CONTROLLED HIGH DENSITY OPERATION BEYOND THE GREENWALD LIMIT ON AUG BY INBOARD PELLET INJECTION

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1. Introduction

The injection of frozen deuterium pellets from the magnetic high field side (HFS) of a tokamak has the potential to become an efficient particle refueling source in next generation fusion devices [1]. Despite being technically more demanding HIS-injection proved to be superior to injection from the torus outside due to the nature of the toroidal curvature which tends to expel ablating pellet clouds injected from the magnetic low field side (LFS) [2]. The same effect is very beneficial for HFS injection where the refueling flux penetrates significantly deeper into the core enabling rapid bulk density enhancement and efficient bulk density control. At the same time, conservation of plasma energy and energy confinement time are crucial to sustain a lasting refueling procedure. In a series of experiments the pellet injection hardware was adapted to operate at very high repetition rates to study and if possible optimize the operation space for controlling densities beyond the empirical density limit [3] as envisaged in ITER scalings [4].

2. Experimental setup

The refueling studies were performed on ASDEX Upgrade (R_o = 1.65 m, plasma radius a_o= 0.5 m, V_{plasma} = 13 m^3, b/a =1.6) with lower single null configuration, I_p = 0.8 MA, $B_t \cong 2$ T, $q_{95} \cong 4$, P_{NI} = 5 - 10 MW. The set up of the pellet injection system is shown in Fig. 1 with two injectors available, a centrifuge and a blower gun. The latter was used only in proof-of-principle experiments [l] where pellets were injected horizontally at a velocity of 130 ms^{-1} and repetition rates of up to 17 Hz.

The centrifuge injector [5], able to deliver pellets of variable velocity and mass, operated in the mode of v_{pel}= 240 ms^{-1} and $m_{pel} = 3.8 \cdot 10^{20}$ particles. The velocity corresponds to a centrifuge revolution frequency of 60 Hz, yielding so far pellet repetition rates of up to 30 Hz. In order to cover the large refueling particle flux required the system was optimized to allow for repetition rates of 60 Hz. On leaving the centrifuge pellets are guided via a funnel and a 5 m long teflon tube toward the magnetic high field side of the torus. They are injected into the plasma under an angle of 44° to the horizontal plane in order to maximize the radius of the guiding tube to minimize the centrifugal forces on the pellet.

Pellets were video monitored on their entrance into plasma. The plasma density enhancement was measured by the DCN-interferometer, the Thomson scattering system and the edge lithium beam diagnostic.

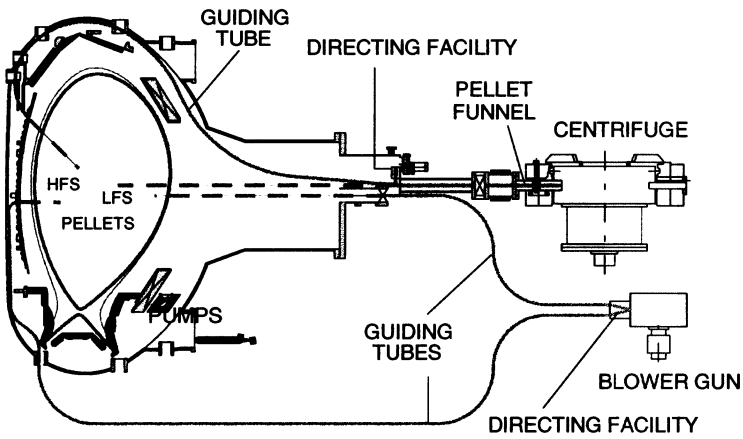

Fig. 1. Experimental arrangement for pellet injection from the magnetic low- (grey) and high field side (black) centrifuge and blower gun injectors.

3. Experimental results

The measured increase of the number of particles in the target plasma divided by the number of particles in the pellet leaving the cryostat is defined as the fueling efficiency ε_f. The graph in Fig. 2 compares HFS- and LFS-refueling efficiencies for both injectors. HFS-fueling efficiency is dominated by pellet mass losses of at least 60% occurring in the guiding tube. However, losses in the plasma approach zero and the fueling efficiency does not degrade with increasing heating power. In contrast, LFS-refueling does not suffer from tube losses, but experiences increasing plasma losses with rising heating power. Expectably, the efficiency of blower gun HFS-refueling is about 15% higher than that of the centrifuge be-cause of the different injection planes and the additional interaction with the funnel experienced by the centrifuge pellets.

