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Bolometer tomography and density limit of the high density H-mode in the W7-AS Stellarator

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1 Introduction

The introduction of divertor modules into the W7-AS stellarator has allowed access to a high density and high power H-mode (HDH) regime where the radiation profiles reach a steady state. This regime exists above a density threshold at line integrated densities, $\bar{n}_e$, up to $4\times10^{20}\,\mathrm{m}^{-3}$ with 4 MW of NBI power [1,2]. This density threshold is power dependent. In limiter discharges density control could not be maintained above 1 MW NBI heating power and the discharge terminated with a radiation collapse at high densities [3]. From laser blow-off experiments with Al, the inward pinch velocity in the core and edge plasma is found to be reduced by at least a factor of 4 while the diffusion coefficient remains approximately constant upon transition to the HDH mode [4,5]. This indicates the important role of changes to the impurity transport coefficients for achieving steady state discharges in the divertor configuration of W7-AS.

2 Results

An overview of plasma parameters in a 1 MW NBI divertor plasma with B = 2.5 T and $\iota(a)$ = 0.5556 for discharges near the density threshold in hydrogen and deuterium is shown in Fig. 1. The discharge in hydrogen is observed to spontaneously make the transition back to the lower confinement regime. The diamagnetic energy decreases and the radiated power now increases with time. The deuterium discharge stays in the HDH mode in a steady state. In hydrogen, discharges with a duration of up to 1.4 s have been attained. A further increase in the density eventually causes detachment. A detached plasma radiating up to 80% of the deposited energy has been maintained for up to 0.8 s.

In Fig. 2, the time evolution of the radial profile of the radiated power in a hydrogen divertor discharge is shown. In the HDH mode, the plasma radiates mainly at the plasma edge. Below the density threshold the radiation profiles are centrally peaked and continue to rise with time until the discharge terminates. Density profiles above the density threshold for the transition to the HDH mode are flat and broad with a steep gradient at the plasma boundary. Below the density threshold the density profiles are centrally peaked. In both cases, the temperature profiles are similar [1].

In Fig. 3, the radial profiles of radiation power in divertor discharges in hydrogen and deuterium are compared. Both are strongly dominated by radiation at the plasma boundary. The temperature profiles are similar, so that the stronger edge radiation in deuterium arises either from a stronger impurity source or the broader density profile in deuterium. In attached plasmas at the same line integrated density the radiated power in deuterium is larger than in hydrogen. The additional puffing of nitrogen in a divertor discharge to induce plasma detachment from the divertor, is also shown in Fig. 3. Enhanced edge radiation and some increase in the central radiation is observed. The edge density and temperature are observed to decrease with nitrogen puffing.

In the triangular plane of W7-AS there are 2 bolometer cameras, each with 32 channels. In the elliptical plane there are 3 bolometer cameras with a total of 44 channels and a photodiode array with 32 channels viewing the divertor region. A tomographic reconstruction of the radiated power density in a detached plasma, with the typical asymmetry observed in the triangular plane, is shown in Fig. 4. With plasma detachment, the photodiode signal decreases significantly from the value expected based upon the bolometer measurements. This indicates that in plasma detachment neutral particle loss could be the dominant loss channel rather than radiation from impurity lines. At lower densities the line impurity radiation dominates. Alternatively, the measured line radiation and recombination from hydrogen below 15 eV would also be consistent with this feature [6]. The photodiode response at these photon energies is reduced by a factor of 3 compared to the response to photon energies above 20 eV.

The bolometer camera view into the divertor chamber shows two localized regions of enhanced radiation at the top and bottom of the vacuum chamber. These observations can be understood in terms of carbon line radiation from a thin shell outside the separatrix [7].

3 Density limit

Power, minor radius and magnetic field scans have been performed in hydrogen and deuterium with a divertor to assess the validity of the scaling law previously defined in limiter discharges [5]. Even though the plasma radiates predominantly at the plasma edge in the HDH mode and the core radiation of limiter discharges no longer determines the density limit [3], the maximum $\bar{n}_e$ measured before the plasma detaches and the diamagnetic energy falls follow the predictions of the scaling law, as shown in Fig. 5. The density limit in stellarators has been treated theoretically using power balance considerations and it has been recognized that radiation in the plasma edge or plasma core can lead to a different power dependency for the density limit scaling law [8].

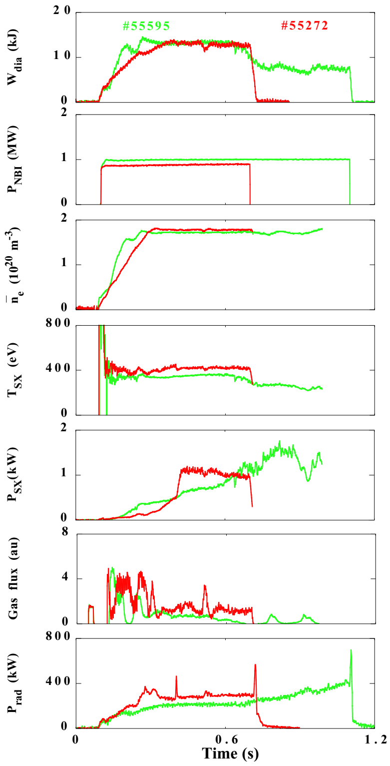

Figure 1: *Time evolution of plasma parameters in a 1 MW NBI divertor discharge in hydrogen (green) and deuterium (red) with B = 2.5 T at a density in the vicinity of the density threshold for transition to the high density H-mode.*

