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Characteristics of ELM activity and fueling efficiency of pellet injection from different locations on DIII-D

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Abstract

Pellet injection from several different locations has been used on the DIII-D tokamak to study core fueling and transport in H-mode and L-mode plasmas. These experiments have provided a variety of conditions in which to examine the fueling efficiency and edge localized mode (ELM) interaction with 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. New injection ports on the DIII-D inner wall enable high field side (HFS) pellet injection from both the midplane and 30 cm above the midplane. These ports, in addition to the previously existing top vertical ports and outside midplane port, enable a comparison of the effect of injection location on fueling efficiency and ELM activity. We find that the ELMs triggered from HFS injected pellets and vertical HFS injected pellets are similar to the nominal background ELMs in ELMing H-mode plasmas. In contrast, the low field side (LFS) injected pellets trigger large-magnitude ELMs that lead to a strong reduction in fueling efficiency. The fueling efficiency of the HFS injected pellets is found to be significantly higher than with the LFS injected pellets and remains high even with significant heating power. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: ELM; DIII-D; Pellet injection

1. Introduction

Fueling a fusion grade plasma with the injection of frozen pellets of hydrogenic isotopes is an important technique developed and refined in the past 20 years [1]. Recently the research in this area has concentrated on pellet fueling from the high field side (HFS), which has been shown to lead to deeper more efficient fueling of tokamak plasmas than the previously standard injection location from the outside midplane or low field side (LFS) [2,3]. The issue of pellet fueling efficiency has not been extensively examined under various conditions until recent studies for LFS injection [4,5]. The efficiency of the fueling system is an important aspect in developing a reactor device that can achieve minimal tritium throughputs and wall inventory. In this study on DIII-D, we examine the extensive experimental results for pellet fueling efficiency from different injection locations in one device (an elongated, diverted, tokamak plasma) under various operating conditions.

The pellet injector on DIII-D [6] produces deuterium pellets of 2.7 mm diameter and length ($\sim 6 \times 10^{20}$ atoms) with speeds of 100–1000 m/s. 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 of the pellet, which has been found to differ significantly from the depth where the fuel particles are deposited [3]. Curved guide tubes have been installed to connect the three barrels of the injector to vertical ports ($V+1$ and $V+3$) and to two inner wall locations (HFS 45 and HFS mid) as shown in Fig. 1. Tests of a mockup 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

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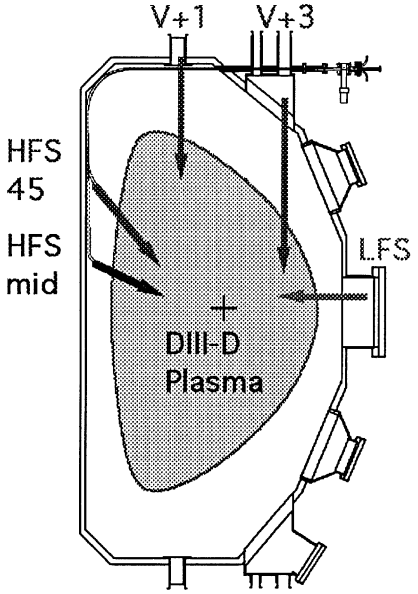

Fig. 1. The pellet injection locations on DIII-D shown in a poloidal cross-section.

through the vertical path. The pellets lose approximately 20% of their mass during the transport through the 12 m long guide tubes [7].

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 electron density profiles before and just after pellet injection along with the pellet mass measured in a resonant microwave cavity. These density profile measurements have been made as close as 20 μs after completion of the pellet ablation process, but are more typically made 1–5 ms after injection of the pellet. The HFS inner wall and vertical injected pellets do not traverse through the microwave cavity and so the nominal pellet size measured from outside midplane injection through the cavity is used with the mass lost in traversing the curved guide tubes in the fueling efficiency calculation.

