Development of a reactor relevant
high density high confinement scenario at ASDEX Upgrade

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INTRODUCTION

The operational scenario foreseen for ITER, DEMO and future fusion power plants is the high confinement mode (H-mode), favourable at high core densities close to or even beyond the Greenwald density n_{Gw} in order to maximize the harvest of fusion power. Most likely, core particle fuelling will rely on pellets, i.e. the injection of mm-sized bodies of solid fuel. In present tokamaks, a loss of the high confinement takes place already when approaching n_{Gw}. This behaviour, attributed to an edge density limit, can be easily overcome by deep pellet particle deposition [1]. Experiments reported here aim at the development of control techniques capable to incorporating pellet fuelling and the investigation of plasma scenarios for their suitability for plasma operation at high densities with good confinement. Covering a couple of reactor relevant features, our device ASDEX Upgrade (AUG) is especially eligible for this kind of investigations. Equipped with an all-metal-wall and a versatile set of diagnostics, it also comprises a flexible pellet system for high speed inboard launching and a powerful well proved and tested control system.

SET UP: ASDEX UPGRADE, PELLET LAUNCHER AND CONTROL SYSTEM

AUG is a mid-size divertor tokamak (major radius $R_0 = 1.65$ m, minor radius $a_0 = 0.5$ m) with all its plasma facing components completely covered with tungsten (W) [2]. The versatile set of auxiliary heating systems comprises 20 MW neutral beam injection (NI), up to 6 MW ion cyclotron resonance heating (ICRH), and 5 MW electron cyclotron resonance heating (ECRH). Investigations reported here were performed operating with the bulk tungsten divertor III configuration [3]. The centrifuge launcher combined with a "looping" guiding system is capable of injecting cubic pellets from the torus inboard (designated path inside the plasma shown in figure 1) with a particle content of either 1.4, 2.8 or 4.3 x10^{20} D atoms in the speed range 240 to 1050 m/s at repetition rates up to 83 Hz [4]. The real-time control system is capable to establish reproducible and stable operation in a wide range of scenarios applying algorithms for integrated control and actuator management on a multiple input multiple output bases. In order to foster investigations reported here a feature was added for the handling of pellet injection, taking into account the peculiarities as e.g. the long response time due to pellet time of flight and the sudden parameter response due to pellet arrival eventually resulting in distorted measurements [5]. A versatile set of diagnostics is available for analysis and characterisation. For the most relevant ones, locations or lines-of-sight are displayed in figure 1, showing AUG with divertor-III operated in the 2015/16 campaign.

RESULTS

Commissioning of the new pellet feedback control algorithm was made in a target scenario showing favourable response to nitrogen (N) seeding for confinement enhancement [6]. We applied a well proven approach, increasing the core density via pellets while keeping the edge density by reducing the gas puffing accordingly. Such, peaked profiles can be generated while keeping the initial confinement [7]. This time, instead of launching a pre-programmed pellet sequence, the density was kept at the requested level. However, all control parameters used have to be pellet resilient. Edge density control is achieved by acting on the neutral gas density in the divertor, the plasma core density via the "validated density". This density
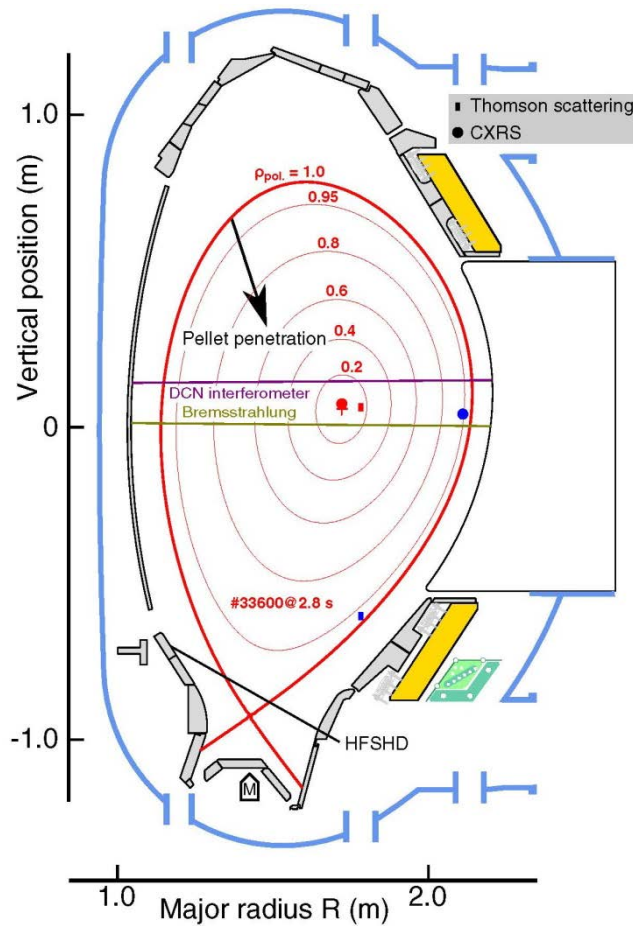
represents the line averaged density $\overline{n_e}$. It is calculated in real time from all available interferometer data. In case a fringe jump is detected, as it is very likely for pellet injection, the according signal is corrected if possible, otherwise de-validated. In case all interferometer channels are lost, algorithm switches to Bremsstrahlung (square root of raw signal), in situ calibrated to the endmost validated values from interferometers.

