ELSEVIER

Journal of Nuclear Materials 313–316 (2003) 530–533

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Comparison of fueling efficiency from different fueling locations on DIII-D

L.R. Baylor [b,*], T.C. Jernigan [b], R.J. Colchin [b], G.L. Jackson [a], L.W. Owen [b], T.W. Petrie [c]

[a] *General Atomics, P.O. Box 85608, San Diego, CA 92186-9784, USA*
[b] *Oak Ridge National Laboratory, Fusion Energy Division, P.O. Box 2009, Oak Ridge, TN 37831-8071, USA*
[c] *Lawrence Livermore National Laboratory, Livermore, CA, USA*

Abstract

Fueling with gas and 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. Specific experiments have been carried out to examine the fueling efficiency into DIII-D H-mode plasmas that have periodic edge localized modes (ELMs). The fueling efficiency, defined as the total increase in number of plasma electrons divided by the number of input fuel atoms, is determined by measurements of plasma electron density profiles before and after a fueling pulse. We have found previously that there is a significantly higher fueling efficiency for pellets injected from the inner wall [J. Nucl. Mater. 290 (2001) 398] versus outside midplane pellet injection or gas puffing. In this study we extend this work to include the investigation of gas puffing from the same inner wall injection locations as the pellets to determine if a similar effect may exist. The mechanism for the improved pellet fueling from the inner wall is hypothesized to be a ∇B induced polarization of the pellet cloud leading to an $E\times B$ drift [Phys. Plasmas 7 (2000) 1968] in the major radius direction. The possibility of similar physics playing a role in gas puff fueling is examined in these experiments and does not appear to be a significant effect.
© 2003 Elsevier Science B.V. All rights reserved.

Keywords: Fueling; Pellet; DIII-D; Recylcing; Gas

1. Introduction

Fueling fusion plasmas with the injection of frozen pellets of hydrogenic isotopes is an important technique developed and refined over the past 25 years [3]. Recently the research in this area has concentrated on pellet fueling from the inner wall or 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) [4,5]. The issue of pellet fueling efficiency has been examined under various conditions with recent studies for LFS injection [6,7] and HFS injection [1]. 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 experimental results for gas and pellet fueling efficiency from different injection locations in one device (an elongated, diverted, tokamak plasma) under ELMing H-mode conditions.

The pellet injector on DIII-D [8] produces 1.8-mm and 2.7-mm diameter and length cylindrical deuterium pellets ($\sim 2\times 10^{20}$ atoms and $\sim 6\times 10^{20}$ atoms respectively) 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

---

[*] Corresponding author. Tel.: +1-865 576 1164; fax:+1-865 576 7926.
E-mail address: baylorlr@ornl.gov (L.R. Baylor).

0022-3115/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)01456-3

the fuel particles are deposited [5]. 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 250 m/s through the inner wall guide tubes and 500 m/s through the vertical path. The pellets lose approximately 20% of their mass during the transport through the 12 m long guide tubes [9]. A gas valve can be connected to the inner wall pellet guide tubes for fueling studies from the inner wall. These guide tubes have an inner diameter of 4 mm and a length of ~2 m. The conductance limit through this tube leads to a ~100 ms delay in the gas arrival to the plasma from the opening of the valve. The flow rate of gas through the inner wall tube was calibrated by the pressure rate of rise in the vacuum vessel.

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 or the gas puff, is determined by Thomson scattering measurements of electron density profiles before and just after the fuel injection. These density profile measurements are typically made 1–5 ms after injection of the pellet. The nominal pellet size measured from outside midplane injection through the microwave cavity is used with the average measured mass lost in traversing the curved guide tubes in the fueling efficiency calculation for the pellets.

