PELLET INJECTION, CONFINEMENT, AND H-MODE FEATURES ON START

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Confinement, H-mode features, and the first results of the pellet injection into a Spherical Tokamak (ST) are presented in purely Ohmic and in Neutral Beam Injection-NBI (≤1MW, 30keV, H^o, ≈10^{20} H^o/second, co-injection) regimes in START {major radius R≈0.3m, minor radius a≈0.2m, R/a ≥1.25, elongation k≈1.7, record toroidal beta β_T≈40% [1]}.

1. Pellet Injection

A deuterium pellet injector has been installed on START. It was manufactured in Risø and is on loan from ENEA-Frascati. The measured pellet velocity is ~300m/s. and the maximum pellet inventory is $1.2x10^{20}$ atoms estimated from the nozzle and the gun barrel of the injector. The pellet is injected almost vertically from the top of the vessel at R=0.36m towards the bottom X-point divertor at R=0.17m so that the ablation can occur at the high field side of the plasma which is predicted to be more efficient [2]. The pellets give a plasma density which normally rises very fast (~1ms) and then decays slowly (e.g. ~7ms in the Ohmic shot #34907). Large increases in electron density have been observed during pellet injection into Ohmic and NBI divertor plasmas. For example, in an Ohmic shot (#34912) a density increase of $n_e(0) \approx 0.9 \rightarrow 5x10^{20}m^{-3}$ and $\bar{n}_e \approx 0.6 \rightarrow 2x10^{20}m^{-3}$, were obtained with $q_\psi(95\%) \approx 6.3$ (from EFIT equilibrium reconstruction), I_p=178kA, B_φ=0.36T, a=0.19m. The temporal profiles of the Ohmic shot #34907 are presented in figure 1. During the pellet ablation (t=37-38ms), $\bar{n}_e$ increases as the electron temperature, T_e , drops (as evidenced by the central soft-X-ray signal from the horizontal camera). The plasma current, I_p, slightly reduces (10% maximum) and the loop voltage, V_l, only slightly increases (7% maximum). This might be due to changes in the resistive and inductive components produced by the abrupt changes in T_e (e.g. for central T_e: 200→100eV from the multi-point Thomson Scattering, TS, measurements at t=39ms). The kinetic stored energy, W (from EFIT), increases by ~36% (700J to 950J) which might indicate that the energy confinement also rises. TS measurements at t=39ms also indicate that W increases since the central electron pressure, $P_e(0)$, increases from 2200Pa to 4200Pa with similar geometry and P_e profiles. The reduction in the level of Mirnov oscillations after the ablation period gives additional evidence for a possible enhancement in confinement. In figures 2 and 3, the operating regime and the Greenwald diagrams are shown. High values of Greenwald number $N^G \equiv n_{e20}\pi a^2/I_p(MA) \approx 1.6$ and Murakami number $M \equiv n_{e20}\, R_0(m)/\, B_\varphi(T) \approx 2.0$, in Ohmic, and $N^G \approx 1.2$ and M≈2.7 (a record, with β_T=23%, β_N=3.7) in NBI discharges have been achieved. These achievements broaden considerably the START operating range.

2. H-mode-like phenomena

There is evidence that some START discharges resemble H-mode behaviour in some NBI regimes in double X-point configuration [3]: Figure 4a shows some of the signatures. Here, ELM-like phenomena are observed following a spontaneous $\bar{n}_e$ rise after the termination of the gas puff at t=30ms. These show the conventional signatures: D_α spikes (τ_{rise} < 10μs, and slower exponential decay of ~300 μs) correlated to similar spikes and features on both CIII traces and on the outermost channels of the vertical SXR array which localise the effect to within ~5cm of the plasma edge. Radiation further into the plasma (e.g. CV line) does not show such correlation. Finally, pellet injection during the ELM-like period does not change this phenomena, nor do the edge T_e and n_e (from the TS profiles), which also suggests an edge localisation of this event (e.g. shot #34881), since edge T_e and n_e are not expected to change during the injection. Moreover, these ELMs can occur between sawteeth and are not associated with low frequency MHD activity. The density and the plasma kinetic energy both rise between the ELMs (<1ms) in this discharge. The energy confinement time between ELMs is estimated to rise by a factor >2, indicating formation of a transport barrier at the plasma edge which is evidenced by the TS profiles. The central toroidal velocity, V_ϕ, and ion temperature, T_i, are both obtained from the charge exchange recombination spectroscopy (CV emission) from the heating neutral beam [4]. In figure 4b, the enhancement in W during ELM-free periods is shown. This might be the consequence of the suppression of microinstabilities due to the rise of the poloidal rotation, V_θ, as observed from a fast Doppler spectrometer (single chord, viewing the edge CIII emission).