2. Pellet plasma interaction and ELMs

Three effects of the plasma on the pellet can reduce pellet fueling efficiency from the ideal 100% value. Some ablation of the pellet occurs in the scrape off layer (SOL) before it reaches the last closed flux surface or separatrix of the plasma due to energetic particles in the SOL that impinges on the pellet. This effect is small on DIII-D for all the injection locations as measured by D_α light emitted by the ablating pellet. Another effect that can reduce the ideal fueling efficiency is the expulsion of pellet ablatant from the plasma by drift effects on the ablatant as it propagates along field lines. Such drifts may be caused by an ExB force that arises from a polarization of the ablatant cloud or from a pressure gradient-driven effect [2,8]. The ablatant would be expected to move in the $-\nabla B$ (outward major radius) direction on a 10 μs time scale and actually leave the plasma confinement region for LFS injected pellets. In pellet experiments where the pellets are injected from the HFS inner wall [2,3], the ablatant is not ejected from the plasma. The third effect that reduces the ideal fueling efficiency is that of pellets triggering edge localized modes (ELMs) in H-mode plasmas, which then eject particles and energy from the edge barrier plasma.

Pellets injected into H-mode plasmas from the different locations often induce an ELM-like event [3,9] that has a similar D_α light perturbation and power flux to the divertor. The ELM-like event is found to expel a significant fraction of the pellet mass by inducing strongly increased particle transport at the plasma edge. The plasma transitions to L-mode following the pellet injection for a short period (<25 ms), which is believed to be responsible for a continued expulsion of the pellet deposited particles, leading in some cases to retention of less than 20% of the pellet mass [5].

Pellets injected from the LFS into previously ELMing plasmas can cause an increase in the Type I ELM frequency as shown in Fig. 2. LFS injected pellets also trigger Type I ELMs when injected into otherwise ELM-free conditions [10] such as VH-mode and can cause synching of ELMs to the pellets when multiple pellets are injected. Compound ELMs occur when purposely shattered pellets from the LFS are injected into high power VH-mode plasmas to trigger edge perturbations. Presumably the pellets cause a rapid change in the edge

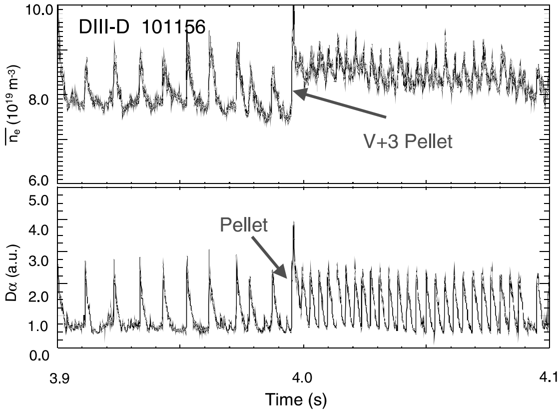

Fig. 2. The line average density for a central interferometer chord and divertor D_α emission in an ELMing H-mode plasma with 7MW NBI. A 2.7 mm pellet is injected from the $V+3$ port just before 4.0 s. The pellet induces a large ELM and increases the subsequent ELM frequency.

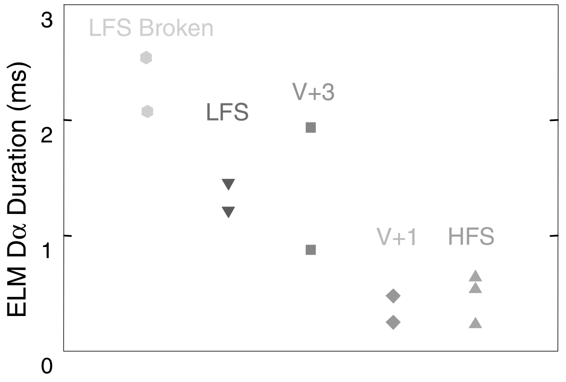

Fig. 3. The duration of the D_α emission following a pellet induced ELM for ELMs triggered by pellets injected from different locations. The broken LFS and $V+3$ pellets were in an upper single null configuration while the other cases were in a lower single null.

pressure gradient that leads to a change in the stability against the ELM.

