Controlled fuelling of high density scenarios at ASDEX Upgrade in support of ITER and DEMO

P. T. Lang, L. Casali, Ch. Day[1], M. Dunne, E. Fable, R. Fischer, O. Kardaun, G. Kocsis[2], B. Kurzan, R. McDermott, V. Mertens, A. Mlynek, B. Ploeckl, Ch. J. Rapson, I. Sharov[3], T. Szepesi[2], W. Treutterer, E. Viezzer, H. Zohm, ASDEX Upgrade Team

MPI für Plasmaphysik, EURATOM Association., Boltzmannstr. 2, 85748 Garching, Germany
1) Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany
2) WIGNER RCP RMKI, POB 49, 1525 Budapest, Hungary
3) State Polytechnical University, 29 Politechnicheskaya st., 195251 Saint Petersburg, Russia

INTRODUCTION

Standard operation in a future fusion reactor will aim to establish a high core density in order to harvest a maximum of output power. In addition, a high separatrix density is essential for achieving the necessary detached divertor scenario [1]. Therefore, in the ITER project and in European DEMO studies [2], core fuelling to planned target densities is envisaged to be performed entirely by injecting pellets formed from frozen fuel and launched from the torus inboard side. On the other hand, the separatrix density will most likely be adjustable by gas puff in these devices, leading to a certain degree of freedom in the control scheme of core and separatrix (edge) density. The development of relevant high-density plasma scenarios and related control strategies capable to cope with pellet actuation became hence an important task within the ASDEX Upgrade (AUG) program [3]. AUG, equipped with a pellet system adapted to efficient inboard fuelling, as well as with a sophisticated discharge control system for flexible real time plasma control and also a versatile set of diagnostics, is very suited for this kind of investigations. Accordingly, a summary of the efforts undertaken will be reported.

SET UP: ASDEX UPGRADE, PELLET LAUNCHER AND CONTROL SYSTEM

ASDEX Upgrade [3] is a divertor tokamak with all plasma facing components completely covered with tungsten (W). In-vessel saddle coils can produce non-axisymmetric magnetic perturbations, presently 16 B-coils (each 8 upper and lower ones, referred to as Bu- and Bl-coils, respectively) are installed which can create a mainly radial field with toroidal mode numbers up to n = 4 [4]. Investigations reported here where performed operating with the newly installed massive tungsten divertor III configuration.

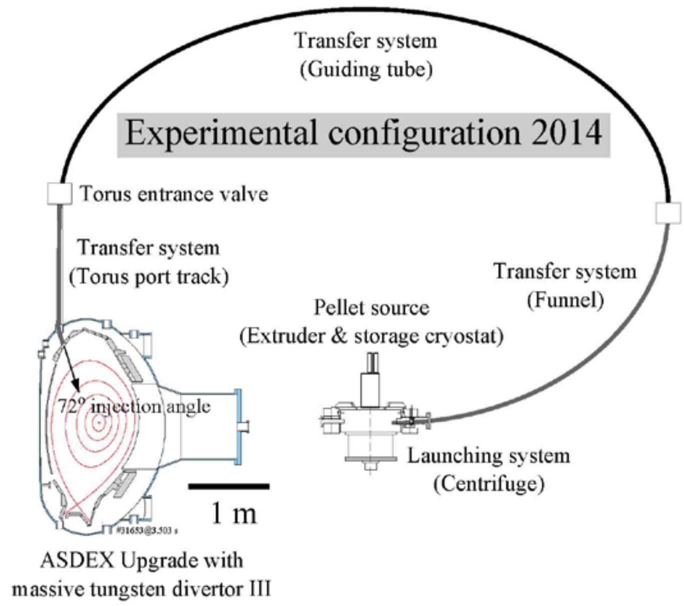

Figure 1: Set up as operated in the campaign 2014. AUG with an all W cladded wall and now also equipped with the massive tungsten divertor III and the full set of B coils. The revitalized pellet launching system was optimized and commissioned for efficient particle fuelling from the torus inboard at high speed and high particle throughput. As well, admixing different gases to the main fuelling species (mostly deuterium) is now facilitated.

