Particle confinement of pellet-fuelled H-mode plasmas in the Mega Ampere Spherical Tokamak

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Abstract. This paper quantifies the particle confinement of pellet-fuelled plasmas in the Mega Ampere Spherical Tokamak (MAST). The dataset is restricted mostly to neutral beam heated plasmas and to shallow pellets launched from the high field side. It is shown that the pellet deposition can be explained only by invoking the $\nabla B$ drift of the pellet ablatant. The pellet creates a zone with positive density gradient and increased temperature gradient. Simulations show that these changes could increase the level of micro-turbulence and thus enhance further the penetration of pellet-deposited particles towards the core. Post–pellet dynamics of the density profile is characterised by the pellet retention time $\tau_{pel}$. It is shown that $\tau_{pel}$ correlates with the status of the edge transport barrier (L-mode or H-mode) and decreases rapidly for pellet deposition radius $r_{pel}$ approaching the plasma edge. For ELMy H-mode and ITER-like pellets, $r_{pel} = 0.8a$, the pellet retention time is about 20% of the energy confinement time. The fuelling requirement by the pellets for ITER is discussed.

1. Introduction

The present consensus is that in a reactor, high densities are difficult to be achieved by gas puffing due to the poor penetration of neutrals into the plasma. The most promising technique to control the density in reactor grade plasmas is the injection of cryogenic pellets. The price to pay for such deeper fuel deposition is a substantial perturbation to the plasma by the pellet itself. For example for ITER, local density increase up to 50% is expected in the pellet deposition zone located at the outer 15% of the minor radius [1, 2]. Pellet-fuelled plasmas are not stationary and the pellet deposition region is in a state of permanent response to perturbations. Pellets modify the confinement physics in the outer part of the plasma and to a large extent the pellet deposition zone takes over the role from the H-mode pedestal for setting up the boundary conditions for the plasma core.

Two practical parameters, the pellet deposition radius $r_{pel}$, and the post-pellet particle confinement time $\tau_{pel}$, provide the link between the confinement physics and the design of the pellet fuelling system. The particle throughput necessary to maintain the required plasma density is then determined by these two parameters as:

$$\Phi_{pel} = n_s S (a - r_{pel}) / \tau_{pel},$$

(1)
where \( a \) is the plasma minor radius, \( S \) is the plasma surface area and \( n_e \) is the time averaged density (over pellets) at \( r_{pel} \) assuming flat profile in \( r_{pel} < r < a \). In the absence of density peaking \( n_e \) is equal to the central density. The present paper reports on first measurement of pellet deposition radius and pellet retention time in MAST.

2. Experimental conditions

The targets for pellet injection were both L-mode and H-mode plasmas with plasma current \( I_p = (0.66 - 0.76)MA \), geometric major radius \( R_{geo} = (0.8 - 0.87)m \), minor radius \( a = (0.55 - 0.60)m \), elongation \( \kappa = 1.8 - 2.1 \), vacuum toroidal field at the geometric radius \( B = (0.47 - 0.50)T \), with double null divertor configuration and line averaged density \( \bar{n}_e = (1.6 - 7.5) \times 10^{19} m^{-3} \). The working gas was deuterium and plasmas were heated with neutral beams with injected power of \( P_{INJ} = (1.1 - 3.0) MW \) and with energy of \( \leq 65 keV \). Pellets were launched from the top and they enter the plasma from the high field side of the machine as shown in figure 1a. The pellet injection system is described in more detail in [3]. Low field side launch is also possible in MAST, but was not used in this study. The nominal pellet sizes are \( d_{pel} = (1.1; 1.35; 1.7) mm \) with \( N_{pel} = (0.6; 1.2; 2.4) \times 10^{20} \) atoms and pellet velocities were in the range of 240-450 m/s. We selected data with only those pellets which cause relatively modest plasma perturbations approaching the conditions similar to those expected in ITER.

