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ABSTRACT
Within the last few years significant progress has been made on the hybrid scenario in JET[1]. By introducing the so called current over-shoot technique significantly improved confinement with $H_{98,y2} \approx 1.3$ in low and high triangularity has been reached. This technique implements a fast current ramp to a high current followed by a current ramp down to remove some current from the edge. The effect is two fold. Firstly, the core q-profile is flatter than in the previous attempts utilising early NBI heating or LHCD and secondly, the magnetic shear is increased in the outer part of the profile $\rho_{tor} > 0.6$ transiently for about 1.5s on JET. Given this success at JET the question arose if a similar technique can be successful on ASDEX Upgrade (AUG), keeping in mind that heating in the current ramp alone can already be sufficient to improve the confinement [2] in AUG.

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As a follow up experiment the current over-shoot technique has been used in some preliminary experiments on AUG in a low δ configuration. Within a few pulses a similar quasi steady performance as seen on JET in a low triangularity shape was reached. The most important time traces can be found in figure 1. From a scenario development point of view there are some critical differences between the two tokamaks. In AUG, NBI preheat with $P_{NBI} = 2.5$MW is used to prevent complete current profile relaxation before the high heating power phase starts. In JET this is not necessary because the larger radius together with higher temperatures due to the better confinement are sufficient at the used current ramp rate to avoid the appearance of $q = 1$. On AUG the NBI preheat is stopped when the highest current is reached. This allows the current to diffuse first inwards and then the excess current from the edge is removed by the current ramp down. Then the plasma heating is increased to $P_{NBI} = 7.5$MW and $P_{ECRH} = 0.7$MWto raise the beta to a similar value as on JET. The additional ECRH heating helps to prevent high Z impurity accumulation in AUG which has a tungsten coated first wall. Also, a small gas puff of $3 \cdot 10^{21} s^{-1}$ is applied to stabilise the ELM frequency and to prevent W accumulation. As a result of this scenario a $\beta_N = 2.5$ with an improved confinement of $H_{98,y2} = 1.25$ has been reached. Unfortunately, due to the relatively low ECRH power and gas inlet some density peaking occurred and impurity accumulation did happen later in the pulse causing the confinement to roll over. The MHD activity consists only of a small 1/1 mode with some fishbones and a very weak n = 5 activity. In figure 2 a comparison of q-profiles from JET Pulse No: 75225 and AUG Pulse No: 25764 is shown. The profiles are from transport code calculations (TRANSP for JET/ASTRA for AUG) using the time evolution of experimental kinetic profiles and models for the neoclassical conductivity, bootstrap current and NBI current drive. The main assumptions used are a starting q-profile from the equilibrium code CLISTE (AUG) or EFIT (JET) with magnetics only constraint. The Zeff is taken from CXRS (assuming carbon as only impurity) for JET and from Bremsstrahlung deconvolution for AUG. For AUG a model for an additional current diffusion which might be produced by sawteeth or resistive fishbones is used.

