Pellet Ablation in FTU discharges

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Abstract. Central fuelling and PEP modes have been obtained with pellets injected vertically from the high field side on FTU tokamak. Four phases have been recognized: ablation of the pellets, drifting plasmoids, MHD modes which take the density to the center of the discharge and finally an anomalous drift which would increase the density peaking. The pellet ablation has been compared to a pellet ablation and deposition code. Comparison between 0.8 MA discharges and 1.1 MA discharges has been carried out, higher performance has been obtained with the latter due to the higher target density and the larger inversion radius which would increase the effects of m=1 modes to take the density to the center of the discharge.

1. Introduction

Fuelling the central plasma region is a major issue in tokamak experiments. The use of high field side (HFS) pellet injection is considered as one of the main method for fuelling the central plasma region and obtaining a peaked density profile. The radial drift of the ablated material could take the density to the plasma center region even if the pellet has been completely ablated before reaching it. FTU ($R = 0.935$ m, $a = 0.3$ m, $B_t = 8$ T, $I_p = 1.5$ MA, $n_e \sim 10^{20}$ m^{-3}) with its high field and density allows to study the pellet ablation and the drift of the ablated material at high magnetic field and density.

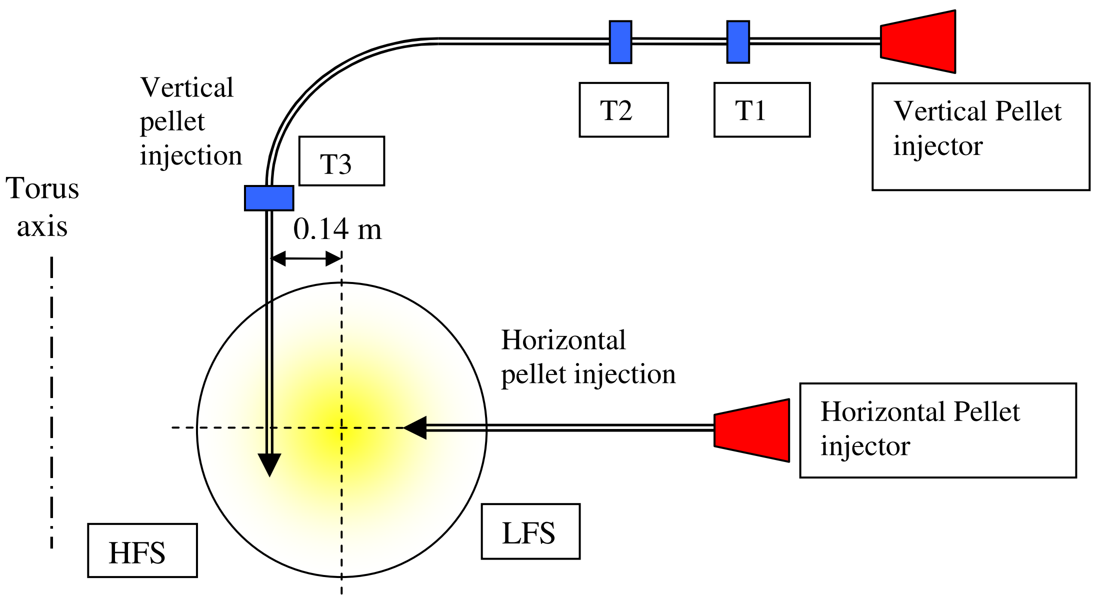

FIG. 1. Schematic view of the pellet injection systems installed on FTU (Major radius R = 0.935, minor radius a = 0.3 m). T1, T2, T3 are optical targets which measure the pellet speed. Similar targets are placed on the horizontal pellet injector.

FTU has two pellet injection systems: a vertical one which is capable of delivering up to 3 deuterium pellets (mass: 1.5×10^{20} particles each; speed: 500-600 m/s) along a vertical chord displaced 0.14 m (r/a ~ 0.5 ÷ 0.6) from the geometrical axis in the HFS direction [1]; and an horizontal one capable of delivering up to 7 deuterium pellets (mass: 1.0×10^{20} particles each; speed: 1200 m/s) from the LFS (*FIG. 1*).