Figure 1. (a) left: The geometry of pellet injection. (b) right: The pellet image in narrow band (\( \lambda_n = 457.25 nm \), \( \Delta \lambda_{FWHM} = 2.43 nm \)) visible bremsstrahlung (exposure is 7ms). The insert shows the emission intensity along the pellet trajectory.
3. Pellet deposition radius

The first parameter controlling the pellet particle throughput in equation (1) is the radius at which the majority of pellet particles are deposited. In MAST, the evaporation and deposition of a single pellet (pellet lifetime) lasts about 2 ms. The end of this process is clearly seen as a sharp inflexion point on the interferometer signal - an interesting observation as in neutral gas and plasma shielding models (NGPS) [4] the pellet evaporation rate decreases continuously with decreasing pellet size. The pellet evaporation and the deposition process is captured in the visible bremsstrahlung emission spectrum (figure 1b) revealing the clear burst-like structure (striations) of this process ([5] and references within). The image also confirms the sharp discontinuity in evaporation rate at the end pellet deposition. Absolute intensity of the emission indicates densities of the cold (1-2 eV [6]) ablatant up to \(10^{23} \text{m}^{-3}\).

In order to measure the pellet deposition profiles without a distorting effect of post-pellet density evolution we triggered the high spatial resolution (~1cm) Thomson scattering system directly from pellet signal with controlled delay. The density profile just at the end of the pellet evaporation is shown in figure 2. It is seen that the the inner and outer density profiles are a relatively good function of the poloidal flux coordinate as determined from magnetic equilibrium reconstruction (EFIT). This shows that the plasma density quickly equilibrates along the flux surfaces already during the pellet life time. This significantly simplifies the post pellet transport analysis as one can assume that shortly after the pellet evaporation the density and temperature profiles are conventional and do not remember the 3D character of the particle source from the pellet. Evolution of the density profile during the pellet deposition cannot be explained by the simple NGPS model [4] as seen from figure 2. Agreement is achieved only if \(\nabla B\)-drift is added which effectively spreads the pellet deposition inwards by \(\sim 0.15 r/a\). The best fit is obtained with the drift distance in the form of \(\lambda = c_s^2 \tau_s^2/(2R)\), where the ion sound speed \(c_s\) corresponds to temperatures of 1-2 eV and duration of the drift is \(\tau_s = 10-40\mu s\) [7, 8, 9].

**Figure 2.** Density profile at the end of pellet deposition. Symbols: experimental data measured by pellet-triggered Thomson scattering. Inboard (magenta) and outboard (red) profiles measured at the same time are shown. Black dashed line: prediction by NGPS model. Blue line: prediction by NGPS model with \(\nabla B\)-drift. \(\psi_N\) is the normalised poloidal flux.

The pellet deposition could be also affected by a temporary change in micro-turbulence induced by the pellet itself. Figure 3b shows two density profiles – one before and one just after the pellet deposition as captured by the 200 Hz Thomson scattering system. It is seen that the pellet creates a
distinct zone with positive density gradient $\nabla n_e > 0$ and electron temperature gradient $a/L_{tr_e} = -a\nabla \ln T_e$ doubled relative to its pre-pellet value (see figure 3a).

Calculations using the linear GS2 and TRANSP codes for the case in figures 3a and 3b show that at the radius of maximum increase of $a/L_{tr_e}$ ($\sqrt{\psi_N} - 0.7$) the mixing length estimate of diffusivity $\gamma/k^2$ increases by a factor of 2 for modes with wavelengths $0.08 < k \rho_i < 0.8$ as seen in figure 3c. Here, $\gamma$ is the linear growth rate, $k$ is the poloidal wave vector perpendicular to total magnetic field, $\rho_i = \sqrt{T_i m_i / eB}$ is the ion Larmor radius where $m_i$ is the ion mass, $e$ is the electron charge. The ion temperature $T_i = T_e$, as measured by charge exchange spectroscopy and neutral particle analyser. The modes $0.08 < k \rho_i < 0.8$ are identified as micro-tearing and ion temperature gradient (ITG) instabilities. Stability of these modes strongly depends on the flow shearing rate $\omega_{keB}$ which is, however, not measured in the pellet case. In the non-pellet case, $\omega_{keB}$ is found to be of the same magnitude as that required to stabilise the long wavelength modes $\omega_{keB} \sim \gamma(k \rho_i < 1)$ [10].

The plasma in figures 3a and 3b has also been modelled by the global nonlinear fluid code CUTIE [11]. Figure 3d shows the relative amplitude of the density fluctuations $\bar{n}/n$ in a simulation at the radius of maximum increase of $a/L_{tr_e}$. It is seen that the amplitude of fluctuations increases threefold for $0.07 < k \rho_i < 0.2$ modes and decreases for modes with $0.2 < k \rho_i < 0.4$, but the overall turbulent transport increases. Here, $k_\theta$ is the poloidal wave number and $\rho_i = \sqrt{(T_e + T_i) m_i / eB}$. Note that a similar enhancement of micro-turbulence in the pellet deposition zone has been also obtained by the CUTIE and TRB codes when simulating JET plasmas [12].