Pellets injected from the HFS also induce Type I ELMs, but the divertor D_α emission after these ELMs is of much shorter duration [3]. Triggering of ELMs is also observed when pellets are injected deep into ELM-free VH-mode plasmas from the HFS. The ELM is sometimes delayed up to 50 ms [10], possibly resulting from the time necessary for the injected particles to transport back out to the plasma edge. In an effort to reduce the usual strong ELM that terminates the VH-mode [11], both HFS and LFS injected pellets were employed to begin an ELMing phase in VH-mode plasmas before natural ELMs occur. This scheme was successful in starting an ELMing phase earlier in the VH-mode plasmas, but did not extend the duration of the VH-mode or reduce the severity of ELMs on core plasma energy confinement.

The duration of the enhanced divertor D_α emission after ELMs triggered by pellet injection is a function of the injection location as shown in Fig. 3. The duration (full width at half maximum) of the divertor light perturbation following the pellet-induced ELM is much shorter for the HFS pellets than for LFS or $V+3$ pellets. This indicates there is a much larger particle flux to the divertor following an LFS pellet induced ELM. The enhanced D_α duration for LFS pellets is believed to be caused by both a stronger ELM collapse of the edge barrier and from a rapid outward major radius drift of pellet mass.

3. Pellet fueling efficiency

The fueling efficiency η, is defined as $\eta = \Delta N_e/N_p$, where N_p is the pellet particle content derived from the measured mass and ΔN_e is the increase in plasma electron content determined by integrating the electron density profiles. The uncertainty in the mass measurement is typically ±15% while the uncertainty in the number of plasma electrons is on the order ±5%. The