Both systems have been used. The horizontal low field side (LFS) system mainly for repetitive PEP mode studies as the high speed pellets can easily reach the center of the plasma [2]. Pellet ablation experiments have been carried out on FTU with the vertical pellet system. A PEP mode was obtained with the last system too.

Two CO_2 interferometer systems were used to determine the density of the plasma. A fixed one which is fast enough to follow the density deposited by the pellets with a time resolution of 5 µs but only along few chords and a scanning one which can obtain a line integrated density profile of the full plasma column every 40 µs [3]. The temperature was measured on a fast time scale (10÷50 µs) by a ECE polychromator. Temperature profiles were measured by a Michelson interferometer every 5 ms and by a Thomson scattering diagnostic. When a laser pulse was available at proper time a post pellet density has been measured by the Thomson scattering.

Experiments with the vertical system have been mainly carried at a magnetic field of 7.1 T with a plasma current of 0.8 MA and 1.1 MA. The central temperature was between 1.2 keV and 2 keV and, the line averaged density range was between 1×10^{20} m^{-3} and 2.5×10^{20} m^{-3} (*FIG. 2*). In the following chapters we are discussing the pellet ablation and the resulting density deposition obtained at different plasma current, and the performances of those discharges compared with the horizontal injection.

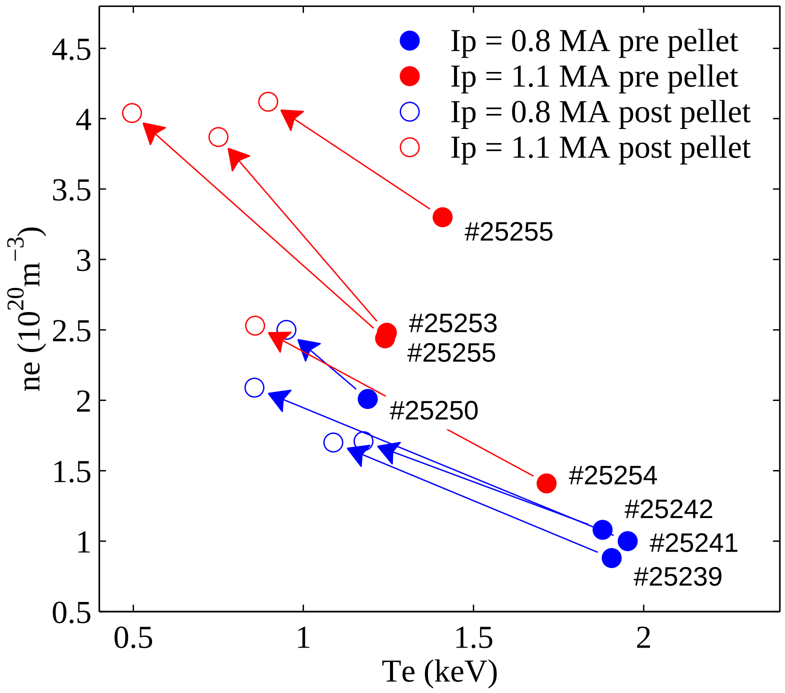

FIG. 2. Line integrated density and central temperature in pellet discharges. Full circles represent pre pellet values, while empty circles are post pellet values. In blue there are the 0.8 MA discharges while in red there are the 1.1 MA discharges. The #25255 discharge had two pellets, the second is the one with higher temperature and density.

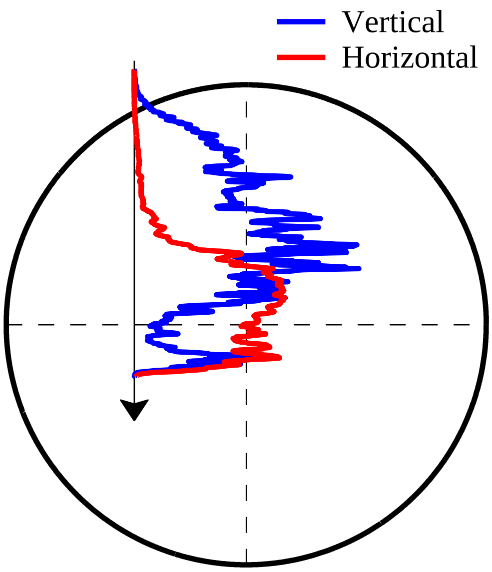

FIG. 3. H_α emission along the path followed by the pellets in the high temperature shot #25254. It is assumed that the pellet is not changing its vertical velocity during the injection, and that most of the emission is due to the pellet ablation and not to the drifting plasmoids. In blue is the emission recorded along a vertical chord, while in red is the emission along an horizontal chord.

