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Fueling efficiency of pellet injection on DIII–D*

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Abstract

Pellet injection has been used on the DIII–D tokamak to study density limits and particle transport in H-mode and inner wall limited L-mode plasmas. These experiments have provided a variety of conditions in which to examine the fueling efficiency of pellets injected into DIII-D plasmas. The fueling efficiency defined as the total increase in number of plasma electrons divided by the number of pellet fuel atoms, is determined by measurements of density profiles before and just after pellet injection. We have found that there is a decrease in the pellet fueling efficiency with increased neutral beam injection power. The pellet penetration depth also decreases with increased neutral beam injection power so that, in general, fueling efficiency increases with penetration depth. The fueling efficiency is generally 25% lower in ELMing H-mode discharges than in L-mode due to an expulsion of particles with a pellet triggered ELM. A comparison with fueling efficiency data from other tokamaks shows similar behavior.

1. Introduction

Pellet fueling is an important technique developed for fueling and density profile control in a fusion grade plasma [1]. Much effort has been devoted in past pellet fueling experiments to understand pellet ablation and pellet induced changes in plasma transport. These studies have yielded an extensive validation of the neutral gas shielding (NGS) scaling law for pellet penetration [2] and have shown the capability of pellet fueling to strongly modify the density profile shape. The issue of pellet fueling efficiency has not been extensively examined under various conditions until a recent study [3] made possible by the development of an international pellet ablation database [4]. This issue is very important in developing fueling systems for a reactor device that can achieve efficient fueling while minimizing the tritium wall inventory with isotopic tailoring [5] of the pellet fuel. In this study of fueling efficiency on DIII-D, we examine the extensive experimental results in one

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device (an elongated, diverted, tokamak plasma) under various operating conditions and compare these experiments to the overall database results.

Density limit and particle transport experiments have been carried out with the three-barrel pneumatic pellet injection system [6] installed on DIII-D in H-mode and inner wall limited L-mode plasmas. These experiments have provided a variety of conditions in which to examine the fueling efficiency of pellets injected into various types of plasmas. Deuterium pellets are produced that have sizes of 1.8mm, 2.7mm, and 4mm diameter cylinders ($2x10^{20}$, $6x10^{20}$, and $2x10^{21}$ particles, respectively) and speeds from 300-1000 m/s. Diagnostics in the pellet injection line measure pellet speed and mass for each pellet. The ablation process is monitored with a photodiode that observes the light emitted by the ablating pellet. The termination of the light from the photodiode and the measured pellet speed gives the penetration depth.

The fueling efficiency, which is defined as the total increase in number of plasma electrons divided by the number of fuel atoms in the pellet, is determined by Thomson scattering measurements of density profiles before and just after pellet injection in conjunction with the pellet mass measured in a microwave cavity. These density measurements have been made as close as 20 μs after completion of the pellet ablation process, but are more typically made 1 to 2 ms after injection of the pellet. Multiple measurements made starting 150 μs following ablation show only very modest changes in the density profile in the first 2 ms following injection [7] after the initial rapid response to the pellet deposited mass. This indicates that no fast particle transport effects occur during this time.

2. Pellet plasma interaction

There are several effects that can reduce pellet fueling efficiency from the ideal 100% level. First, there is some ablation of the pellet in the scrape off layer (SOL) before it reaches the last closed flux surface or seperatrix of the plasma. This is due to energetic particles in the SOL that impinge on the pellet as it traverses the SOL. The magnitude of this ablation is rather small on DIII-D as measured by D_α light emitted by the ablating pellet. Another possible effect that reduces the ideal fueling efficiency is the expulsion of pellet ablatant from the plasma by outward drift effects on the ablatant as it propagates away from the pellet along field lines. These drift effects can be caused by an ExB drift that arises from a polarization of the ablatant cloud or from a pressure gradient driven effect on the ablatant

[8]. The time scale of such drifts for DIII-D are on the order of 10 μs. In both cases the ablatant would be expected to move in the ∇B (outward radial) direction. An effect of this type has been hypothesized to occur from measurements of the resulting density profiles [9] and was shown to be significantly reduced in pellet experiments where the pellets were injected from the high field side (HFS) specifically , the inner wall [8]. Some portion of the pellet ablatant is believed to propagate some 10 cm or more in the ∇B direction and actually leaves the plasma confinement region, thus reducing the fueling efficiency. A third effect that reduces the ideal fueling efficiency is that of pellets triggering edge localized modes (ELMs) in H-mode plasmas.

