A Comparison of Fueling with Deuterium Pellet Injection from Different Locations on the DIII-D Tokamak

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1. Introduction

Pellet fueling has been employed on DIII-D to provide density control and induce changes in plasma transport. Initially pellets were injected only from the outer midplane and these experiments verified an anomalous mass deposition that was first shown to exist on JET and TFTR [1,2]. This suggested that a fast outward radial transport occurs during the pellet ablation and toroidal symmetrization process. Results from pellet injection in ASDEX Upgrade from the inner wall [3] showed an improved fueling efficiency, which motivated studies to optimize the pellet fueling location on DIII-D. Studies of pellet transport through curved guide tubes [4] led to a design for injection from the high field side (HFS) through available ports on DIII-D. Injection ports on the inner wall and a vertical port inside the magnetic axis were added making it possible to compare pellets injected from three different locations in the same plasma discharge.

2. Pellet Injection Locations

The DIII-D pellet injector consists of three independent repeating pneumatic guns each with its own guide tube [5]. Curved guide tubes have been installed to connect the three barrels of the injector to a vertical port (V+1) and to two inner wall locations (HFS 45 and HFS mid) as shown in Fig. 1. Tests of a mock-up of these injection lines indicate that deuterium pellets survive intact with speeds up to 300 m/s through the inner wall guide tubes and 500 m/s through the vertical guide tube path. They lose approximately 20% of their mass during the transport through the 12m long guide tubes [4]. A specially modified gun with a mechanical punch is required to produce slow pellets c300 m/s for injection from the inner wall locations.

Pellets of the same size (2.7-mm diameter) have been injected from the different locations in a wide range of plasma conditions on DIII-D. The penetration depth of the pellets □ has been determined from the duration of the $;_\alpha$ emission of the ablating pellet and from the density profile perturbation depth measured by Thomson scattering. We have used the measured pellet speed and mass along with the measured plasma electron temperature and density profiles and the actual plasma geometry to model the pellet ablation process using the neutral gas shielding (NGS) model in the PELLET code that was used to model pellet penetration results from JET [6]. The calculated penetration depth of the pellets is compared with the measured density perturbation depth in Fig. 2. The pellets injected from both HFS inner wall ports and from the V+1 port result in deeper density perturbations than calculated from the model, while the low field side (LFS) pellet penetration depth agrees reasonably well with the model.

Direct comparisons of pellets injected into the same plasma discharge are possible with the three independent guns. An example where the same size pellets (at formation) were injected from the HFS 45, V+1, and LFS locations in a neutral beam heated L-mode plasma are shown in Fig. 3. The density perturbation from the inner wall pellet is clearly greater on the central interferometer chord even though the pellet speed is a factor of 4 slower. The $;_\alpha$ light in the divertor shows a much larger increase with the LFS pellet indicating that mass from the pellet is immediately expelled from the plasma.

A similar comparison is shown in Fig. 4 for pellets injected into a neutral beam heated H-mode plasma. The density perturbation is larger with the HFS pellet like in the L-mode case. Edge localized modes (ELMs) are triggered by the pellets from all locations, however, the duration of the ELM or transition back to L-mode is much longer for the LFS pellets, lasting up to 30 ms. The ELMs from the HFS and V+1 pellets are qualitatively no different than the normal background ELMs.

The fueling efficiency, defined as the fraction of pellet mass that is retained in the plasma, is higher for the HFS injected pellets than the LFS injected pellets, approaching 90% or greater if the pellet mass loss in the curved guide tube is taken into account. The LFS injected pellets have been shown [7] to have a fueling efficiency inversely dependent on heating power dropping to under 50% with 10 MW of heating power.

The pellet ablation light emission shows striations in the emission intensity that are believed to be caused by a rotation instability in the pellet cloud [8]. Striations are observed in the HFS and vertical injected pellets with no qualitative difference from the LFS injected pellets, leading us to believe that the cloud instability is not strongly affected by the increased magnetic field inside the magnetic axis.