2. Pellet ablation

In almost all discharges with vertical injection the pellet would penetrate close to the midplane, and in some case it went beyond. This is seen in the H_α measurements even though we cannot distinguish between emission due to the pellet ablation and that of plasmoids (*FIG. 3*).

The H_α light is collected by two optical fibers aligned along the pellet paths (both for the vertical and the horizontal system). The signals are not absolutely calibrated, so they are just an indication of the pellet emission. The horizontal optical fiber is basically sensitive to light emitted close to the midplane, but at the moment there is no calibration of acceptance angle. This is clearly seen on FIG 3. where the H_α signals collected along the vertical and the horizontal chords are plotted along the path followed by the vertical pellet. In the figure the time axis is aligned along the pellet path assuming the pellet is moving at constant speed. Both signals stopped after the pellet had crossed the midplane, the horizontal one is mainly coming from zones close to the midplane as expected. Similar results can be obtained from the rise time of the central chord of the interferometer [4]. Pellet ablation codes give almost the same conclusion with pellets ablated near the midplane even in the high temperature discharges.

3. Post pellet density

In two 0.8 MA discharges we had a Thomson scattering measurement less than one millisecond after pellet injection. The measured density was hollow initially, but later the density reached the plasma center (*FIG. 4*). There were no interferometric density measurements in these discharges to support Thomson scattering measurements. A pellet ablation code was used to simulate the deposited density. The code uses the following ablation formula for the pellet:

$$dr_p/dt = 1.2882 \times T_e^{1.7153} n_e^{0.4022} B^{-0.0189} R^{-0.0940} r_p^{-0.5949} C$$

r_p is the pellet radius in mm, T_e is the electron temperature in keV, n_e is the density in 10^{19} m^{-3}, B in tesla, and the major radius R is in meters, the variable C accounts for small corrections, the full expression can be found on [5].

In effect the density deposition is not very sensitive to the parameters of the ablation formula as the ablation is always close to the midplane due to geometric effects. At every time step of the code a plasmoid is assumed to be formed, which would drift with a constant velocity v_{plas} and decay exponentially. In the code, it is possible to change the plasmoid velocity and the decay constant λ_{plas} independently. The assumed model for the plasmoids is very crude but it can give us some useful information. The plasmoid speed is not really changing the deposited density at least for plasmoid speed larger than the pellet speed and for small λ_{plas} ($\lambda_{plas} < 0.05$ m). The only effect of the plasmoid speed is to change the zones where pre-cooling of the plasma occurs reducing the ablation rate, it is mainly a geometric effect due to the vertical injection. On the other hand λ_{plas} affects strongly the deposition zone, as expected. A simulation is shown in FIG. 4 for the discharge #25242 (B_t = 7.1 T, I_p = 0.8 MA), the deposited density is compared with that obtained by Thomson scattering diagnostic. The simulation has been obtained with a plasmoid speed of 500 m/s (but plasmoid speed from 50 m/s up to 50000 m/s give almost the same results) and a λ_{plas} = 3.5 cm. The pellet mass has been chosen $m_p = 1.0\times10^{20}$ particles in order to be consistent with the post pellet volume integrated density. The post pellet density is reasonably well reproduced by the simulation. The best estimate for λ_{plas} is about 3.5 cm, but more experiments would be needed to obtain a more reliable value. It should be stressed that a strong m=1 mode would peak the density in 1.1 MA discharges in less than one millisecond as explained in the following chapter. On the contrary, a hollow density profile could last more than one millisecond in 0.8 MA discharges.

