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Impact of wall materials and seeding gases on the pedestal and on core plasma performance

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ABSTRACT

Plasmas in machines with all metal plasma facing components have a lower Z_{eff}, less radiation cooling in the scrape-off layer and divertor regions and are prone to impurity accumulation in the core. Higher gas puff and the seeding of low-Z impurities are applied to prevent impurity accumulation, to increase the frequency of edge localised modes and to cool the divertor. A lower power threshold for the transition from low-confinement mode to high confinement mode has been found in all metal wall machines when compared to carbon wall machines. The application of lithium before or during discharges can lead to ELM free H-modes. The seeding of high-Z impurities increases core radiation, reduces the power flux across the separatrix and, if applied in the right amount, does not lead to deterioration of the confinement. All these effects have in common that they can often be explained by the shape or position of the density profile. Not only the peakedness of the density profile in the core but also the position of the edge pressure gradient influences global confinement. It is shown how (i) ionisation in the pedestal region due to higher reflection of deuterium from high-Z walls, (ii) reduced recycling in consequence of lithium wall conditioning, (iii) the fostering of edge modes with lithium dropping, (iv) increased gas puff and (v) the cooling of the scrape-off layer by medium-Z impurities such as nitrogen affect the edge density profile. The consequence is a shift in the pressure profile relative to the separatrix, leading to improved pedestal stability of H-mode plasmas when the direction is inwards.

1. Introduction

The high erosion rates of carbon as well as the large co-deposition of hydrogen isotopes on carbon plasma facing components (PFCs) [1] has led to the decision to change to metal PFCs in several machines. While Alcator C-Mod has been operated with a molybdenum wall since 1993 [2], ASDEX Upgrade gradually changed from a carbon first wall to a fully tungsten coated first wall from 1999 until 2007 [3], and JET has implemented the so-called ITER-like wall (ILW) in the year 2011 [4], consisting of beryllium coated main chamber plasma facing components (PFCs) and W divertor tiles.

With the change from carbon PFCs to metal ones, both ASDEX Upgrade (full W) and JET (Be, W) experienced some changes of plasma behaviour, such as a lower power threshold at the transition from L-mode (low-confinement mode) to H-mode (high-confinement mode) [5,6] and the difficulty of running well heated

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discharges at low density [7–10]. The transition to a full metal wall has removed carbon as main radiator in the scrape-off layer (SOL) and the divertor region, consequently leading to higher divertor temperatures [11]. With C missing as SOL radiator, W is sputtered in the hot divertor and can accumulate in the core. Not only the change to a full metal wall, but also the predicted heat loads for ITER [12,13] call for additional divertor cooling, which is realised by puffing D and by seeding of impurities. Experiments with impurity seeding have been carried out on machines worldwide, e.g. C-Mod, JET, EAST, D-IIID, JT60-U and AUG with different effects on plasma confinement. While seeding nitrogen in machines with carbon PFCs did not have any positive effect on confinement [14], it can replace carbon as radiator in the SOL and the divertor in metal-clad machines and can sometimes lead to improved confinement [15,16]. Experimentally, not only *N* results in improved confinement, also the seeding of lithium improves the plasma performance, as has been demonstrated in NSTX [17], EAST [18] and DIII-D [19]. In NSTX it is a consequence of reduced recycling, while in DIII-D a mode in the pedestal is fostered which increases particle transport across the edge transport barrier.

High radiation scenarios with a significant fraction of radiation in the core plasma as well as in the divertor are investigated in Alcator C-Mod, JT60-U and ASDEX Upgrade in order to reduce the power across the separatrix.

In all these experiments a common observation is that the pedestal properties are changed. Some influence the temperature directly by higher local radiation, others change the position of the density profile, which in turn alters the pedestal stability. In addition to pedestal structure changes, the ELM behaviour is also altered, presenting a new view of the ELM as a combination of a fast magneto hydrodynamic (MHD) crash and a subsequent slower transport event.

Far from being complete, in this review we will show in which way the metal wall changes the pedestal properties, why seeding impurities can improve confinement and how high radiation scenarios affect the pedestal and the core.

