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Supersonic Molecular Beam Fuelling at ASDEX Upgrade

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Introduction

Besides the two common fuelling techniques used in all major tokamak experiments, namely the gas puff and the frozen pellet injection, a new technique, the so-called supersonic molecular beam injection (SMBI), has been developed at Tore Supra. This technique is based on the fast expansion of a small volume of deuterium at high pressure (typically 2-5 bars) through a laval nozzle into the plasma chamber. Results obtained in limiter configuration look promising: enhanced fuelling efficiency (defined as the increase in plasma particle content divided by the number of injected particles) compared to gas puff, in the 30-50% range, have been observed. Recently, one SMB injector has been implemented in the divertor tokamak ASDEX Upgrade in order to study ELM control [1] and assess the fuelling potential of the technique. First fuelling results obtained in divertor configuration are reported and discussed in this paper.

Experimental setup

The supersonic pulsed injector installed in ASDEX Upgrade was built at CEA Cadarache and is identical to those installed in Tore Supra [2]. The injector head is imbedded in the torus low field side, slightly above the equatorial plane ($R = 2.25$, $z = 0.16$ m) in the shelter of an antenna protection limiter (figure 1). Due to restrained space in the vicinity of the torus, the magnetic compressor orientation had to be modified compared to the original design, leading to somewhat reduced operational parameters. Reliable conditions were found with the following parameters: gas pressure 2.5 bars, frequency 2 Hz. Note that the nozzle throat diameter is 2 mm for an exit diameter of 8 mm. It produces a molecular beam at mach ~4.5, which corresponds to a beam divergence of ~20° and a molecular speed at the exit of the nozzle of ~1.8 km/s (theoretical values), about twice the initial sound speed of D_2 molecules (at 20°C). In situ calibration pulses were performed to measure the amount of particle release per pulse. For this operating conditions, $7\ (\pm 1)\ 10^{19}$ D were injected per pulse. 1-2 ms pulse duration gives a flow rate in the 3-8 10^{22} D/s range. The beam trajectory is crossed at the plasma edge by the line of sight of a D_α diode. Typical distance from the nozzle to the separatrix was about 9 cm.

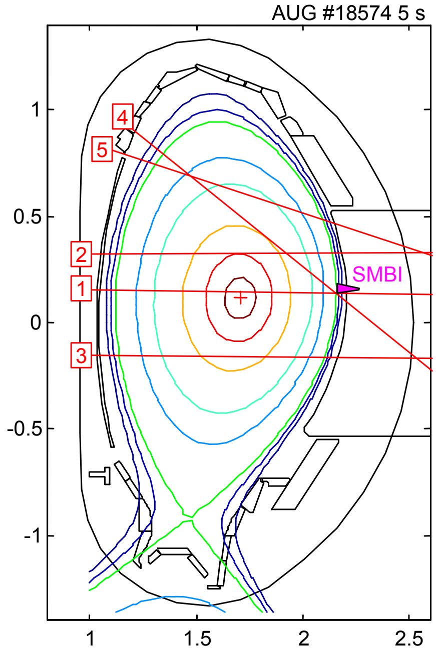

Figure 1. Cross section of ASDEX Upgrade showing the location of the SMBI (on the LFS) and the horizontal chords of the DCN interferometer (H-1 → H-5).

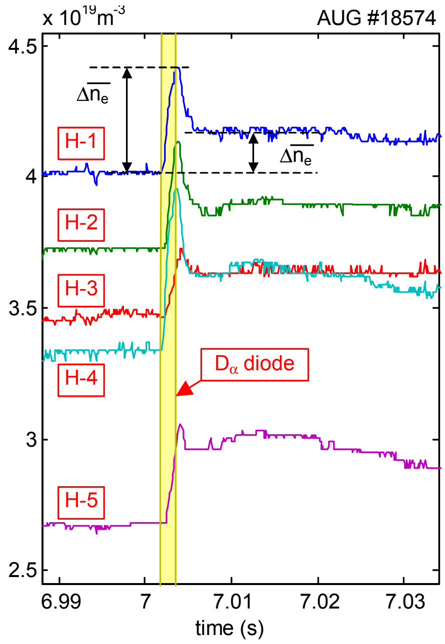

Figure 2. Temporal evolution of the line averaged density from the DCN interferometer channels during a SMBI pulse delimited by the D_α diode signal (ohmic pulse).