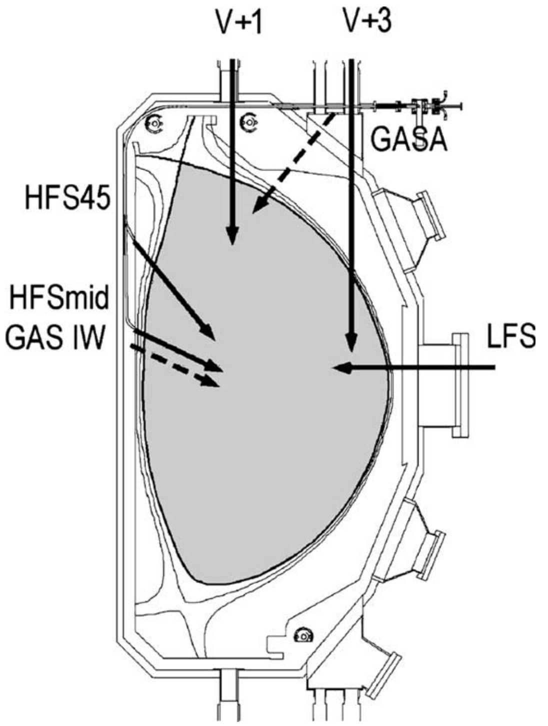

Fig. 1. The pellet (solid arrow) and gas injection (dashed arrow) locations on DIII-D shown in a poloidal cross-section. The ports are not in the same toroidal location. The plasma shape is that used in the gas fueling comparison.

2. Fueling experimental results

A specific experiment to compare gas puffing locations was carried out in edge localized mode (ELM)ing H-mode with a plasma current of 1.3 MA and 4.6 MW of neutral beam injection (NBI) in both upper single-null (USN) configuration and double-null (DN) configuration. The plasma quickly transitions into ELMing H-mode once the NBI turns on. A fixed rate gas puff is then turned on for 2.5 s shortly after the H-mode transition occurs. The plasma was moved close (~3.5 cm) to the inner wall in order to minimize the scrape off layer (SOL) thickness between the inner wall port and the core plasma so as to maximize neutral penetration into the plasma.

An increase in the ELM frequency from ~100 to 150 Hz is observed once the gas puff is initiated. The resulting ELM frequency is about 10% higher for the equivalent puff rate from the outside (GASA) location. As expected, the baseline D_α intensity increases more at the outer strike points with outside fueling (GASA) and more at the inside strike points with inner wall puffing (IW). At low puff rates of 60 Torr-l/s, very little increase in density is seen in the USN configuration, while a modest increase is seen in the DN configuration. At the highest puff rate attempted, 120 Torr-l/s, some increase in density is seen in a 3 s long fueling pulse from the inner wall location as shown in Fig. 2. Very little density increase is observed for the same puff rate from the GASA fueling port after an initial small increase observed within the first 400 ms of the puff, as also seen in Fig. 2.

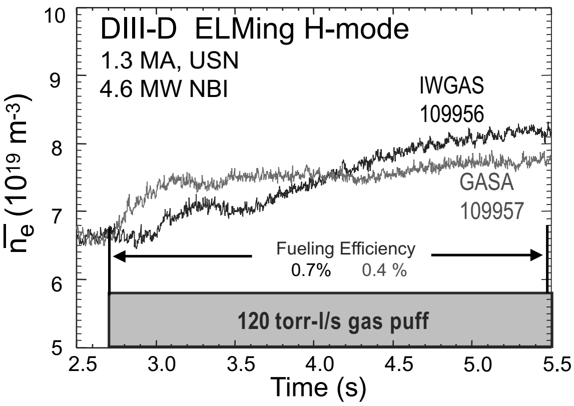

Fig. 2. Temporal evolution of the line average electron density in a 120 Torr-l/s gas-fueled comparison between inner wall and outside top injection locations in an USN configuration.

Pellets were also injected into similar shaped H-mode plasmas in separate experiments with approximately the same NBI power level. The pellets from the different locations often induce an ELM-like event [5,10] 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 <50% of the pellet mass [7].

Pellets injected from the HFS also induce Type I ELMs, but the divertor D_α emission after these ELMs is of much shorter duration [5] than from the LFS injected pellets.