Figure 1: Set up of AUG with divertor-III in the W all-metal-wall configuration as operated during the 2015/16 campaign. Plasma shape of #33600 at 2.8 s; typical pellet penetration depth along designated injection trajectory. Locations and lines-of-sight of several relevant diagnostics or corresponding channels are indicated (M: manometer measuring divertor neutral density).
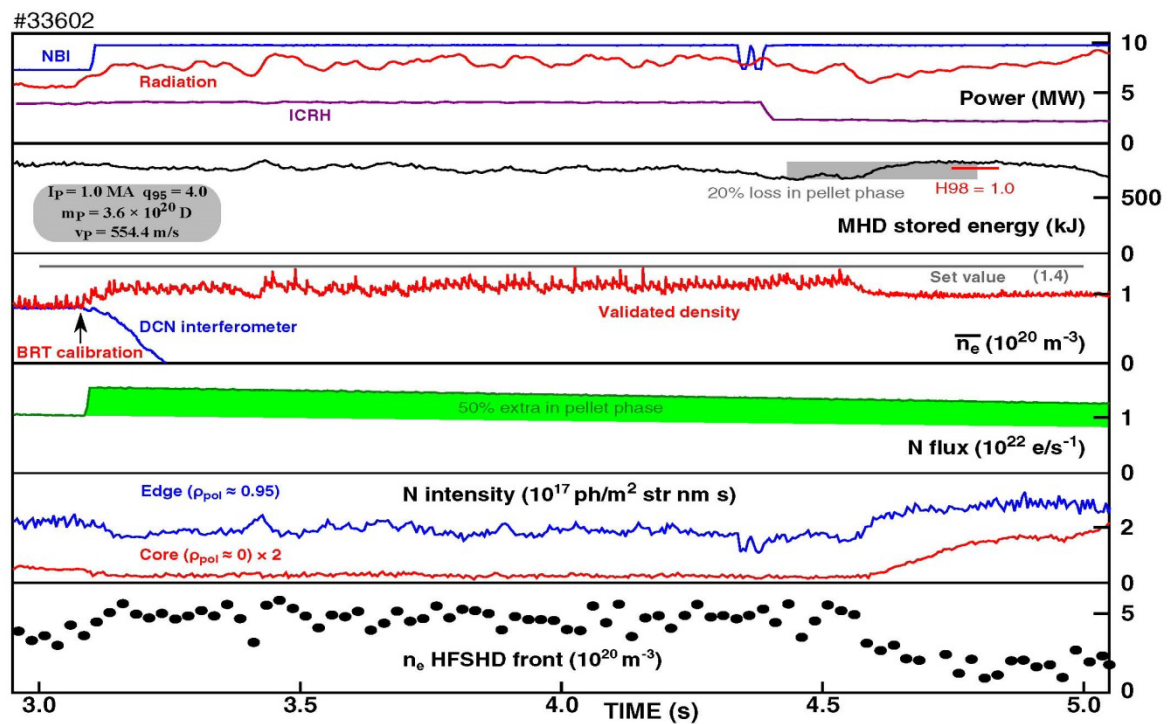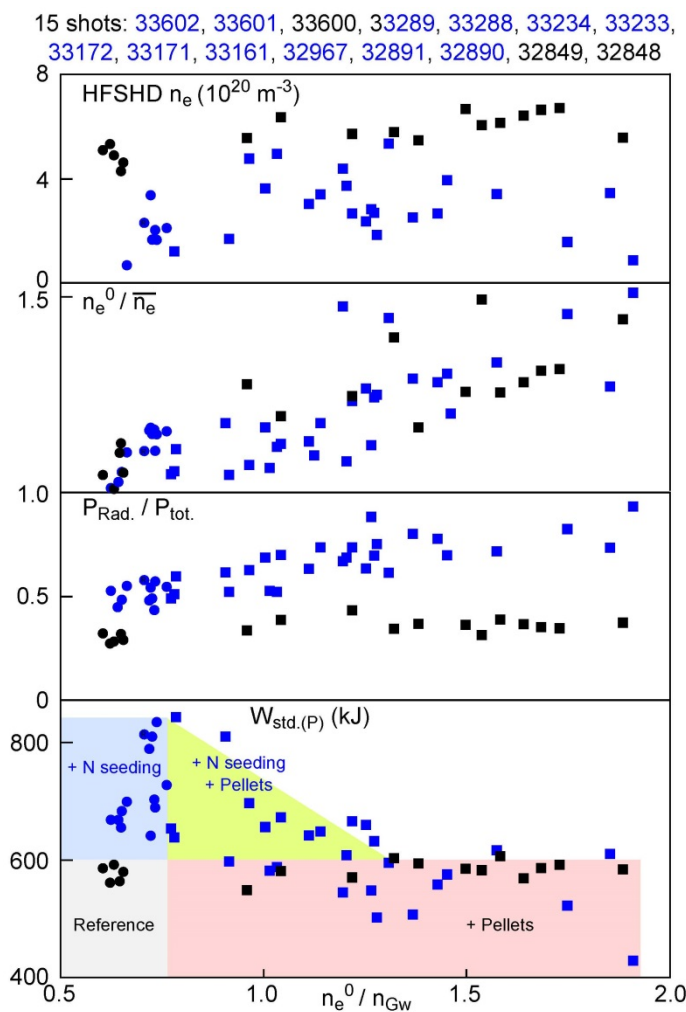