3. Energy Confinement Time

An extensive database of the energy confinement time has now been generated. The confinement in START is better than predicted by ITER H-mode ELMy scaling, that is, τ_E^{max}(Ohmic) ~1.3 x $\tau_{E\ ITER97elmy}$, τ_E^{max}(NBI) ~1.3 x $\tau_{E\ ITER97elmy}$ (low-β regime), τ_E^{max}(NBI) ~1.1 x $\tau_{E\ ITER97elmy}$ (high-β regime[1]). In figure 5, τ_E is plotted versus the line averaged density and the input power. Values of $\tau_E \approx 3.7$ms (≈ 70% τ_E enhancement compared with a similar discharge without pellet injection) at $\bar{n}_e \approx 1.3 \times 10^{20} m^{-3}$ in medium-β regimes, i.e., $\beta_T \approx 9.2\%$, $\beta_N \approx 2.7$, have been achieved in pellet fuelled NBI discharges.

4. Conclusions

It has been shown that tight aspect ratio plasmas in START exhibit relatively high energy confinement times and density limits together with high toroidal beta. H-mode like signatures have been observed in some NBI double X-point discharges. Pellet injection has greatly extended the operating space and the density limits beyond the Greenwald limit. Preliminary analysis of the confinement with pellet fuelled discharges suggest an energy confinement enhancement at high densities. These results represent a considerable expansion of the range of tokamak physics that can be explored in the new environment of the ST.

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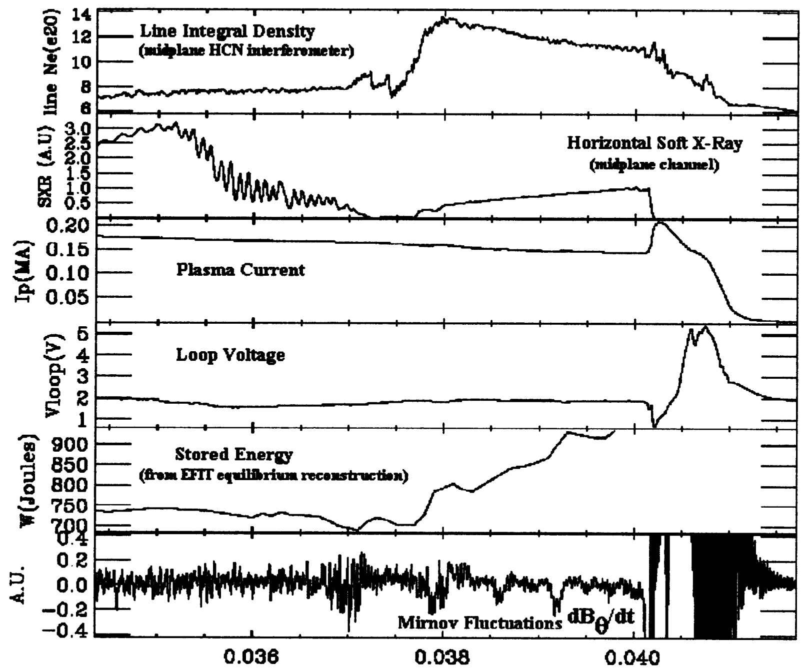


Figure 1 Traces showing the behaviour of a typical Ohmic plasma after an injection of a single pellet at ~36ms. The measured pellet velocity and mass were 337m/s and 62 μg (3.7x10^19 atoms of deuterium), respectively.