3. Fueling profiles and efficiency

Analysis of the USN configuration high gas puff rate experiments to determine the fueling profiles has been carried out using the 2-D transport code *B*2.5 with the DEGAS Monte Carlo neutrals code [11]. In this analysis, the measured T_e and n_e profiles measured by Thomson scattering are simulated with *B*2.5, which computes integrated ion fluxes across the separatrix of 7×10^{21} ions/s for these shots. The NBI fueling rate is 5.8×10^{20} ions/s and the divertor recycling is 5.5×10^{21} ions/s to balance the core fueling with the efflux calculated with *B*2.5. The core fueling rate profile for the outside top location (GASA) depends somewhat on the plasma parameters in the 'halo' region between the simulation region and the wall. For reasonable assumptions in this halo region the fueling rate profile for inner wall gas fueling is slightly higher than for the outside top location. The resulting calculated fueling rate profiles are shown in Fig. 3 for the divertor recycling source and the inner wall gas puff. The calculated core fueling rate for the 120 Torr-l/s cases is <20% of the divertor recycling in this discharge and about twice that from the neutral beams.

The fueling efficiency η, is defined as $\eta = \Delta N_e / N_s$, where N_s is the particle content from the pellet or gas puff derived from the measured pellet mass or calibrated gas puff. ΔN_e is the increase in plasma electron content determined by integrating the electron density profiles. The uncertainty in the pellet mass measurement is typically ±15% while the uncertainty in the number of plasma electrons and the gas puff rate is on the order ±5%. The calculated fueling efficiency η as a function of the penetration depth in DIII-D ELMing H-mode plasmas for the different injection locations is presented in Fig. 4. The gas-fueled results are shown for the USN case in Fig. 2 to be 0.7% and 0.4% respectively for the 120 Torr-l/s puff rate. These results comprise essentially a single point at ~1% efficiency at very low penetration depth on the Fig. 4 plot. The strong ELMing undoubtedly has a negative effect on the gas fueling by frequent ejection of particles into the SOL. The higher inner wall fueling efficiency for this configuration is consistent with methane puffing from the inner wall that has shown a higher penetration factor than puffing from the outside [12]. The fueling efficiency in a DN configuration at low puff rates of 60 Torr-l/s was very similar for the two gas puff locations with a value of 1.2%.

The results from the pellet fueling show a strong dependence of η on the injection location. The HFS

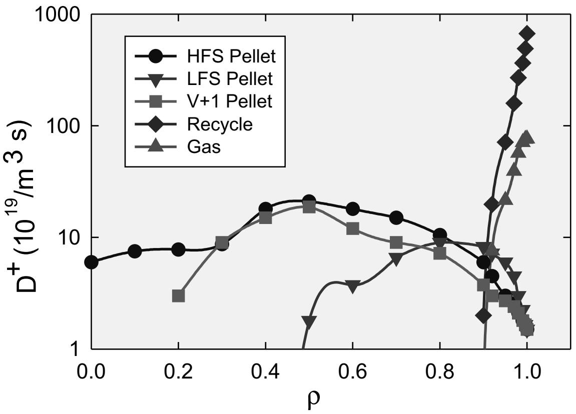

Fig. 3. The fueling source profiles in the core plasma in a 4.6 MW ELMing H-mode plasma for different fueling schemes. The gas and divertor recycle profiles are calculated from the USN discharges in Fig. 2. The IW and GASA gas source profiles cannot be distinguished on this plot. The pellet fueling profiles are from experimental results in similar H-mode shots and assume continuous 3 Hz injection of 2.7-mm size pellets.

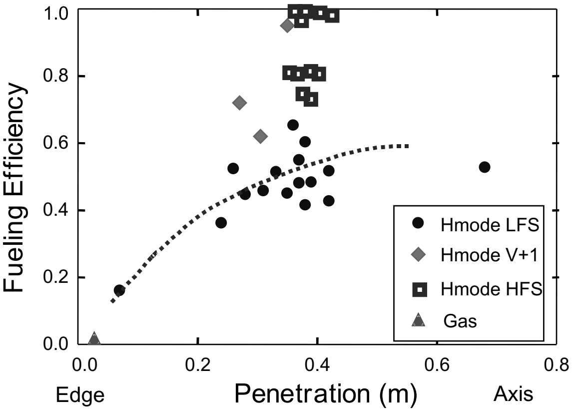

Fig. 4. Fueling efficiency in ELMing H-mode as a function of fuel penetration for LFS pellets, vertical pellets, HFS pellets and inner wall and outside top gas puffing. The dashed line is an approximate fit to the LFS injected pellet data.