Figure 2: Feedback control on core and edge density via pellets and gas puffing, respectively. During the pellet driven high density phase, a confinement reduction of about 20% is observed with respect to the post-pellet reference phase with N seeding recovering confinement. This recovery correlates with a drastic drop of the HFSHD front density.

In pure deuterium plasmas, successful steady density control of $\overline{n_e}$ up to 1.4 x n_{Gw} was demonstrated, again smoothly keeping the initial plasma energy content. However, as rather typical for an all-metal-wall device, strong gas bleeding required to prevent impurity accumulation was accompanied by a slight ($\approx 20\%$) confinement reduction.

Adding appropriate N seeding can recover this loss by enhancing the pedestal stability via an inward shifted density profile by mitigating the high-field-side high-density (HFSHD) front [6]. Consequently, an approach was made combining pellet fuelling with N seeding. A typical attempt is shown in figure 2. Like in favourable seeding reference discharges, the N flux was ramped down accounting for the N legacy in the vessel in order to achieve a steady N level. As on the other hand it was observed N enrichment in the divertor is even stronger during pellet phases [8], the resulting N depletion in the plasma requires enhanced N puffing. Hence, we applied typically 50% extra N flux during the pellet phase. While the set density is approached smoothly, plasma energy gradually decreases finally dropping back to non-seeding reference value. This loss correlates to a reappearance of the HFSHD density front and a shift back of edge profiles. After the pellet phase, the initial seeding behaviour quickly recovers. Evidence of pellet actuation abolishing beneficial impact of N is further substantiated by the data from a set of 15 shots, 3 non-seeding references and 12 with N seeding, displayed in figure 3. All data are taken from all reasonably steady phases and ordered with respect to the central density n_e^0 normalized to n_{Gw}. As can be clearly seen from the achieved plasma energies (small variations in the total heating power are standardized by $\sim P_{tot}^{1/3}$) pellets do expand the operational space towards higher densities while N seeding

15 shots: 33602, 33601, 33600, 33289, 33288, 33234, 33233, 33172, 33171, 33161, 32967, 32891, 32890, 32849, 32848

improves the confinement – however their combination only modestly can merges both benefits. N seeding results in a higher radiative power fraction, getting even stronger with increasing density although the profile peaking remains unaffected. The reason of the reverted N effect becomes clear from the uppermost box of figure 3. With the onset of the core density increase, the HFSHD front reappears causing a loss of all positive effects on density profile and edge stability. Although the HFSHD density seems to roll over towards the highest densities, the deterioration cannot be reverted. We attribute this to the high loss fraction caused by the strong radiation.