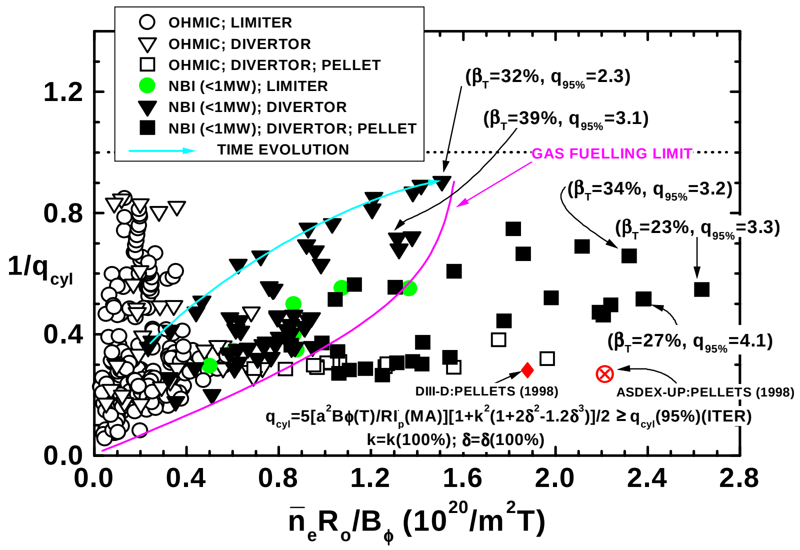


Figure 2 START Operating Diagram for different magnetic configuration, heating and fuelling. Note a record of normalised density, that is, $\bar{n}_{e20}R_0(m)/\ B_\varphi(T)\approx 2.7$ yet at relatively high toroidal beta, i.e., β_T=23%, β_N=3.7, in a X-point NBI discharge.