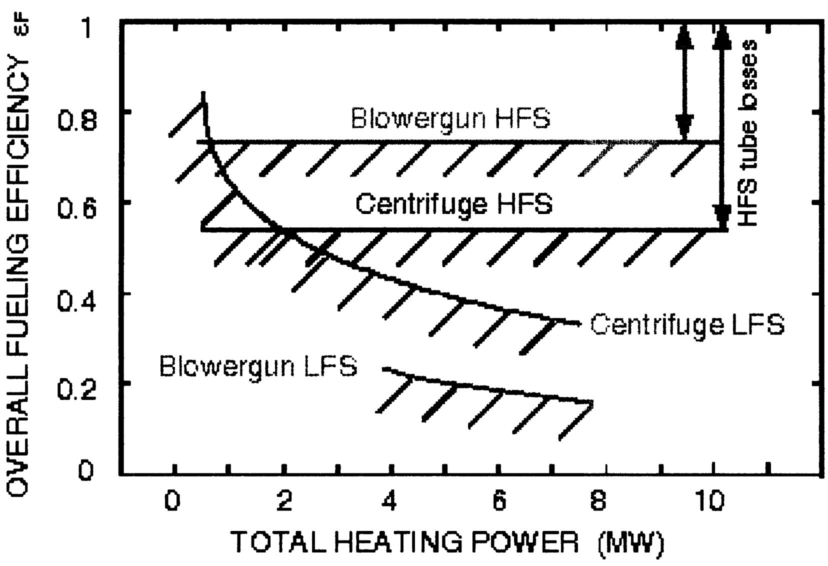

Fig. 2. Maximum fueling efficiencies achieved for pellet injection from the magnetic low- (gray) and high field sides (black), curves of centrifuge (solid) and blower gun (dashed). 15% loss common to all types of injection is already taken into account.

Taking into account the losses the particle flux supplied by the centrifuge to the torus inside reduced from 2.40 $\cdot 10^{22}$ particles/s to 10^{22} particles/s. In spite of this, an ice reservoir of up to 96 pellets enabled density control over 3 s bearing in mind that permanent operation at 60 Hz was not required due to the very fast density ramp up at this frequency (t_{rise} < 100 ms). Quasi-steady-state operation was attained by feedback controlling two parameters, the line averaged electron density and the divertor neutral gas pressure, $n_{o,div}$, as a measure of the separatrix density. An exemplary discharge is displayed in Fig. 3. After the rapid density ramp-up steady state H-mode operation is retained around the Greenwald limit for a 2 s fueling phase controlled by bursts of 60 Hz pellet trains. The particle flux is supported by very little gas puffing such that the divertor pressure could be kept at low value, one of the conditions for good energy confinement [6].

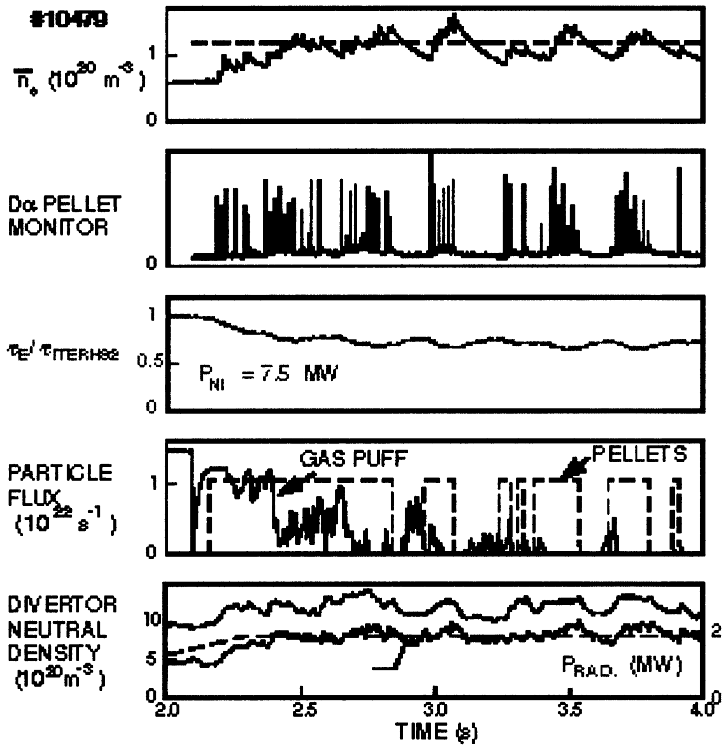

Fig. 3. Quasi steady-state pellet fueling at a feedback controlled density of $1.2 \cdot 10^{20}$ m^{-3} (dashed line, $n_{e,GW}$ ~ $1.07 \cdot 10^{20}$ m^{-3}) by HFS pellet injection.