Figure 3: Bottom to top: Plasma energy (standardized with respect to P_{tot}), ratio of radiated power, density peaking factor and magnitude of the HFSHD front versus core density (normalized to n_{Gw}). Dots: reference, squares: pellet phases; black: non-seeding, blue N seeding plasma.

Interestingly, also in the non-seeding phase pellet actuation results in an enhancement of the HFSHD front density. Starting from an already elevated level, here the further increase has no

effect on the energy confinement. Obviously, the deleterious effect of the HFSHD on edge and confinement seems to saturate at a certain level. This can be seen more clearly in figure 4, displaying the standardized plasma energy versus HFSHD front density for cases without excessive radiative losses. Beyond a density of about $4 - 5 \times 10^{20}$ m^{-3} no further energy reduction takes place. Thus, pellet actuation in the pure D case does not show any more negative impact on the confinement. Recently, we turned our investigations to different scenarios. Two options have been identified, both showing good performance with however yet modest pellet fuelling operating a medium densities still below n_{Gw}. The first one is the ITER base line scenario where small pellets injected for the sake of ELM control in the $q_{95} = 3$ showed efficient fuelling response. However, the "alternative" variant at $q_{95} = 3.6$ seems to be a more eligible target since for this scenario operation at a higher Greenwald fraction is expected more favourable [9]. The other on is a close to double-null scenario at high triangularity yielding access to type-II ELM regime responds very positively to pellet fuelling. Here, replacing the entire gas puffing by pellets carrying only about 35% of the reference gas particle flux resulted in a slight enhancement of the core density to about $0.9 \times n_{Gw}$ while keeping almost full energy confinement. This is accompanied by a strong drop of the divertor neutral gas pressure and a drastic increase of ELM frequency. Showing only small type-II ELMs in the gas phase, type-I ELMs returned by pellet fuelling in these plasmas [10]. Within error bars, the pedestal pressure was kept constant as well as the gradients of temperature and density. For both scenarios, further investigations are currently under way.
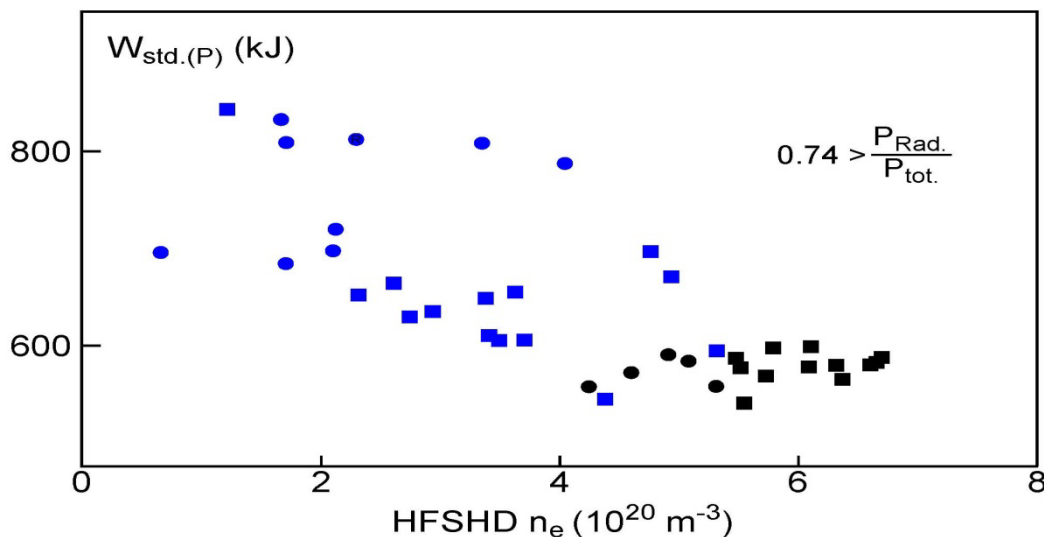

Figure 4: HFSHD front density versus standardized plasma energy. Data from shots indicated in figure 3 (blue: N-seeding, black pure D; circles reference phases, squares pellet phases). Data set restricted to cases with limited radiated power fraction.

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