Figure 3. (a) Electron temperature, $T_e$, and (b) electron density, $n_e$, profiles before (blue) and after (red) the pellet injection as measured by 200Hz Thomson scattering. The insert panel shows the normalised electron temperature gradient $a/L_{tr_e}$ over a small range of minor radius as indicated. The plasma is in ELMy H-mode, pulse number is 16335. (c) Normalised growth rates of micro-turbulence calculated by linear GS2 code without rotation shear. (d) Amplitudes of density fluctuations of micro-turbulence calculated by CUTIE code. Both GS2 and CUTIE results (c) and (d) refer to the normalised poloidal flux surface of $\sqrt{\psi_N} - 0.7$.

The temporary increase of particle transport in the zone with $\nabla n_e > 0$, as indicated above by both simulations, would result in further inward particle propagation in addition to the $\nabla B$-drift and thus would be favourable for pellet deposition. Finally note that the distinct zone described above
could takeover the role from the pedestal for setting-up the boundary condition for transport in the plasma core in general.

4. Pellet retention time
Deposition of pellet particles causes a significant perturbation to the plasma and therefore post-pellet plasma confinement can differ from that just before the pellet injection. In MAST, the response of the plasma to the pellet can be complex and this is illustrated in figure 4 which shows a full spectrum of observed cases. Figure 4c shows a common situation when the plasma density rapidly decays after the pellet deposition as a result of increased ELM frequency or even a short transition to L-mode. Figure 4b shows a case unique to MAST when the pellet is not followed by ELMs and plasma remains in ELM-free H-mode for very long time period until the first natural ELM occurs. Finally, the pellet can also induce a transition from L-mode to H-mode as shown in figure 4a. This full spectrum of post pellet plasma behaviour also demonstrates the potential of pellets as a control tool for particle transport in general.

Figure 4. Different post-pellet behaviour in MAST. Top traces, $\bar{n}_e$, are the line averaged densities as measured by an interferometer. Lower traces show the emission of Balmer $D_\alpha$ line. Times of injection of pellets are indicated by arrows.

The post-pellet dynamics determines the second parameter which controls the fuelling efficiency in equation (1): the pellet retention time, $\tau_{pel}$. In MAST this parameter can be measured directly with the help of the 200Hz Thomson scattering diagnostic. Here $\tau_{pel}$ is determined from the evolution of plasma density at fixed radial position:

$$n_e(t, \rho_{pel}) - n_{e,N}(t, \rho_{pel}) \propto \exp\left[-(t-t_{pel})/\tau_{pel}\right],$$

where, $\rho_{pel} = r_{pel}/a$ is the radius of maximum density perturbation due to the pellet and is referred to as the pellet deposition radius later in the text. $t_{pel}$ is the time point just after the pellet deposition and $n_{e,N}(t, \rho_{pel})$ is the “natural density” due to the gas and beam fuelling and it is determined by a linear extrapolation from the pre-pellet trend. The parameter $\tau_{pel}$ is then calculated by a log-linear regression from discrete time slices.

It has to be noted that the time constant $\tau_{pel}$ encapsulates the very complex nature of post pellet transport. Firstly, the post pellet decay is not necessarily exponential and typically the time constant is shorter at the beginning of the decay than later on. Another complication is that the pellet retention time, as defined above, can depend on the fraction of gas and beam fuelling. In most of today’s plasmas the contribution of gas and beam fuelling is much larger than expected in future devices.

Figure 5 shows the pellet retention time $\tau_{pel}$ as a function of pellet deposition radius. The error bars of $\tau_{pel}$ measure the goodness of exponential fit described above. The error bars of the pellet deposition radius, $\rho_{pel}$, are small as this is calculated as a position of the maximum of the fitted curve
through the density profile. The width of the pellet deposition zone is, however, comparable to $\rho_{pel}$ as seen on example in figure 3b.