This model prevents the central q from dropping far below one and is one reason for the centrally flat q-profile. Nevertheless it has been shown in the past e.g. by [3] that the current evolution in AUG can deviate from the one calculated by a transport code - whereas at JET it was found to agree nicely in the presented discharge [1]. The q-profiles look rather similar even though the edge q in AUG is higher because the magnetic field had to be chosen to allow central heating of the ECRH system at 140GHz. This is not well represented in the figure because the equilibrium in the transport codes at the edge in an X-point plasma are not precise and depend on the level of detail in the provided fixed boundary. In figure 3 the temperatures and the electron density profiles for the AUG pulse are shown. The density peaking $n_e\,(\rho_{\mathrm{tor}} = 0.4)/n_e\,(\rho_{\mathrm{tor}} = 0.8) = 1.33$ is weaker than in JET [1] where it amounts to 1.54. $T_i/T_e\,(\rho_{\mathrm{tor}} = 0.5) = 1.29$ is equal to the one of JET but $T_i/T_e\,(\rho_{\mathrm{tor}} = 0.2) = 1.3$ is smaller than the 1.43 for JET. The electron temperature profile inside $\rho_{\mathrm{tor}} = 0.3$ is more peaked on AUG. This might be connected to the fact that in AUG central ECRH was used but not in JET. Another observation here is that the toroidal rotation frequency profile plotted over ρ_{tor} is very similar to the one in JET. Therefore the gradient in ρ_{tor} is about the same and in major radius it is almost a factor of two higher. The dimension less parameters for the JET discharge shown are $\rho^* = 5.7\cdot10^{-3}$, $v^* = 1.2\cdot10^{-2}$, $\beta^{\mathrm{th}}_N = 2.16$, M = 0.49, $q_{95} = 3.96$, $R/L_{Ti}\,(\rho_{\mathrm{tor}} = 0.4) = 6.6$. The differences in normalised parameters ($\rho^* = 7.5\cdot10^{-3}$, $v^* = 4.5\cdot10^{-2}$, $\beta^{\mathrm{th}}_N = 2.1$, M = 0.33, $q_{95} = 4.24$, R/L_{Ti} $(\rho_{tor} = 0.4) = 6.8$ for AUG) is considerable in ρ^* and v^*. It has been shown that the density peaking depends on v^* [4]. The observation presented here is qualitatively consistent. The similarities in the confinement quality measured by $H_{98,\mathrm{y2}}$, q-profile shape and also the characteristics of the different kinetic profiles suggest that the scenarios are very similar on the two machines. This allows us to be more optimistic in further extrapolations to future machines e.g. ITER.

To put the results into the context of the AUG scenario development a comparison with other AUG improved H-mode scenarios is performed. To look into opposite corners of operation space a low density “classical” improved H-mode Pulse No: 15840 [2] ($\rho^* = 10\cdot10^{-3}$, $v^* = 2.2\cdot10^{-2}$, $\beta^{\mathrm{th}}_N = 2.1$, $q_{95} = 3.2$, $R/L_{Ti}(\rho_{\mathrm{tor}} = 0.4) = 6.55$) is compared with a more recent nitrogen seeded improved H-mode at high density Pulse No: 23777 [6] ($\rho^* = 7\cdot10^{-3}$, $v^* = 7\cdot10^{-2}$, $\beta^{\mathrm{th}}_N = 2$, $q_{95} = 4.7$, $R/L_{Ti}(\rho_{\mathrm{tor}} = 0.4) = 2.5$) and the newly achieved pulses with current overshoot. Since almost a decade in time has passed between the oldest pulse and the newest there are some caveats in this choice. The discharge selection has been done in a way that the achieved stored energy is matched at the same plasma current and heating power. This choice needs to make a compromise on the match of the toroidal magnetic field and by design on the plasma density and impurity content. On the other hand the $H_{98,\mathrm{y2}}$-factor is matched relatively well. The chosen discharges do not represent the best performance pulses. The “classical” improved H-mode can be run at higher normalised confinement at lower heating power and density or at higher beta with similar confinement as the example in this paper. The best performance with nitrogen seeding is reached at higher heating powers. The time traces are shown in figure 4. Both pulses are run with a straight current ramp to the maximum current with NBI preheat. The nitrogen seeded discharge starts with relatively large ELMs which shrink when the seeding in divertor temperature feedback is applied. Both plasmas are more stable than the current over-shoot plasmas achieved so far. In figure 5 the temperature and the density profiles are compared for the three AUG pulses. As one can see the ion temperature profile peaking is very similar for the “classical” improved H-mode (in black) and the current over-shoot pulse (in red). The nitrogen seeded discharge (in blue) has a much lower and flatter ion temperature profile but a higher density, which is still peaked. In figure 6 the q-profiles at the start of the main heating calculated by ASTRA (using the same assumptions as discussed before) are shown. The q-profiles at this time are different between the presented pulses, whereas the nitrogen seeded discharge (in blue) already has a mostly relaxed q-profile with q_0 below/close to 1, the “classical” improved H-mode (in black) has a slightly higher q in the core region and is relatively flat. The current over-shoot (in red) pulse is even flatter in the core and has a higher magnetic shear in the outer part of the plasma. Since all three plasmas have different q-profiles it is difficult to make a firm conclusion on the influence of q on the transport at this point in time. For reference a q-profile from a late heating (in green) [5] pulse is plotted as well. The central part of the q-profile is very similar to the ASTRA calculated profile for the current-overshoot pulse. In [5] the beneficial effect of the q-profile shaping on the turbulent transport is discussed in more detail.