Injection of pellets into H-mode plasmas induces an ELM like event [7, 10] that has a similar duration and magnitude of divertor D_α light perturbation and similar power incident on the divertor to a normal non-pellet induced ELM. This suggests that pellet fueling of reactor plasmas may be no more detrimental to divertor operation than inherent ELM activity. The ELM-like event is found to expel a significant fraction of the pellet deposited mass by inducing strongly increased particle transport at the plasma edge. A short transition of the plasma to L-mode following the pellet injection (< 15 ms) is believed to be responsible for a continued expulsion of the pellet deposited mass, leading in some cases to retention of less than 20% of the pellet mass [11].

The difference in the measured plasma density profile just before and after injection of the pellet give a deposition profile. This deposition profile when compared to the modeled deposition from the NGS based ablation models [12] in general shows a translation of the deposited pellet mass toward the outside edge of the plasma. This is believed to be due to the drift effects mentioned earlier that occur on a time scale much shorter than the time delay before the density profile measurement. The measured penetration depth of the pellet is, however, found to be in reasonable agreement with the ablation models.

In Fig. 1 we show the measured density profiles before and after 2.7 mm pellet injection in an H-mode and an L-mode discharge. The expected deposition from the NGS ablation model [12] is also shown, which indicates the level of radial displacement of the pellet mass that is believed to occur. In the example of H mode deposition shown in Fig. 1a there is, in addition to the radial mass displacement, a clear collapse of the H-mode edge density pedestal, leading to significant mass ejected into the SOL where it shows up in the divertor and is labeled ELM loss. In the L-mode case there is no collapse of edge density, but there is a detectable increase of plasma density in the SOL even though the ablation rate in the SOL is virtually undetectable.

In order to study the effects of injecting pellets from inside the magnetic axis to take advantage of a ∇B drift of the ablatant, a vertical injection port was recently installed at the top of the DIII-D machine. This installation has been made using 10 m long curved guide tubes from the horizontal pellet injector location. Initial results from pellets that are injected about 10 cm inside the magnetic axis through the vertical port show a deeper density perturbation depth than expected from the models. The mass of the vertical pellets is not measured so a full size pellet is assumed, which is highly unlikely after traveling through the curved guide tube.

3. Fueling Efficiency

The pellet mass N_p measured by the microwave cavity and the increase in plasma particle content ΔN_e, determined by integrating the difference in measured Thomson scattering density profiles, is used to calculate the fueling efficiency η, defined as $\eta = \Delta N_e/N_p$. The uncertainty in the mass measurement is typically ±15% while the uncertainty in the plasma particle number is on the order ±5% for the profiles measured within 3ms of the pellet event. Plots of the calculated fueling efficiency η as a function of the neutral beam injection (NBI) power and as a function of the penetration depth of the pellet are given in Fig. 2. There is clearly a strong dependence of η on both the NBI power and penetration depth.

The calculated fueling efficiency in H-mode plasmas is in general lower than in L-mode for the same power and or penetration depth. This is presumably because of the expulsion of some of the pellet mass due to the triggering of an ELM like event as discussed in the previous section. A significant fraction of the pellet mass is seen to be lost in the edge pedestal region, which collapses while the pellet is injected. This is believed to be due to a fast (<200 μs) change in the edge pressure gradient triggered by the pellet at the edge [9]. In ELM-free H-mode discharges, the fueling efficiency is nearly as high as in L-mode discharges except in some cases where the pellet induced a very large ELM.