The pellet system based on a centrifuge accelerator and a looping transfer line has been optimized and commissioned for efficient core particle fuelling. Presently, the system is capable of delivering pellets with a nominal particle content ranging from 1.5 – 3.7 x 10^{20} D in the velocity range 240 – 1040 m/s from the magnetic high field side of the torus with repetition rates of up to 70 Hz. Within a given pellet train launched into a discharge both pellet speed and size are fixed. The pellet imposed particle flux applied for fuelling can be adjusted by changing the pellet repetition rate. However, due to the centrifuge principle only rates equal to an integer fraction of the centrifuge revolution frequency can be chosen. Recently, the pellet source was modified now allowing admixing small amounts (up to 5%) of other gas species to the main pellet carrier gas (usually deuterium). Hence, investigations became possible with pellets composed essentially from fuel but with some admixtures [5]. The pellet observation system was also upgraded to include two ultra-fast CMOS cameras and is now capable of fast individual pellet tracking up to 1 Mframe/s.

The discharge control system (DCS) [6] is our tool for fully-automated and controlled execution of the plasma discharges. It supplies sophisticated real-time control methods comprising real-time diagnostic integration, dynamically adaptable multivariable feedback schemes, actuator management and a powerful monitoring and pulse supervision concept based on segment scheduling and exception handling. Therefore, the DCS requires reliable and valid information about the plasma density. Usually measured by a DCN laser interferometer, data can become invalid due to the strong pellet imposed local perturbation. Therefore, a sophisticated performance evaluator electron density module was designed. It computes the density from different DCN and CO_2 laser interferometer channels and a specially adapted Bremsstrahlung channel. Results are auto-corrected if possible (e.g. by detecting and eliminating DCN fringe jumps) or set invalid. A replacement strategy for invalidated interferometer densities tries to compute a substitution value from the average of the remaining valid interferometer channels. If no valid interferometers signals remain the value BRT calculated from the Bremsstrahlung (density assumed proportional to square root of signal) are adopted. In order to avoid offset errors, the BRT signal is calibrated against the last trusted density measurement from the interferometer.

CONDITIONING OF LAUNCHING AND CONTROL SYSTEM

The newly set up density module first was carefully tested and commissioned to ensure reliable and safe machine operation with the pellet actuator. It turned out helpful to provide the DCS information of an envisaged pellet arrival as “a priory” information for the fringe correction and substitution algorithm and to take eventually according control actuation by e.g. pausing ECR heating during the pellet ablation (“notching technique”). The pellet launching system was optimized with respect to the fuelling performance taking into account the pellet production process [7] and all pellet parameters. The best setting found, applied for essentially all fuelling experiments is at a speed of about 560 m/s for the largest available pellets. Thus, at a maximum rate of 70 Hz a pellet particle flux of about 2.6 x 10^{22} D/s could be established.

FUELLING OF THE NITROGEN SEEDED IMPROVED H-MODE SCENARIO

In the all-metal wall configuration, considerable energy confinement improvements can be realized in some plasma scenarios by applying N seeding [8]. This is in particular the case for the scenario applied for our recent investigations of the high density regime. Here, pellet fuelling easily achieved core densities far beyond the Greenwald limit n_{Gw} with high density operation resulting in benign ELM behaviour without affecting the energy confinement [9]. Steady state phases could be achieved but only at a moderate value of H98 $\approx$ 0.76. Incorporating N seeding at an appropriate level enhanced this value to about 1 for cases applying sole gas (D and N) puffing reaching densities of about 0.7 x n_{Gw}. In the approach

reported here it was aimed to combine pellet fuelling and N seeding in order to establish high density high confinement operation if possible still emerging benign ELM behaviour.
Ultimately, simultaneous real-time control of the edge and the core density will be requested. Here, the purpose was to establish a high central electron density n_e^0 beyond n_{Gw} while keeping the separatrix density n_e^{sep} constant in order to prevent edge-induced confinement degradation. For this, pellet injection and conventional gas puffing are employed as actuators; the pellet sequence pre-programmed and the gas puff in feedback control. Standard n_e^0 and n_e^{sep} measurements are not compatible with pellet actuation. However, unambiguously correlated substitutes have been identified utilisable for the investigated high density scenario. The divertor neutral gas pressure n_0^{div}, measured by a pressure gauge, was found to be directly correlated with n_e^{sep}. For n_e^0 control, the validated line-averaged plasma density $\overline{n_e}$ as provided by the DCS density module can be employed. By employing these surrogate control parameters, core densities up to 1.9 x n_{Gw} have been established by pellet injection while n_e^{sep} was kept stable by controlled reduction of the initial gas puff rate. An example is displayed in figure 2. There, n_e^{sep} is kept by controlling n_0^{div} via actuation on the gas puff while a steady train of pellets evokes a strong core density rise.