The nitrogen seeding definitely has a strong influence on the transport as discussed in [7] by the dilution of thermal ions. The kinetic profiles of the classical improved H-mode look very similar to the profiles of the current over-shoot pulse. It seems probable that the current overshoot on AUG and JET are basically the same scenario as the “classical” improved H-mode. Unfortunately, the unavailability of measured q-profiles on AUG makes it very difficult to take this comparison further and to understand why the over-shoot technique is necessary at JET but optional on AUG. Nevertheless, it can be used on AUG as well and the obtained results are very similar to the ones of JET and strengthen the assumption that the scenario can be ported to even larger machines like ITER.

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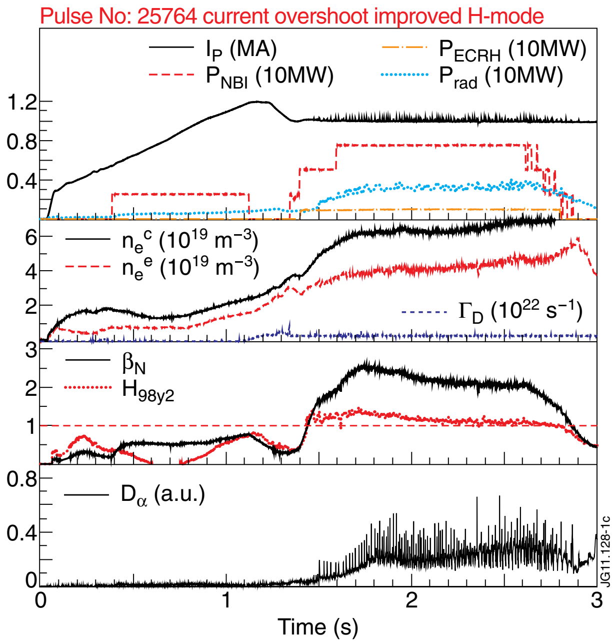

Figure 1: Time traces of a ASDEX Upgrade improved H-mode with current overshoot. Plasma current (black), NBI heating power (blue), ECRH heating power (orange) and radiated power in the upper graph. Line integrated electron density trough the core (black), edge (red) and applied gas puff rate (blue) in the second graph. The normalised beta and $H_{98,y2}$ in the third plot. D_a time trace in the bottom graph.

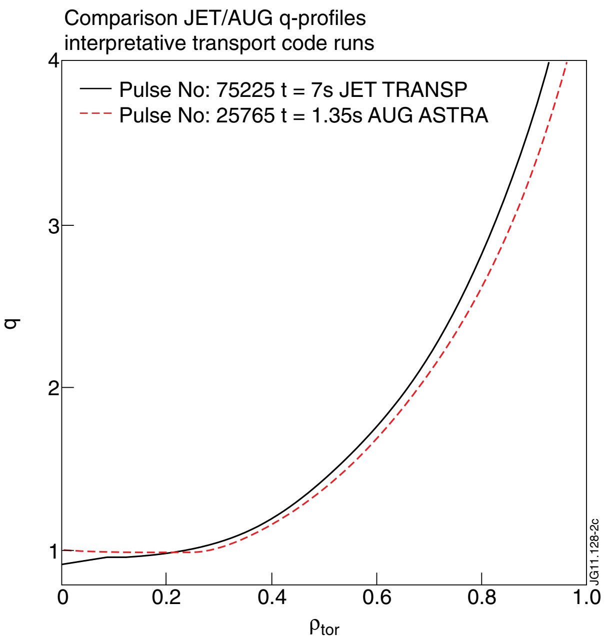

Figure 2: q-profiles shortly after the start of strong heating, from JET in black for AUG in red.