The fueling efficiency results from DIII-D are consistent with data from other machines, specifically the observed increase of η with penetration depth. In Fig. 3 we show a plot of a subset of the IPADBASE fueling efficiency data reported in Ref. [3]. The Tore Supra L-mode data shows the same increase with penetration as the DIII-D L-mode data. The ASDEX-Upgrade (AUG) data shows a strong difference in η between H-mode (ELMing) and L-mode as does DIII-D. The AUG data is perhaps conservatively estimated since the pellet mass is not measured. The unique data from DIII-D are in the ELM-free H-mode condition. Here η is more like in L-mode conditions, although ELMs are triggered and do dump some mass to the divertor. Generally the ELM that is triggered is smaller in magnitude that those in an already ELMing discharge.

An important question for a fusion reactor environment is whether the fueling by pellet injection is consistent with divertor lifetime requirements. The question of whether repeated ablation events cause any increased damage to the divertor needs to be studied. In order to investigate this question, the particle and heat flux to the divertor during a pellet injection event has been measured on DIII-D and compared with that from ELMs in the same discharge. The total heat flux is measured in the divertor with an infrared camera measuring the temperature rise on the graphite tiles at two toroidal locations [13]. The peak heat flux is comparable to that measured for ELMs in the same discharges as shown in Fig. 4. There does appear to be more toroidal asymmetry in the divertor heat flux from the pellets than generated by the ELMs. The particle flux from the plasma during a pellet injection event is measured with fast ion pressure gauges in the divertor baffle region. The particle flux during a pellet event is as much as 10 times larger than for non-pellet induced ELMs in the same discharge [13].

A limited amount of data has been collected to date from vertical pellet injection inside the magnetic axis. The vertically injected pellets in H-mode do cause an ELM-like event, however, it appears to be smaller in magnitude than those from pellets injected horizontally on the low field side (LFS). This can be seen in Fig. 5 where the D_α light is measured in both the lower divertor and upper divertor regions for 2.7mm pellets injected horizontally and vertically in the same discharge, a lower single null H-mode plasma. The measured D_α light perturbation on both the lower and upper divertor locations is smaller for the vertically injected pellets, presumably indicating a reduced expulsion of pellet mass. This reduction in D_α magnitude is believed to be due to a reduced ELM amplitude and a reduced outward propagation distance of the ablatant, leading to improved fueling efficiency for the vertical pellets. There may also be differences due to different toroidal locations of the horizontal and vertical injected pellets, which is under investigation. The fueling efficiency of these pellets appears to be better than normal horizontally injected pellets into the same plasma discharges and is shown for a limited data set in Fig 2. The deposition from these pellets is deeper than from equivalent LFS injected pellets and is more comparable to the theoretical predictions from the NGS models [14].

4. Discussion

Pellet fueling of H-mode plasmas has been seen to cause ELM events, which may prove to be beneficial for situations where ELMs are needed to flush impurities or reduce edge pressure gradients. As has been seen on other individual machines, the fueling efficiency is reduced when the applied auxiliary heating power is increased. In DIII-D this correlates to higher edge electron temperatures, which increases the pellet ablation rate in the edge region since the ablation is a strong function of the local electron temperature. For high fueling efficiency from the LFS, maximum penetration is desirable.

The ELMing region in the DIII-D H-mode discharges studies is in the range of 5cm inside the seperatrix. In all the cases on DIII-D the pellets penetrate well beyond the ELMing region because of the pellet size and speed. If the pellets were to not penetrate beyond the ELMing region, it is likely that the fueling efficiency would be reduced. The AUG data shows a lower fueling efficiency, which may be due in part to shallower penetration that is just beyond the ELMing region in that device.

It is hypothesized that a radial outward drift of the ablatant occurs during the process of the pellet mass symmetrization along the field lines. This drift of ablatant in the ∇B direction, pushes some of the pellet mass out of the confinement region and reduces the fueling efficiency for LFS injection. This is the motivation for attempting vertical injection inside the magnetic axis and for trying HFS injection from the inner wall. The initial results from vertical injection of pellets inside the magnetic axis on DIII-D looks promising for increased penetration and fueling efficiency. A reduced ELM effect from the vertical pellets is observed that is believed to be partially responsible for improved fueling efficiency. More data is needed to verify these initial results.