Experimental results

SMBI pulses have been performed on various plasmas. A typical plasma density response in L-mode plasma (#18574, Ip = 1 MA, Bt = -2.75 T, ohmic phase) is shown in figure 2: the injection lasts 1.9 ms (diode signal), meanwhile the plasma density rises accordingly. Note that the density increase is significantly different from channel to channel: channel #4, which is the first to rise, exhibits the highest Δn_e while #5, the last to react, shows no rapid decrease after the pulse. This inhomogeneous behaviour can be attributed to local effects. Indeed, the SMBI and the DCN interferometer are located in the same toroidal sector (11) and the channels responses are correlated with their poloidal distance to the beam (see figure 1 and 2). Hence, the peaks are probably due to the local density build up produced by the ionisation of the beam passing through, which is expanding at sound speed. The increase in plasma particle content due to the SMBI, worked out a few ms after the pulse, after toroidal and poloidal homogenisation, is about 1.9 10^{19} D, corresponding to a fuelling efficiency of about 30%. Figure 3 shows some SMBI in the preceding ELMy-III phase (PNI = 2.5 MW) in the same discharge. The computed fuelling efficiency is very similar. Besides, standard gas bleed was necessary to maintain the density after the NBI switch off. The drops in the gas bleed flux highlight the impact of the SMBI in the L-mode phase. In ELMy-I plasma (PNBI = 5 MW), at higher density, the SMBI perturbation is smaller as shown in figure 4, even smaller than the ELM perturbation. However, substantial steps in density are still observed, sensitive to the timing with respect to the ELM-I, and the worked out fuelling efficiency reaches up to 15%. No confinement degradation is observed.

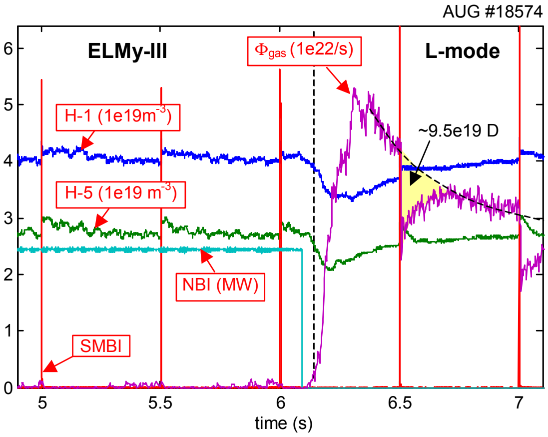

Figure 3. Temporal evolution of central and pedestal density, NBI heating, gas puff flux with SMBI pulses at 5, 5.5, 6, 6.5, 7 s (diode signal).

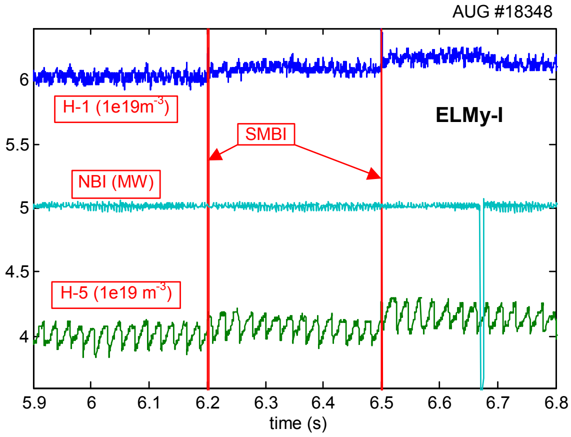

Figure 4. Temporal evolution of central and pedestal density in a 5 MW NBI ELMy-I H-mode plasma with 2 SMBI pulses at 6.2 and 6.5 s (diode signal).