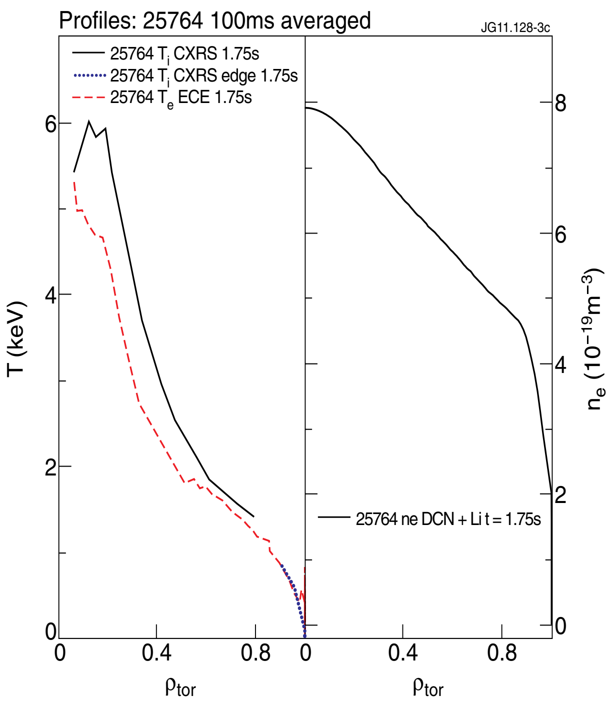

Figure 3: T_i from CXRS in black (thick for the edge system) and T_e from ECE in red in the left part. n_e from a deconvolution of 5 DCN channels and a Li beam edge density profile on the right hand graph.