The future plan for pellet injection on DIII-D is to install curved guide tubes inside the machine to the inner wall in order to examine HFS injection to compare with the AUG results [8] and with the already installed vertical injection port. The obvious advantage of vertical injection is that an injector can be installed above the device with a straight guide tube so that high speed pellets can be injected. Curved guide tubes to reach the inner wall location will limit the pellet speed to about 300 m/s.

In conclusion, pellet experiments on DIII-D have been examined for the pellet fueling efficiency. Pellet injection in ELMing H-mode plasmas has lower fueling efficiency than ELM-free H-mode or L-mode plasmas due to the pellet induced ELM ejecting a sizeable portion of the edge density pedestal. The heat flux to the divertor from a pellet injection event is comparable to that caused by ELMs, thus pellet fueling is not likely to be more detrimental to divertor operation than ELMing H-mode operation. The particle flux in the divertor is measured to be somewhat higher that from intrinsic ELMs. Exciting new possibilities of improved pellet penetration depth and increased fueling efficiency with vertical and inner wall injection inside the magnetic axis are currently being investigated on DIII-D.

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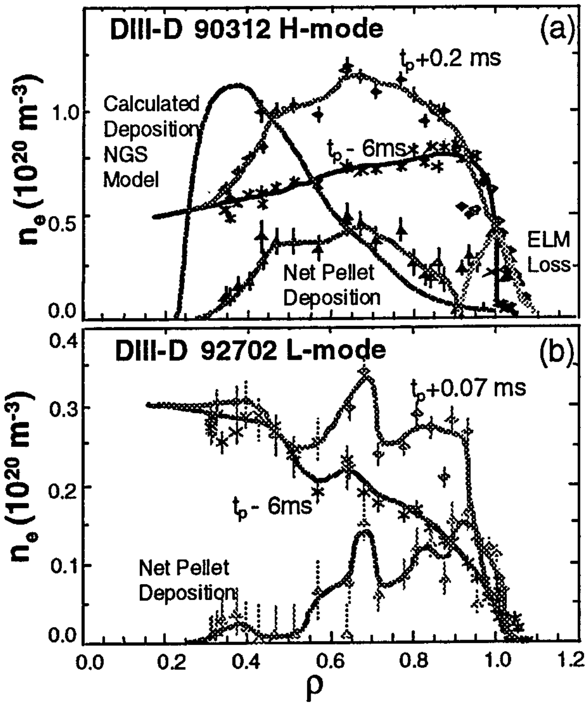

Fig. 1 Density profiles before and just after injection of 2.7mm pellets on DIII-D. ρ is the minor radius normalized to the square root of toroidal magnetic flux. (a) H-mode discharge with 5 MW NBI. The calculated deposition profile from the NGS ablation model [12] is shown for comparison. (b) L-mode discharge with 4.8MW NBI.