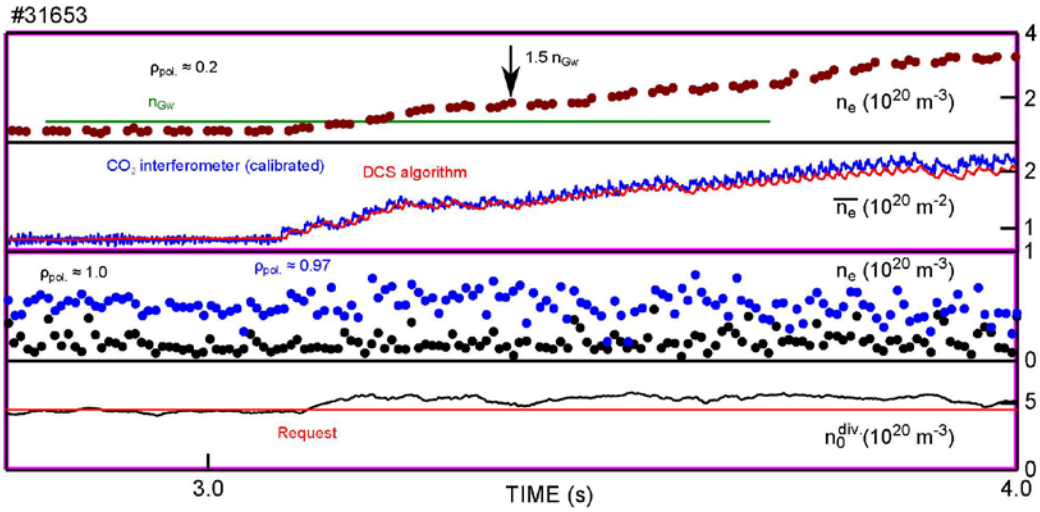

Figure 2: Controlling the divertor neutral gas pressure keeps the local edge density (close to separatrix at $\rho_{pol} \approx 1.0$ and pedestal top at $\rho_{pol} \approx 0.97$) constant. The increase of the validated line average density correlates well with the evolution of the core density at $\rho_{pol} \approx 0.2$.

Obviously, high density operation is achieved straightforward with pellet fuelling in the N seeding scenario as well. However, a strong N pump out was observed for peaked density profiles generated by pellet injection. Depletion of N resulted in an ensuing loss of the N induced confinement surplus, ultimately causing a setback of confinement to values typical for unseeded discharges. As a countermeasure, enhanced N puffing was applied during the pellet phase. Such the depletion effect can be mitigated, however too strong puffing resulted in impurity accumulation causing finally a radiative collapse. The best case achieved so far applying simple feed forward N puffing is shown in figure 3. It also shows the discharge from figure 2 with a steady single pellet train and feedback controlled edge density.
During the pellet induced high density phase, ELM amelioration is still observed. Nitrogen puffing during the initial phase results in a significant confinement surplus with respect to the unseeded reference. The N depletion in the high density phase is here partially compensated by an added extra to the reference puffing rate. However, this causes obviously an accumulation of heavy impurities (particularly W, concentration c_W displayed) towards the end of the high density phase finally resulting in a strong confinement reduction due to the increasing radiative loss power. Nevertheless it becomes obvious high density operation is feasible with at least some of the N induced extra confinement still preserved. A first step

consequently envisaged for the campaign 2015/16 is to extend feedback control also on pellet actuator. Aiming to control n_e^0 at a reasonable level by accordingly reducing the pellet rate/flux is expect to result in less N depletion and confinement surplus loss. Next, N seeding in feedback control will be implemented to avoid unbearable radiative losses.