3. Pellet Deposition Measurements

The deposition of injected pellet mass is determined by the measured density profiles before and immediately after injection of the pellet. The earlier measurements of deposition on JET and TFTR in both L-mode and H-mode LFS injection experiments showed that the mass deposition was skewed toward the edge when compared to the ablation model prediction. More precise measurements have been made on the DIII-D tokamak that show similar characteristics [2]. The depth of the density perturbation from the LFS injected pellets agrees with the pellet light emission duration and ablation modeling as shown in Fig. 2. Fig. 5 shows an example of the deposition profile measurement from DIII-D for a pellet injected from the HFS 45 inner wall location in a neutral beam heated H-mode plasma. The density profile was measured 250 s after the pellet finished ablating. The deposition profile that is calculated from the NGS model using the PELLET code [6] and the measured pellet ablation light mapped onto minor radius (normalized to the square root of toroidal flux) are also shown in the figure. As was noted before [1,2], the ablation light emission and calculated ablation rate have a qualitatively similar temporal evolution. The view of the pellet is from a tangentially mounted photodiode and so toroidal deflection would not move the pellet out of the field of view. Clearly the radial extent of the measured deposition is deeper than the depth that the pellet travels based on the light emission from the pellet. The time of the start of light emission is correlated with the time that increased density is seen by the interferometer chords. The endpoint of the pellet trajectory based on the light emission puts the pellet at a minor radius of 0.8. If the pellet mass were to move outward in major radius, the endpoint would map to a minimum minor radius of 0.4, which is the radius that the density perturbation reaches.

The mechanism responsible for the apparent outward drift of pellet ablatant is hypothesized to be caused by an o × 4 drift that arises from a polarization of the ablatant cloud moving along the curved magnetic field [8] or from a pressure gradient driven effect on the ablatant [3]. The time scale of such drifts for DIII-D are on the order of 10s of s. In both cases the ablatant would be expected to move in the -∇4 (outward radial) direction. Some portion of the pellet ablatant is believed to propagate some 10 cm or more in the -∇4 direction and is actually expelled from the plasma confinement region for LFS injected pellets as recently observed on RTP [10], thus reducing the fueling efficiency and producing a strong source of particles in the scrape off layer as is seen in Fig 3.

4. Modeling and Future Work

A radial displacement model of the pellet cloud has been developed by Parks [11] to account for the apparent radial drift of the pellet mass due to an o × 4 drift that arises from a vertical polarization of the ablatant cloud from ∇B and curvature drifts [9]. This model calculates the radial drift of the pellet ablatant cloud as a function of the measured local plasma parameters and calculated pellet cloud parameters given by the following formula

$$\Delta \mathsf{p} = 035\#_0 \;{}_c\;{}_p \frac{8_{A\infty}}{\square_0} \langle \tilde{\Psi} \rangle \tag{1}$$

where $\Delta \mathsf{p}$ is the radial drift, $\#_0$ is the cloud #, ${}_c$ is the cloud radius normalized to the pellet radius, ${}_p$ is the pellet radius, $8_{A\infty}$ is the background Alfvén velocity, $\square_0$ is the sound speed at the cloud boundary, and $\langle \tilde{\Psi} \rangle$ is a source term for the electrostatic drive. Using experimental values for the case shown in Fig. 5, $\Delta \mathsf{p} = 17$ cm near the end of the pellet trajectory. This is approximately the level of radial displacement needed to explain the observed deposition profile extending beyond the pellet penetration depth. The model predicts stonger displacement as the pellet enters higher # background plasma, so that there is predicted to be more displacement the deeper the pellet enters the plasma.

Modeling of the ablation and deposition process of pellets is under development using an ablation code modified with the radial displacement model. Further development of the model is needed to take into account the 3-D nature of the mass distribution process.

In future experiments we plan to investigate the differences in the HFS 45 and HFS mid inner wall ports in the same plasma discharge, which will require a second gun capable of slow pellets. This capability will also make direct comparison of similar speed pellets from different locations possible.

5. Summary

Initial pellet injection experiments on DIII-D with HFS injection have demonstrated that deeper pellet fuel deposition is possible even with HFS injected pellets that are significantly slower than pellets injected from the LFS (outer midplane) location. A radial displacement of the pellet mass shortly after or during the ablation process is consistent with the observed mass deposition profiles measured shortly after injection. Vertical injection inside the magnetic axis shows some improvement in fueling efficiency over LFS injection and may provide an optimal injection location for fueling with high speed pellets.

Acknowledgments

We gratefully acknowledge the assistance of the DIII-D operations group at General Atomics and the Plasma Fueling Group at Oak Ridge National Laboratory. This research was sponsored by the Office of Fusion Energy Science, U.S. Department of Energy, under contracts DE-AC05-96OR22464 and DE-AC03-99ER54463.

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