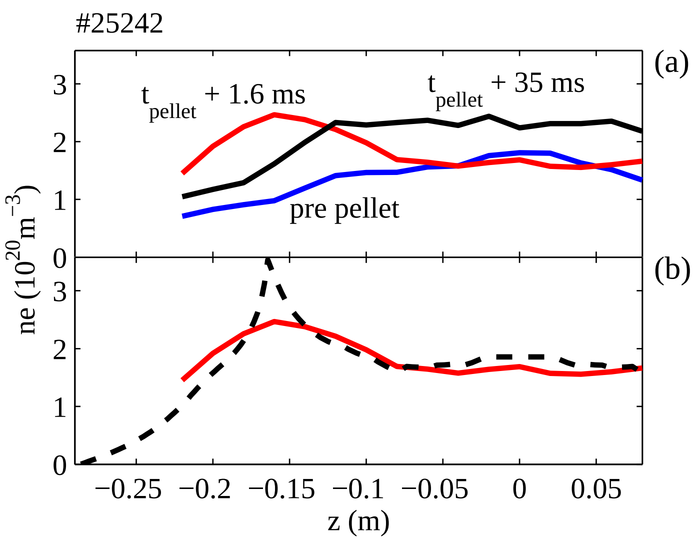

FIG. 4. a) Density profiles as measured from the Thomson scattering, before, 1.6 ms and 35 ms after the pellet injection. The density profile is hollow just after the pellet injection, later the density gets to the plasma center. b) Density profile 1.6 ms after pellet injection and a simulation with v_{plas} = 500 m/ λ_{plas}= 3.5 cm.

4. MHD modes and central fuelling

Sawteeth or m=1 modes can take the density from the ablation region toward the plasma center on larger timescale. Only a small fraction of the density is taken to the center in 0.8 MA discharges at every sawtooth, the overall density increase and temperature decrease in the center is slow, lasting a few milliseconds. This is probably due to the smaller inversion and mixing radii (respectively r/a = 0.27 and r/a ~ 0.5) of the 0.8 MA discharges compared to the 1.1 MA discharges (r/a = 0.31 and r/a ~ 0.6). The pellet injection would trigger a large reconnection in 1.1 MA discharges. This reconnection would take the density to the center in less than a half millisecond, on the timescale of pellet time of flight (*FIG. 5*).

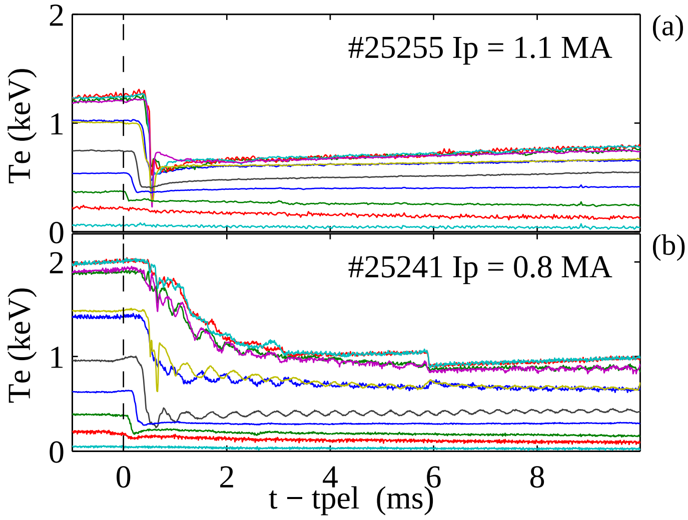

FIG. 5. Temporal evolution of electron temperature in two discharges: a) 1.1 MA discharge, there is a fast reconnection when the pellet get close to the q=1 surface. This reconnection lower the central temperature on a very short timescale (0.5 ms); b) 0.8 MA discharge, reconnection and sawteeth lower the central temperature on a longer timescale (~4 ms).

The fast reconnection is caused probably by a strong inverted density gradient near the inversion radius, but there is no conclusive evidence of that, a drifting plasmoid could also cause it [6]. Four phases can be recognized during pellet injection: 1) the pellet is ablated and plasmoids are formed; 2) these plasmoids would drift and deposit there density closer to the plasma center; 3) MHD reconnections would take the density from the q=1 surface to the plasma center; 4) an anomalous drift would peak the density, this has been seen by Thomson scattering measurements and density profiles obtained inverting interferometer measurements (FIG. 6).