The plasma energy falls by about 20% during the refueling phase despite the low level control of $n_{o,div}$. In addition to the neutral pressure dependence confinement degrades with MHD-mode activity [7]. A first series of discharges aiming to improve energy confinement during HFS-refueling was performed (one discharge was LFS-refueled). The divertor gas pressure was controlled by additional cryopumping. The switching on of the neutral injection heating power, P_{NI} was adjusted so as to delay the onset of neoclassical tearing modes, and the influence of the radiated power, P_{rad} was studied by the injection of impurity gases such as neon and CD_4.

The results are summarized in Fig. 4 (note suppressed zero). The plasma energy is plotted against line averaged density, and each discharge is represented by the temporal evolution of its energy confinement. Apparently, there is a clear cut limit in energy confinement independent of auxiliary heating and pumping scenario. Although at medium densities plasma energies beyond values expected by the ITER H92P_{tot}(y) scaling law are obtained, densities close to and beyond the Greenwald limit are only achieved with increasing losses in energy confinement. Possible indications for transport enhancement during these refueling phases are discussed in a paper by V. Mertens et al. [8]. Expectably, a gas-puff fueled discharge trace plotted for comparison seems to subscribe to the density limit.

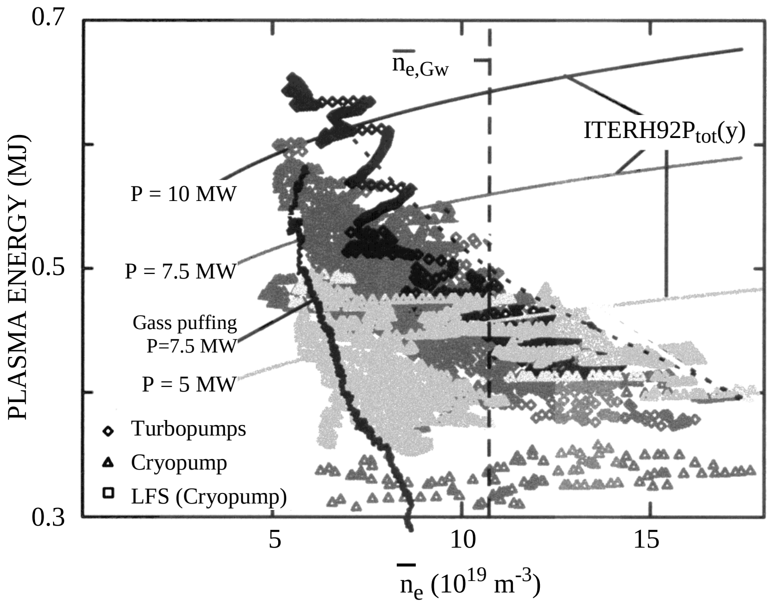

Fig. 4. MHD plasma energy vs. n_e in pellet refueled discharges; note suppressed zero; all discharges have the same magnetic configuration.

Legend: achieved plasma energies at different P_{NI} levels (10 MW - black; 7.5 MW –gray, 5 MW - light gray) are compared to the values calculated using the ITERH92P_{tot}(y) scaling.

The dotted line marking the confinement limit is only for orientation.

4. Summary

HFS pellet injection using a centrifuge confirms that the fueling efficiency does not decrease with increasing heating power. The system has been upgraded to enable controlled high density operation during refueling phases as long as 3 s. A series of discharges aimed at better energy confinement by trying to delay MHD-mode activity and adjusting divertor gas pressure and impurity puffing revealed a preliminary confinement limit. The underlying scenarios have to be understood, but scaling laws such as ITERH92P_{tot}(y) should be used with caution when extrapolating to density regions close to and beyond the Greenwald limit.

References

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