycles.

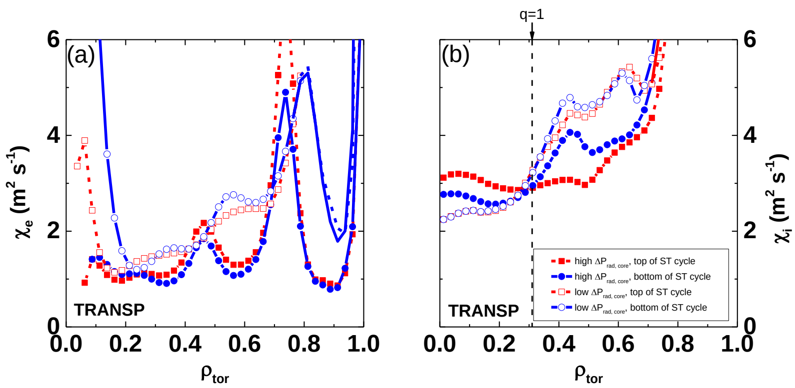

Figure 4: The radial profiles of (a) the electron heat diffusion coefficient (χ_e) and (b) the ion heat diffusion coefficient (χ_i) before and during the discharges with high core radiation. The values are deduced by TRANSP.

radius but are reduced outside the q = 1 region (Fig. 4 (b)) in the presence of core radiation. The observed variation in χ_e is expected as the core radiation directly impacts the T_e profile and, most importantly, the gradient of the T_e profile (∇T_e). ∇T_e, in turn, sets the electron heat diffusivity across the core. The stiffness of the T_e and n_e pedestal profiles has been analysed previously [5] and shown to be equally stiff before and during the discharges with high core radiation. This further constrains the radial plasma pressure profile to remain constant, and, in turn, the heat transport coefficients to become reduced. The situation with χ_i is more complex, as the T_i profiles depend on the strength of the electron-ion coupling. Note that the opposite effect – no change in W_{MHD} with an increase in core ECRH heating – was previously observed on AUG [6] and is linked to ∇T_e, ∇T_i, and n_e via collisionality [6].

4. Conclusion

Discharges with high core radiation fraction were examined to determine the applicability of core radiation as a means of mitigating thermal heat loads on the plasma facing components, while maintaining stable, high-performance core plasma. W "seeded" by an active ICRF antenna operated in non-standard phasing was used to change the core radiated power. The early results reveal that W_{MHD} and H98 factor remain robust in the discharges with high core radiation. Since the increase in P_{rad} originates from the core due to the presence of W, it implies that $\tau_{E, th}$ is improved in the discharges with high core radiation.

5. Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

6. References

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