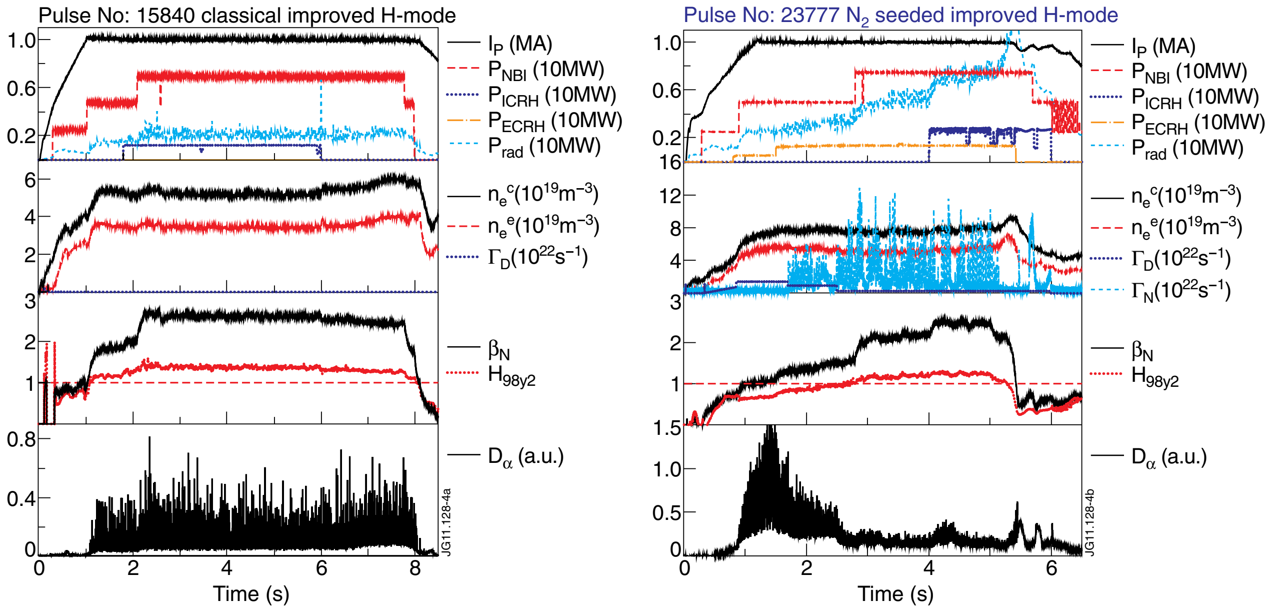

Figure 4: Time traces of two different improved H-modes, on the left hand a low density "classical" improved H-mode, on the right hand side a nitrogen seeded high density improved H-mode. The notation is the same as in figure 1. The electron density uses a different scale in the two figures.

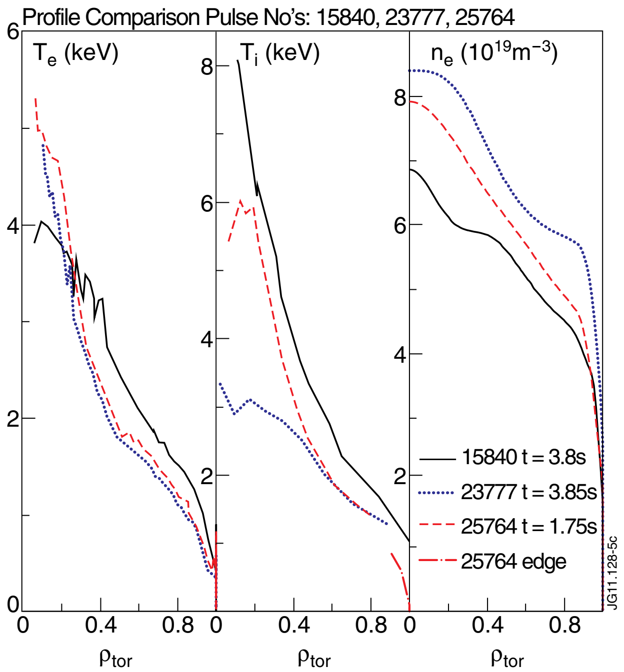

Figure 5: T_e from ECE in the left part. T_i from CXRS in the middle graph and n_e from is a deconvolution of 5 DCN channels and a Li beam edge density profile is plotted on the right hand graph.

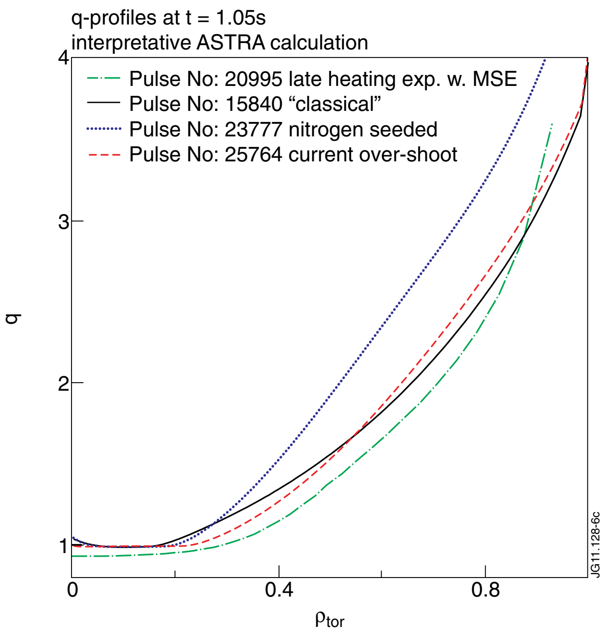

Figure 6: q-profiles shortly after the start of strong heating in AUG for the three pulses in different colors.