Because the leading theory which describes the limits to the pedestal pressure is the peeling ballooning theory, in Section 2 a brief sketch is presented of how the pedestal stability reacts to changes in the pressure profile position and in the core normalised pressure. The actuators which change the pressure profile are described. Section 3 describes the effect of particle and energy reflection of D from C- and W-walls on the density profile with its consequence on both the power threshold for the transition from L- to H-mode and the change of plasma performance in AUG and JET with all metal PFCs. In Section 4 wall conditioning and lithium seeding experiments are summarised, again with an emphasis on the achieved changes due to the location of the pedestal density profile. The effects of N seeding as well as effects of increased fuelling are reported in Section 5 and finally, in Section 6 the results of highly radiative scenarios with medium- to high-Z core radiation experiments as well as combined core and edge radiators are presented.

2. Pedestal stability reaction to pressure profile location and core pressure as well as actuators

Pedestal stability is calculated from linear ideal MHD theory where a dominant role is played by the magnitudes of the edge pressure gradient and the edge current density and its gradient. The strong edge pressure gradients drive ballooning modes on the outboard mid-plane while the concomitant large edge current density peaks drive kink/peeling modes, both of which then couple to peeling-ballooning modes [20,21].

A standard stability diagram depicts the mode number with maximum growth rate of such modes in dependence of the normalised pressure gradients α (with $\alpha = -2V'/(4\pi^2)\cdot(V/(2\pi^2 R_0))^{1/2}\mu_0 p'$; with V being the plasma volume, R_0 the major radius, μ_0 the vacuum permeability, p the pressure and the prime denotes the derivative with respect to the poloidal flux ψ [22]) and peak edge current densities j. However, the parameters α and j are not the only factors influencing the pedestal stability; the plasma shape, the pedestal width, the core pressure and the relative position of the pressure gradient to the calculation boundary, which is equivalent to the separatrix in experiments, are also important. Plasmas with higher shaping can sustain higher α-values, while wider pedestals lead to a flattening of the sustainable α as more m-modes can become unstable. An increased core pressure changes the Shafranov shift and consequently the edge q profile, with both the increased q-shear stabilising ballooning modes and the alignment of the pressure gradient with lower q allowing a higher pressure gradient for the same α. The further inside the plasma α_{max} is located, the lower j and j' is at the separatrix reducing the drive for kink/peeling modes, also leading to higher α. Conversely, localising the edge pressure gradient further towards the separatrix flattens the q profile and the smaller q shear has a destabilising effect on high n modes [23,19].

Fig. 1(a) shows how the maximum achievable pedestal top pressure calculated with a predictive stability work flow [24] using the ideal MHD stability code MISHKA [25] for a low and a high triangularity (δ) equilibrium depends on the total pressure, expressed as β_N. Also shown is the small effect of an increased effective charge $Z_{eff} = 2$ (dashed lines) over the reference $Z_{eff} = 1.3$ (solid lines). An increase in β_N from 1.5 to 2.5 leads to increased pedestal top pressure values by 5–10% for low-δ plasmas and ~15% for high-δ plasmas in typical ASDEX Upgrade plasmas. In Fig. 1(b) the effect of the position of the pressure profile is demonstrated. A small shift of only 5 mm (here equivalent to $\Delta\rho_{pol} \sim 0.01$) further inside and away from the boundary leads to an improvement of the stable pedestal pressure by 25%. Together these two effects can lead to a self-amplifying loop: if the pressure profile is shifted further inside, higher pedestal pressures can be achieved and yield higher core pressures via stiff temperature profiles, which in turn allow even higher pedestal top pressures.

2.1. Actuators which influence the pressure profile in the pedestal

The pressure profile is composed of the temperature and the density profile. It has been shown that the boundary condition of the electron temperature profile at the separatrix can be described by the two-point model [26], in which collisional heat conductivity along the field lines connects the mid-plane with the divertor target plates. The strong dependence of heat conductivity on the temperature as well as the increase of heat flux with the parallel temperature gradient does not allow large changes of the separatrix electron temperature at similar heating powers. A lowering of the separatrix temperature could be expressed as a shift of the pressure profile inward [27] with the same effect on pedestal stability as a shift in the electron density (n_e) profile depicted in Fig. 1(b). A significant shift of the electron temperature (T_e) profile can only be achieved with a dramatic reduction of heat flux across the separatrix. Because the density profile is governed by a complex interplay of poloidally varying transport and ionisation sources, the edge density profile position is much more flexible than the position of the electron temperature profile.

With these effects on the behaviour of the pedestal stability in mind, the actuators which influence the position of the density profile in the pedestal will now be discussed with special attention to wall materials and impurity seeding.