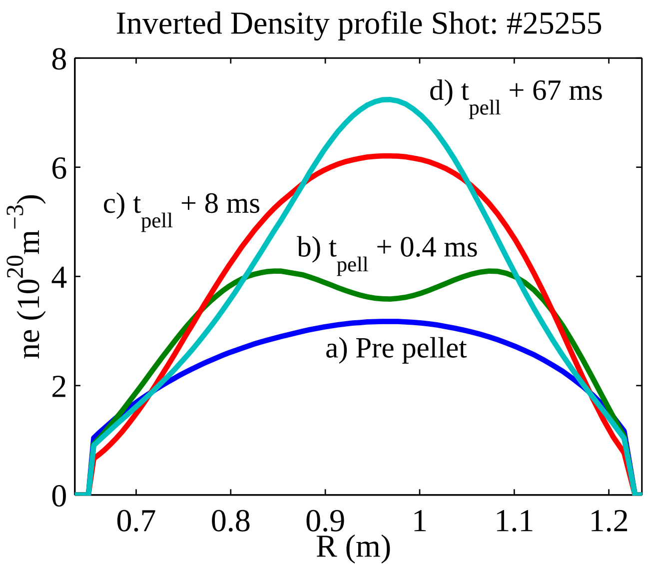

FIG. 6. Inverted density profile of the interferometer at four times, a) before pellet injection; b) at the end of the pellet ablation before the MHD mode would take the density to the plasma center; c) after the MHD mode took the density to the center; d) after the anomalous drift peaked the density. Later on a sawtooth would flatten the density.

Sawtooth crashes tend to contrast pinch effect, removing particles from the plasma center. On the other hand sawteeth avoid impurity accumulation in the center which would degrade performances and could lead the discharge to disruption. Injecting more than one pellet allows for a long lasting PEP mode. The same behaviour has already been seen in discharges with horizontal pellet injection and PEP mode [7,8].

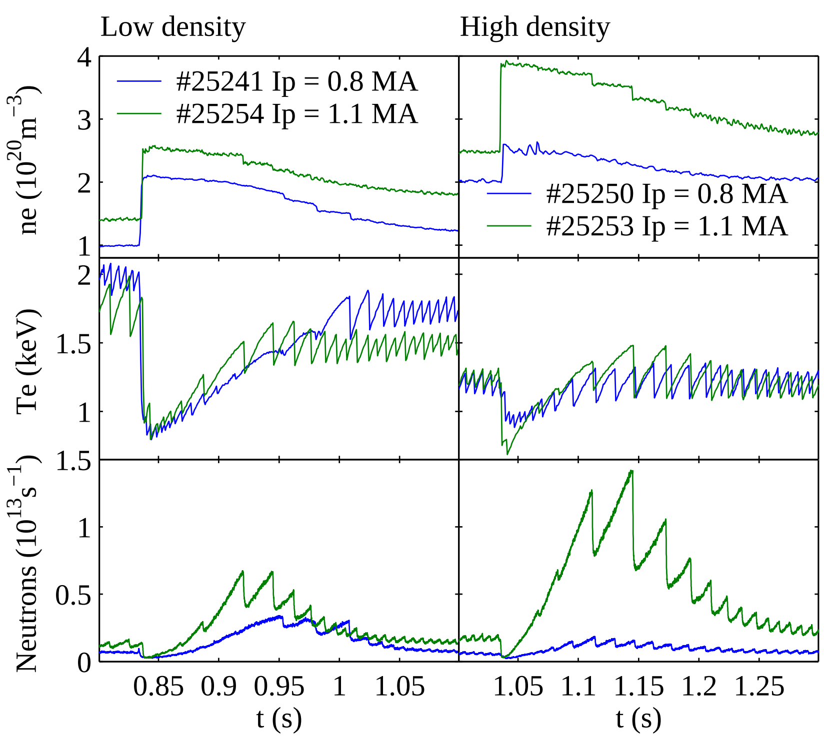

FIG. 7. Line integrated density, electron temperature and neutron yield for two low density discharges (0.8 MA, 1.1 MA), and for two high density discharge (0.8 MA, 1.1 MA) during pellet injection. The 1.1 MA discharges have a higher target density than the 0.8 MA ones even at the same temperature. This associated with the larger inversion radius gives a better performance, especially at high density.

5. Performance

The effects of increased density in the plasma center is similar in 0.8 MA discharges and in 1.1 MA discharges (*FIG. 7*) at relatively low target density. At high density the performance of 1.1 MA discharges is far better than at 0.8 MA as appear on the neutron yield. The higher current can easily support a larger target density before pellet injection while keeping the temperature at the ablation zone not too low.