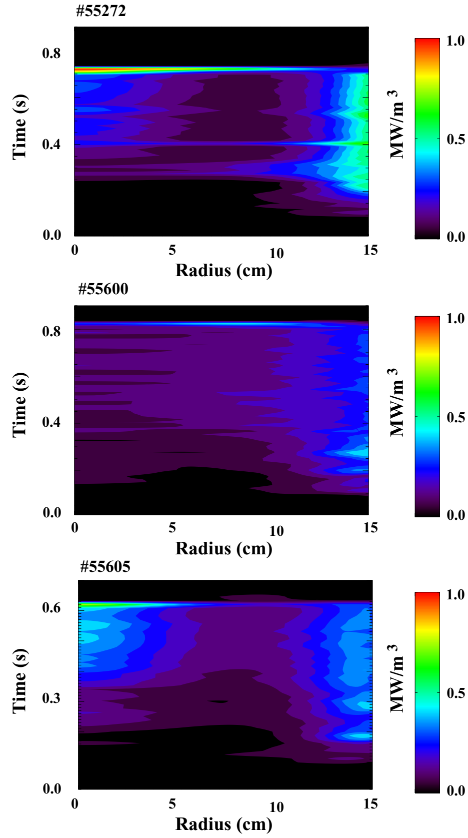

Figure 3: *Time evolution of radial profiles of radiated power in a 1 MW NBI divertor plasma above the density threshold with B = 2.5 T in D (top), H (middle) and H with N puffing (lower). N puffing begins at 0.25 s.*

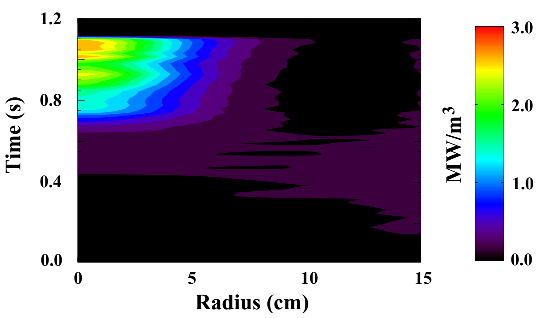

Figure 2: *Time evolution of radial profiles of radiated power in a 1 MW NBI divertor plasma at the density threshold with B = 2.5 T in hydrogen. See #55595 in Fig. 1.*

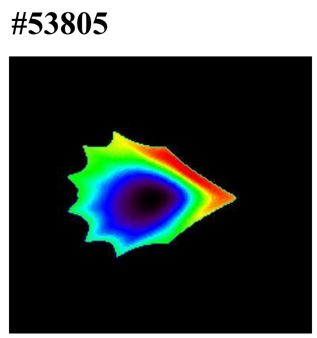

Figure 4: *Tomographic reconstruction in the triangular plane of radiated power in a 1 MW NBI partially detached divertor plasma with B = 2.5 T in hydrogen.*

For example, with 2 MW NBI in deuterium a maximum of $\bar{n}_e = 3.8 \times 10^{20}\,\mathrm{m}^{-3}$ is attained before plasma detachment begins and the diamagnetic energy decreases. The scaling law predicts a value of $\bar{n}_e = 3.5 \times 10^{20}\,\mathrm{m}^{-3}$. The observation that this maximum density is 25% lower at this power in hydrogen is conjectured to be a consequence of the differences in the radial profiles of density, temperature and radiation power.

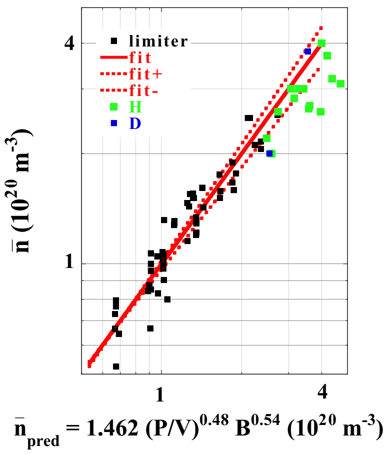

Figure 5: *Comparison of achieved and predicted values of line integrated densities, $\bar{n}_e$, for density limit discharges in divertor and limiter configurations.*

Time dependent simulations of the evolution of plasma parameters in density limit shots are in progress [9]. To understand the connection between the changes in density profile, improvement in energy confinement and the reduction of the inwards drift coefficient of impurities observed in the transition to the HDH mode, these simulations must take into account the neutral particle source from the neutral beams and gas puffing and the density dependence of the neutral beam heating deposition profile. Measurements of the radial electric field, E_r, also show a change in the radial profile after the transition out of the HDH mode. For the 1 MW NBI discharge in hydrogen shown in Figure 1, the value of E_r at r = 12 cm decreases from -8 kV/m in the HDH mode to -3 kV/m in the lower confinement regime, indicating that the electric field is also relevant to modelling of the HDH mode. Ultimately, understanding the physics of HDH operation in W7-AS will assist in attaining the HDH mode and steady state operation in the W7-X stellarator.

4 References

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