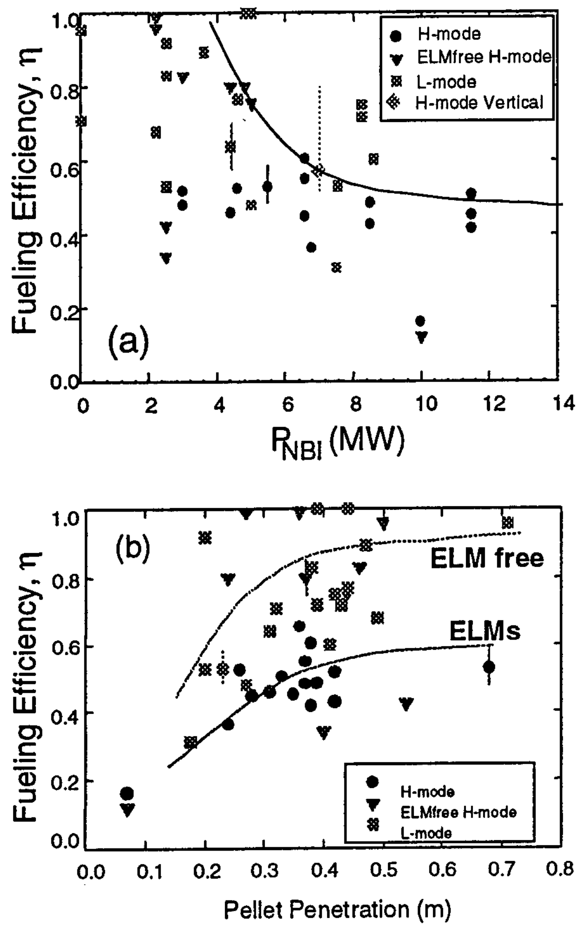

Fig. 2a.) Fueling efficiency as a function of neutral beam injection power. b.) Fueling efficiency as a function of penetration depth. Curves showing the trend for ELM-free and ELMing discharges are shown.

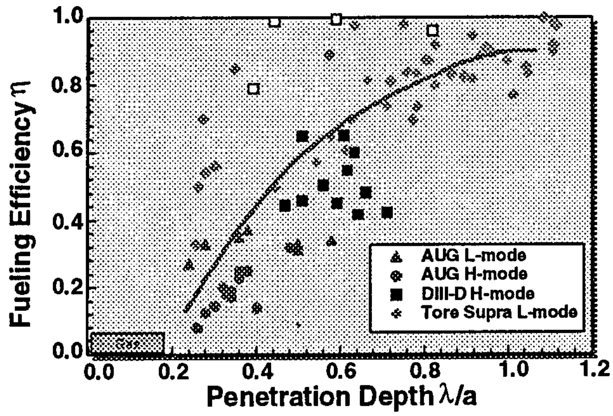

Fig.3 Fueling efficiency as a function of penetration depth normalized to the minor radius for data from three machines in the IPADBASE [4]. The approximate gas puff fueling efficiency is shown for comparison.

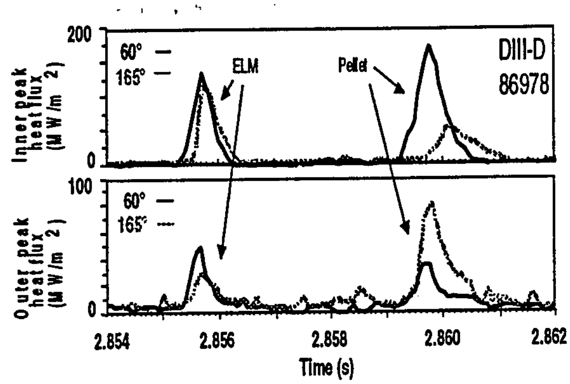

Fig. 4 Measured peak heat flux on the divertor from two toroidal locations during an intrinsic ELM and during a 2.7mm pellet injection event in the same discharge. The pellet is injected at a 135 degree toroidal location.

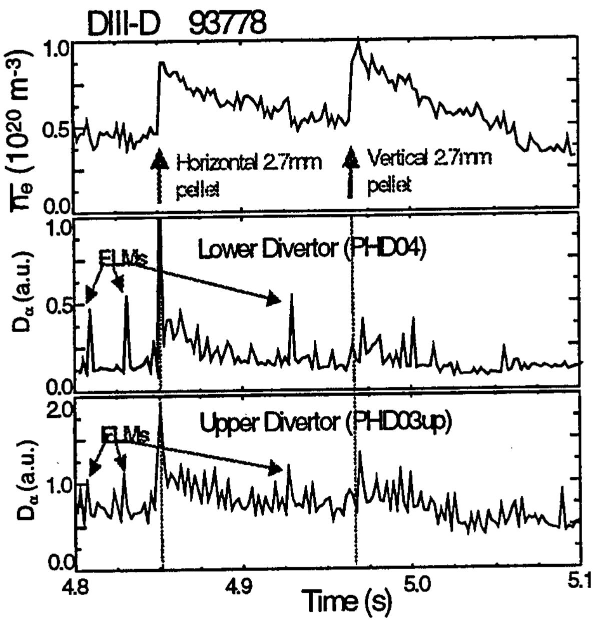

Fig. 5 Density perturbations and divertor D_α measured from 2.7mm pellets injected into an ELMing H-mode discharge with 7 MW NBI in a lower single null configuration. The first pellet is injected horizontally while the second is from a vertical port.

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