Two types of correlations are evident from the data. Firstly, the values of $\tau_{pel}$ correlate with the status of the edge transport barrier. It is seen that for fixed pellet deposition radius $\rho_{pel}$ L-modes have the poorer particle confinement while extremely good confinement is found in ELM-free H-modes. Secondly, the pellet retention time correlates with the pellet deposition radius. For a given group of data (L-mode, ELMy and ELM-free) the retention time $\tau_{pel}$ decreases for decreasing pellet penetration. In figure 5 this decreasing trend is compared with expectation due to diffusive loss if the effective diffusion coefficient, $D_{eff}$ is independent of minor radius. It is seen that for L-mode, and to a lesser extent for ELMy H-mode, the pellet retention time decreases faster with decreasing pellet penetration than expected from the fixed value of $D_{eff}$ indicating that effective diffusivity increases towards the edge.

![Figure 5](image1.png)  
**Figure 5.** Pellet retention time $\tau_{pel}$ plotted against the normalised radius $\rho_{pel} = \sqrt{\psi_{\psi_{pel}}}$ taken at the maximum of the density perturbation by the pellet. The lines are the curves $(a - r_{pel})^2 / 2D_{eff}$ for two values of effective diffusivity $D_{eff}$ with $a = 0.55m$.

![Figure 6](image2.png)  
**Figure 6.** Pellet retention time normalised to total energy confinement time $\tau_{pel}/\tau_{E, tot}$ plotted against the pellet deposition radius as defined in figure 5.

Post pellet density evolution has been simulated by the CUTIE code. The starting profiles and plasma parameters were chosen to represent the discharge shown in figures 3a, 3b. The pellet retention time was found to be $\tau_{pel} = 4.5ms$ and as seen from figure 5 this value is in a good agreement with the data.

In order to obtain useful scalings the anomalous particle transport is usually normalised to the heat transport [13]. This is analogous to introduction of Prandtl-Peclet numbers in hydrodynamics and reflects the assumption that both the heat and particle fluxes are driven by the same turbulence. Figure 6 shows the pellet retention time $\tau_{pel}$ normalised to the global energy confinement time $\tau_{E, tot}$ for L-mode and ELMy H-mode plasmas. It is seen that similarly to $\tau_{pel}$ the ratio $\tau_{pel}/\tau_{E, tot}$ also decreases rapidly for shallower pellets. Further improvement of the scaling for $\tau_{pel}$ will require normalisation to the energy confinement time evaluated at the pellet deposition radius, analogous to the definition of pedestal energy confinement time in the two term energy scaling law [14].
5. Fuelling requirement for ITER

For pellet deposition expected in ITER, \( r_{pel} = 0.80a \), the data in figure 6 extrapolate to the pellet retention time of \( \tau_{pel} \approx 0.2 \). For this value the particle throughput calculated from equation (1) is 
\[
\Phi_{pel} = n_e S (a - r_{pel}) / \tau_{pel} = 70 \text{Pa m}^3/\text{s} .
\]
Here we used the parameters for a nominal ITER discharge [15] where the plasma density is \( n_e = 10^{20} \text{m}^{-3} \), plasma surface \( S = 680 \text{m}^2 \) and the energy confinement time \( \tau_e = 3.7 \text{s} \). Such value of pellet throughput is about 70% of the present ITER design value for steady state operation [15]. Choosing even the largest envisaged pellet (5mm) implies that the interval between pellets has to be much shorter than the pellet retention time: 
\[
\tau_{r} = 4.4 / f_{pel} \text{Hz} .
\]
Such conditions are rare in present pellet fuelled plasmas. Another uncertainty is due to the fact that the gas and beam fuelling in ITER will be small while this is not the case in present plasmas with pellet injection. These two effects could result in shorter pellet retention time in ITER than the value given above and thus the required particle throughput \( \Phi_{pel} \) might be underestimated.

6. Conclusion

Two key parameters controlling the pellet fuelling efficiency, the pellet deposition radius and the pellet retention time, were measured in MAST using high field side pellet injection. The pellet deposition reveals the existence of \( \nabla B \)-drift. The pellet creates a zone with positive density gradient and increased temperature gradient. Simulations show that these changes could increase the level of micro-turbulence and thus enhance further the penetration of pellet-deposited particles towards the core. In addition, this zone could modify the role of pedestal for setting-up the boundary condition for transport in the plasma core. The pellet retention time correlates with the status of the edge transport barrier and decreases rapidly for pellet deposition radius approaching the plasma edge. For shallow pellets, as expected in ITER, the data extrapolate to a pellet retention time to be about 20% of the confinement time. This would imply that the required pellet particle throughput is close to the design value for ITER for steady state operation. Large uncertainty of prediction in both parameters justifies further refinements of databases and models.

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