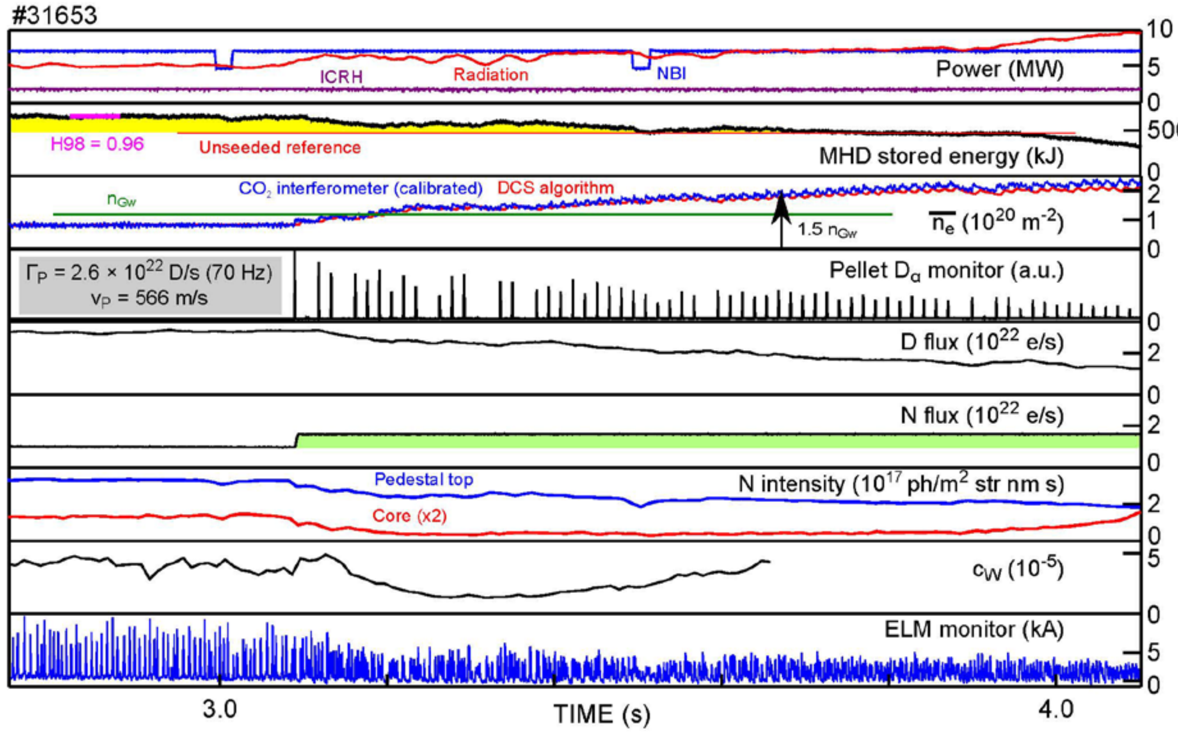

Figure 3: The N pump out can be mitigated by an increased N puffing rate during the high density phase. Thus, high density operation with benign ELM behavior and still higher confinement compared to the unseeded reference can be achieved.

PELLETS WITH NITROGEN ADMIXED

Motivated by the higher fuelling efficiency of the pellets with respect to gas puffing and the prediction N admixed to D ice can enhance the mechanical stability [10], we performed an attempt to supply the N for seeding at least partially by the pellets. Indeed, by forming pellets from a gas mixture containing 1% N, an N contends of 0.8% in the pellets could be detected. As well, an enhancement of the N concentration in the plasma during the pellet phase was confirmed by spectroscopy. However, although delivering of N was found more efficient than by gas puffing, the N flux carried by the pellets was still insufficient to gain significant impact on the confinement. In addition, no positive influence on the mechanical stability of the pellets could be found. Contrary to these expectations, less density increase was observed when injecting N admixed pellets compared a train of pure D pellets. This seems to indicate for higher pellet mass losses during the transfer and hence a reduction of mechanical stability.

REFERENCES:

[1] H. Zohm et al., Nucl. Fusion 53, 073019 (2013)
[2] P.T. Lang et al., Fusion Eng. Des., in press (2015)
http://www.sciencedirect.com/science/article/pii/S0920379615002434
[3] U. Stroth et al., Nucl. Fusion **53,** 104003 (2013)
[4] W. A. Suttrop et al., Proc. 40th EPS conference (Espoo), P4.117 (2013)
[5] B. Ploeckl et al., Fusion Eng. Des., in press (2015)
http://www.sciencedirect.com/science/article/pii/S0920379615000241
[6] G. Raupp et al Fusion Eng. Des. **84**, 1575 (2009)
[7] B. Plöckl and P. T. Lang, Rev. Sci. Inst. **84**, 103509 (2013)
[8] J. Schweinzer et al., Nucl. Fusion **51,** 113003 (2011)
[9] P.T. Lang et al., Nucl. Fusion **54,** 083009 (2014)
[10] L.A. Alekseeva et al, Physics of the Solid State **48**, 1513 (2006)