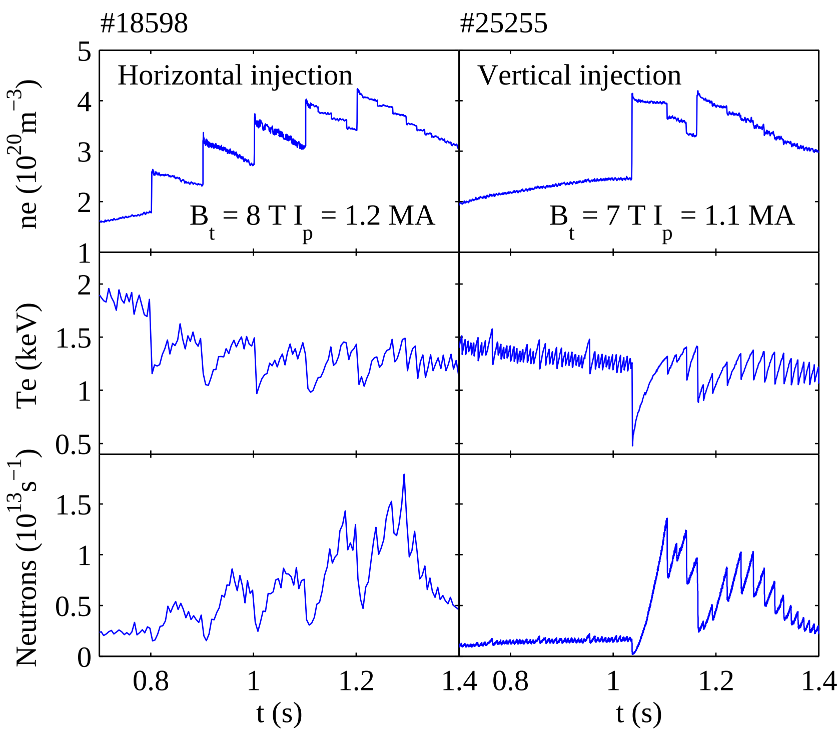

FIG. 8. Two discharges with vertical and horizontal pellet injection are compared. They have a similar behaviour and a PEP mode is obtained in both discharges. The density increase is larger with the vertical pellet injector due to the bigger pellet mass, about 1.5×10^{20} particles, compared to that of the horizontal system (1×10^{20} particles). The target density was also higher than that of the horizontal injection.

A line averaged density up to 4×10^{20} m-3 has been observed and a neutron yield of 1.4×10^{13} neutrons per second has been obtained. On the other hand high current discharges are very sensitive to the oxygen content which change the current profile, a strong tearing mode can develop after pellet injection, it would lead the discharge to disruption.

A comparison between vertical and horizontal injection has been carried out. A PEP mode has been obtained with the vertical injection system similar to the one already obtained with horizontal one (*FIG. 8*). Fewer pellets were needed with the vertical injector to achieve the same density and neutron yield, this is in part due to the bigger pellet we have on the vertical system (1.5×10^{20} particles) compared to the horizontal one (1.0×10^{20} particle) and to the higher target density in the discharges fuelled by the vertical system.

6. Conclusion

A PEP mode has been obtained with a vertical pellet injection in high current discharges (1.1 MA) similar to the one already obtained with the horizontal one. The larger q=1 surface in the 1.1 MA discharges seems to be a key ingredient for a more effective central fuelling. Four phases has been recognized: pellet ablation, plasmoid drift towards the plasma center, MHD modes or sawteeth who take the density to the center and a final density peaking due to an anomalous drift. The higher current of the 1.1 MA discharges helps the fast reheating of the plasma, and the pre pellet plasma temperature is restored before the density is lost.

In 0.8 discharge the fuelling of the center is not so efficient and due also to the lower current, lower performance are obtained On the other hand high current discharges are more sensitive to oxygen content and can sustain a pellet injection only if they are very clean. Pellet ablation is almost consistent with that obtained by a simple pellet ablation and deposition code. A central mode triggered by the ablated pellet is a necessary condition to obtain a good fuelling of the plasma center.

This MHD effect may release the requirements for pellet fuelling ITER discharges, since the pellets wouldn't need to reach the plasma center but it would be sufficient if they got reasonably close to the q=1 surface.

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