Discussion

The comparison of this results with those obtained at Tore Supra [3] with the same hardware leads to the following conclusion: the impact of the SMBI on the plasma is much weaker. The main reason comes from the difference in the amount of particle involved per pulse (limited for technical reasons). While nearly 10% of the plasma content was injected in AUG, 50% was injected in TS, provoking a massive cooling of the plasma edge (T_{LFCS} <10 eV) that even extends in the confined region. Indeed, there is not enough energy in the peripheral plasma, density and temperature profiles being peaked, to fully ionise and heat the intense molecular flow. The consecutive detached phase that lasts a few tens of ms benefits the penetration of the incoming neutrals from the beam and the recycling flux. In AUG, the density increase and the temperature drop (~30 eV) are more modest, smaller than a type-I ELM perturbation. But if the edge profiles are weakly altered, a global fuelling effect is observed, effect significantly attenuated in high-density H-mode discharges. The penetration of the beam has been analysed with a crude 1D model for the different cases reported in this paper. The deposition profile of the supersonic molecules is first calculated (molecular ionization and dissociation). Then the resulting atoms are propagated, half in both directions, either with 3 eV energy (FC atoms) or with 100 eV to simulate an enhancement of the penetration due to the charge exchange reactions. Recycling is not considered. Results with temperature and density profiles used in the calculation, respectively from O-mode reflectometry and ECE measurements (with tanhfit), are presented in figure 5.

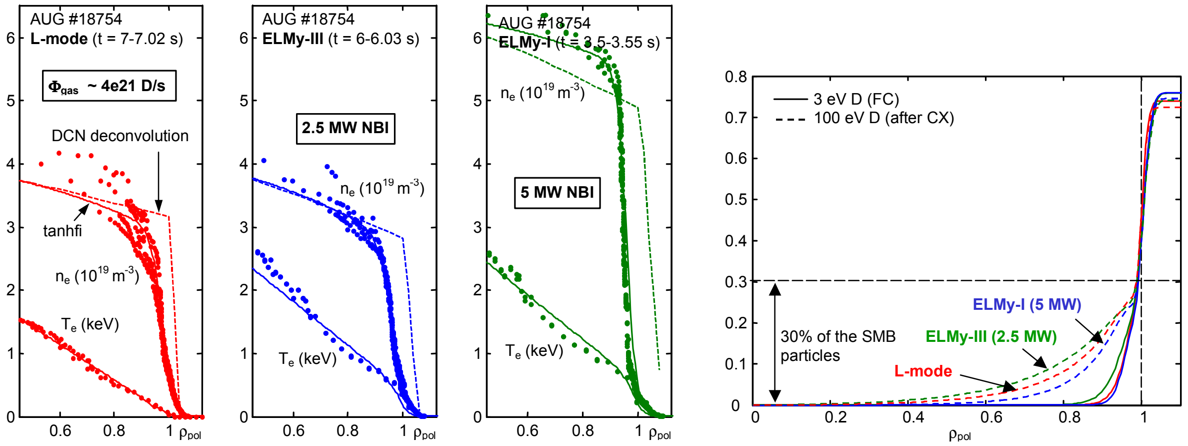

Figure 5. Edge electron temperature (ECE) and electron density profiles (O-mode reflectometry) in L-mode (0 MW NBI), ELMy-III (2.5 MW NBI) and ELMy-I phases (5 MW NBI) from #18574 and corresponding calculated integrated beam deposition as a function of the normalized poloidal flux radius.

According to this calculation, the reduced fuelling efficiency observed in the 5 MW NBI plasma is due to the higher pedestal density that hinders the atom penetration. Indeed, above 25 eV, the temperature does not play a major role. Therefore, one way to improve the beam penetration into a high density plasma is to reduce the plasma temperature inside the separatrix below 25 eV in order to allow for the molecules to enter deeper into the confined region. A feasible way consists in increasing the amount of particle per pulse in order to transiently bring down the edge temperature like it was achieved in Tore Supra. However, such a strong pedestal perturbation would certainly impact on the global confinement and ELM activity.

Conclusion

Supersonic molecular beam injection has been used in ASDEX Upgrade divertor plasmas. The fuelling efficiency reaches 30% in L-mode and low density H-mode plasmas and is reduced to less than 15% in high density H-mode discharges. The amount of particle per pulse was about 10-15% of the plasma content leading to a small edge perturbation, smaller than a typical type-I ELM. A significant increase in the beam flux could improve the beam penetration and consequently the fuelling efficiency by a stronger edge cooling but the impact of such a perturbation on the confinement is still to assess.

References

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