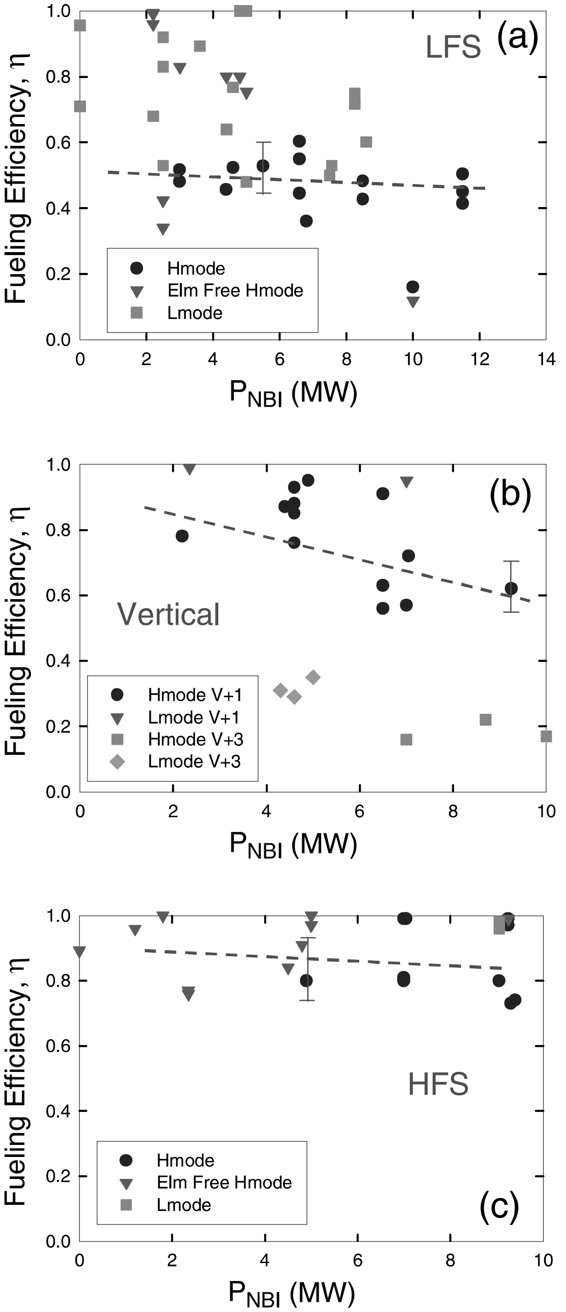

Fig. 4. Fueling efficiency as a function of neutral beam input power for: (a) LFS pellets, (b) vertical pellets, and (c) HFS inner wall injected pellets. Dashed lines indicate an average fit to the ELMing H-mode data.

calculated fueling efficiency η as a function of the neutral beam injection (NBI) power on DIII-D for the different injection locations is presented in Fig. 4. showing a strong dependence of η on the injection location.

The pellet fueling efficiency in H-mode plasmas is in general lower than in L-mode, especially for the LFS injected pellets. This is presumably because of the expulsion of pellet mass due to the triggering of the ELM-like event. A significant fraction of the pellet mass is lost in the edge pedestal region, which collapses while the pellet is injected. In ELM-free H-mode discharges, the fueling efficiency is nearly as high as in L-mode discharges except in cases where the pellet induced a very strong ELM.

The inner wall and $V+1$ injected pellets in H-mode do trigger an ELM-like event; however, it is smaller than those from pellets injected on the LFS or $V+3$ port. This reduced ELM amplitude and a negligible ejection of the ablatant out of the core plasma, leads to improved fueling efficiency for the HFS pellets. The fueling efficiency is higher and mass deposition deeper for the vertical injected $V+1$ pellets than LFS injected pellets into the same plasma discharges [12]. The HFS pellets have very deep mass deposition [3] and have fueling efficiency on the order of 90% and show no degradation with increased NBI power as shown in Fig. 4(c). Since the nominal pellet mass is assumed for these pellets, the actual mass may be lower giving a fueling efficiency that is nearly ideal.

4. Discussion

Injection of pellets from all locations on DIII-D into H-mode plasmas has been observed to trigger ELM events, which may prove to be beneficial if ELMs are needed to flush impurities or reduce edge pressure gradients. In all the cases on DIII-D the pellets penetrate well beyond the ~5 cm ELMing region because of the pellet size and speed. The ASDEX-Upgrade results indicate a lower fueling efficiency, which may be due in part to shallower penetration that is just beyond the ELMing region in that device [9].

Drift of ablatant in the $-\nabla B$ direction due to magnetic field curvature and gradients expels some of the pellet mass out of the confinement region and reduces the fueling efficiency for LFS injection. This is the primary motivation for injection inside the magnetic axis from the inner wall and from a vertical port. The results from vertical injection of pellets inside the magnetic axis on DIII-D show a reduced ELM perturbation and look promising for increased penetration and fueling efficiency. The advantage of vertical HFS injection over that from the inner wall is that an injector can be installed above the device with a straight guide tube so that high speed pellets can be injected deep into a large plasma. Inner wall injection will always limit the pellet speed, which may limit the fueling capability in a large reactor scale device.

In conclusion, pellet fueling experiments on DIII-D have been used to examine the pellet fueling efficiency from different injection locations. LFS pellet injection in ELMing H-mode plasmas has lower fueling efficiency than in ELM-free H-mode or L-mode plasmas due to the pellet inducing an ELM that ejects a sizeable portion of the edge density pedestal. HFS pellet injection has much higher fueling efficiency than LFS injection due to deeper mass penetration and a reduced ELM perturbation. The new methods of vertical and inner wall pellet injection inside the magnetic axis provide deep pellet mass penetration depth and increased fueling efficiency that gives DIII-D a flexible tool for transport and density control studies.

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