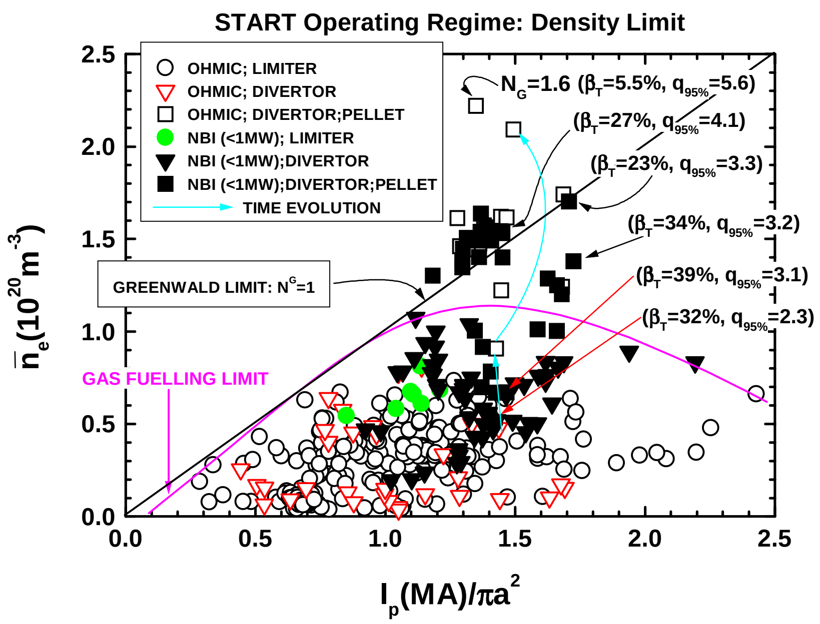
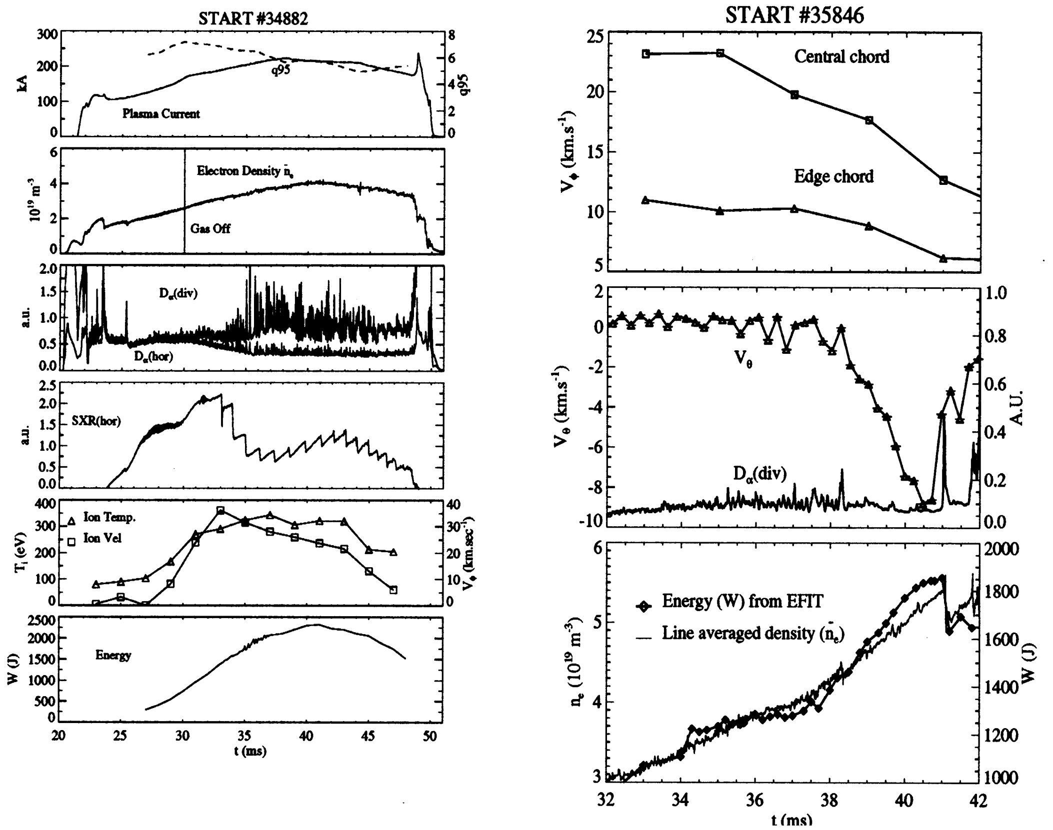
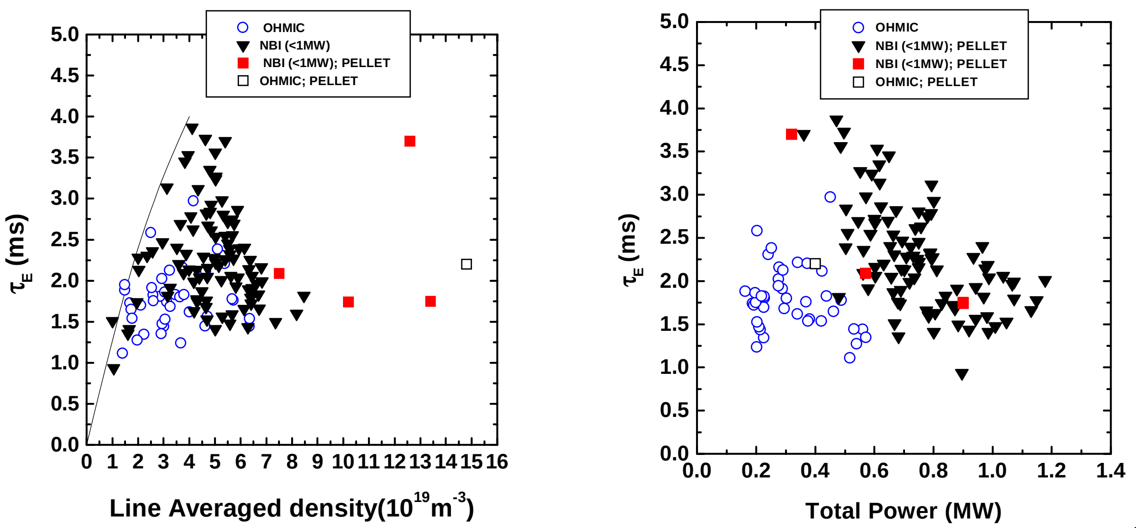


Figure 3 Density Limit on START: Greenwald Diagram. Pellets were always injected after NBI applied.



(a) (b)

Figure 4 *H-mode-like discharges on START [3]: (a) behaviour of several parameters including the ELM-like features on D_α signal at t=34ms after the gas puff termination at t=30ms; (b) Behaviour of the poloidal (V_θ) and the toroidal (V_ϕ) plasma velocities during the ELM-like-free period (38.5-41.0ms). I_p, NBI and V_ϕ are in the same direction. High V_θ excursion (≈9km/s) is accompanied by increase in $\bar{n}_e$, τ_E (τ_E ≈ 1.7ms at t=36.5ms) before the ELM-like-free period, reaching a peak of τ_E ≈ 4.3ms at 4.3ms at 38.5ms, reducing to τ_E ≈ 2.7ms at 40ms , towards the end of the ELM-like-free period.*



(a) *(b)*

Figure 5 *Energy confinement time dependence on (a) the line integral density and (b) the input power for Ohmic and NBI regimes, with and without pellet injection. Note the improvement of the confinement dependence on the density by means of pellet injection.*