pellets have very deep mass deposition [5] and have fueling efficiency on the order of 80–100% and show no function of penetration partly because the penetration is quite deep for all the pellets studied. Future experiments with smaller HFS pellets will help elucidate what effect shallower penetration may have. The vertical $V+1$ injected pellets have better fueling efficiency than the LFS injected pellets, which average about 50% efficiency. The equivalent pellet fueling rate profiles for the pellets from the different location are shown in Fig. 3 to compare with the gas fueling profiles. These pellet fueling rate profiles assume a 3-Hz operation of the injector and identical fuel deposition from each pellet.

4. Discussion

The gas fueling efficiency in a burning plasma experiment is likely to be even less efficient than determined for DIII-D due to higher edge density operation leading to poorer neutral particle penetration. Gas fueling with tritium will lead to $<1\%$ of the tritium puffed in directly fueling the plasma, thus leading to walls that are heavily loaded with tritium. Pellet fueling from inside the magnetic axis promises to deliver a fairly high fueling efficiency, especially if penetration beyond the ELMing layer can be achieved. Research into penetration by high-speed vertical injection inside the magnetic axis is needed to explore this option for a burning plasma. The isotopic fueling scheme proposed by Gouge et al. [13], in which deuterium gas is puffed and tritium rich pellets are injected, looks promising for achieving a reasonable core fueling of DT for burning plasma operation.

The apparent drift of the pellet ablatant in the $-\nabla B$ direction due to magnetic field curvature and gradient induced polarization clearly leads to higher fueling efficiency from pellets injected inside the magnetic axis versus from the outside midplane of tokamaks. Vertical injection from inside the magnetic axis has the advantage 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. Inner wall gas fueling does not show the significant increase in fueling efficiency as do the pellets because of the poorer penetration depth and a lack of a significant polarization drift effect.

In conclusion, gas and pellet fueling experiments on DIII-D have been used to examine the fueling efficiency from different fuel injection locations in ELMing H-mode. Inner wall gas fueling is slightly more efficient than outside top gas fueling in an USN configuration at high puff rates, however this efficiency is still quite low and does not appear to be strongly affected by the same ∇B effect as with the pellet clouds. 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. Further studies to extrapolate both gas and pellet fueling to a burning plasma regime are planned for the future.

Acknowledgements

We gratefully acknowledge the support and assistance of the DIII-D Operations Group at General Atomics and S.K. Combs and C.R. Foust at ORNL. Work supported by US Department of Energy under Contracts Nos. DE-AC03-99ER54463, DE-AC05-00OR22725 and W-74-5-ENG-48.

References

[1] L.R. Baylor, T.C. Jernigan, et al., J. Nucl. Mater. 290 (2001) 398.
[2] P.B. Parks et al., Phys. Plasmas 7 (2000) 1968.
[3] S.L. Milora et al., Nucl. Fusion 35 (1995) 967.
[4] P.T. Lang et al., Phys. Rev. Lett. 79 (1997) 1487.
[5] L.R. Baylor et al., Phys. Plasmas 7 (2000) 1878.
[6] A. Geraud et al., Proc. 23rd Europ. Conf. On Controlled Fusion and Plasma Physics, Kiev, Ukraine, vol. 20C, Part I, 1996, 460.
[7] L.R. Baylor, T.C. Jernigan, et al., J. Nucl. Mater. 457 (1999) 266.
[8] S.K. Combs et al., J. Vac. Sci. Technol. A 6 (3) (1988) 1901.
[9] S.K. Combs et al., Proc. of 18th IEEE/NPSS Symposium of Fusion Engineering, IEEE, 1999, 202.
[10] P.T. Lang et al., Nucl. Fusion 36 (1996) 1531.
[11] L.W. Owen et al., J. Nucl. Mater. 290 (2001) 464.
[12] W.P. West et al., these Proceedings.
[13] M.J. Gouge et al., Fusion Technol. 28 (1995) 1644.