"The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. DE-AC05-96OR22464. Accordingly, the U.S. Government retains a non-exclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes."

ORNL/CP-98520

DEPOSITION OF FUEL PELLETS INJECTED INTO TOKAMAK PLASMAS

CONF-980606--

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

RECEIVED
JUN 24 1998
OSTI

MASTER

Larry R. Baylor, T. C. Jernigan
Oak Ridge National Laboratory
Box 2009
Oak Ridge, TN 37831-8071
(423) 574-1164

C. Hsieh
General Atomics
P.O. Box 85608
San Diego, CA 92138
(619) 455- 4491

ABSTRACT

Pellet injection has been used on tokamak devices in a number of experiments to provide plasma fueling and density profile control. The mass deposition of these fuel pellets, defined as the change in density profile caused by the pellet, has been found to show an outward displacement of the ablated material from that expected by mapping the theoretical ablation rate onto the flux surfaces. This suggests that fast transport of the pellet ablatant occurs during the flow along field lines that may be driven by ∇B drift effects. A comparison of the deposition of pellets from different machines shows similar behavior. Initial results from alternative injection locations designed to take advantage of the outward ablatant drift is presented.

I. 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, 3, 4] and have shown the capability of pellet fueling to strongly modify the density profile shape. The resulting density profile modification from pellet injection was shown in JET and TFTR experiments to disagree with conventional pellet ablation theory [5] and suggested that a fast outward radial transport may occur during the pellet ablation and toroidal symmetrization process.

The issue of the resulting density profile from pellet injection, or pellet deposition, is very important in developing fueling systems for a reactor device that can achieve efficient fueling and density profile control. In this paper, we examine the experimental results from several devices in different operating conditions and try to extrapolate what may be expected in a large reactor grade tokamak.

In the ideal case, the pellet deposition is expected to follow directly from the pellet ablation rate. As the pellet ablates, the particles coming off the pellet are ionized and then follow the undisturbed background field lines until the density and temperature has equilibrated around the torus. Since no work is done the process is expected to be adiabatic. In actuality, the background field lines may be disturbed and the cold dense plasma coming off the pellet may be subject to forces perpendicular to the field lines as it flows along them. High-density localized regions of ablatant have been observed traveling around the torus during this symmetrization of the ablatant [6], suggesting a non-diffusive process. The light emitted from ablating pellets follows the predicted temporal behavior from the NGS model. Since both the penetration depth and ablation light emission are in agreement with the models, we make the supposition that the basic physics of pellet ablation is reasonably well explained by the NGS model with some shielding enhancements [7]. The mass distribution process, however, is still not well understood.

The pellet deposition, which is defined as the change in plasma electron density immediately after ablation, is determined by precise measurements of electron density profiles before and just after pellet injection. These density measurements were made by Thomson scattering diagnostics several milliseconds after injection of the pellet in JET and TFTR [5], but more recently have been made on DIII-D as close as 20μs after completion of the pellet ablation process. Multiple measurements made starting 150μs following ablation show only very modest changes in the density profile in the first 2 ms following injection [8] after the initial rapid response to the pellet

*Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

deposited mass. This indicates that anomalous fast particle transport effects are not observed during this post ablation period.

II. DEPOSITION MEASUREMENTS

The deposition of injected pellets is determined by the measured density profiles before and after injection of the pellet. The density profile measurement by multi-chord interferometry has its limitations due to the fact that it is a chordal measurement and therefore has limited spatial resolution. Nonetheless it has been used to determine the pellet deposition in some experiments [9], which also show a discrepancy with the ideal deposition from the ablation theory. A more accurate local measurement of the density profile can be made with multi-point Thomson scattering diagnostics such as that used on the DIII-D tokamak [10] or the LIDAR diagnostic on JET. The earlier measurements of deposition on JET and TFTR had good spatial resolution, but were not timed as close to the pellet ablation as desired. A minor limitation of the DIII-D Thomson scattering diagnostic for these measurements is that it looks directly at pellet ablation light from midplane injected pellets and is saturated when measurements are taken while the pellet is ablating.

The earlier measurements of deposition on JET and TFTR in both L-mode and H-mode showed plasma deposition that was skewed toward the low field side (LFS) edge when compared to the ablation model prediction. More precise measurements have been made recently on the DIII-D tokamak that show similar characteristics.

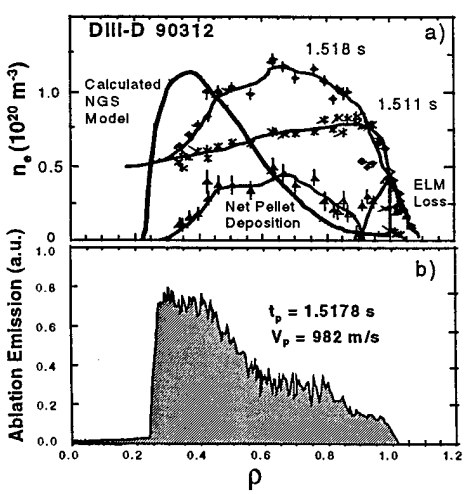

Fig. 1 a) Density profiles before and 200 μs after a pellet injected into a 5 MW NBI H-mode plasma on DIII-D. b) The ablation light emission mapped onto minor radius.

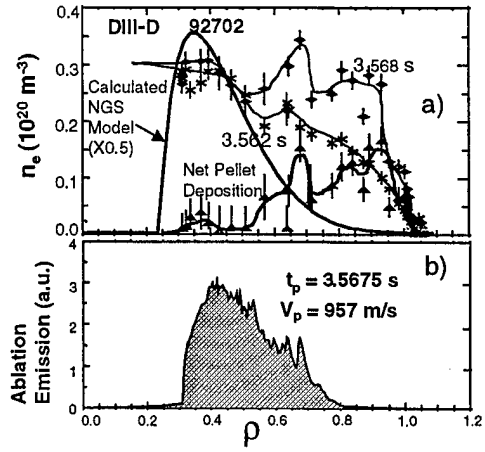

Fig. 2 a) Density profiles before and 70 μs after a pellet injected into a 4.8 MW NBI L-mode plasma on DIII-D. The deposition and calculated deposition are also shown. b) The ablation light emission mapped onto minor radius.

Figures 1 and 2 show two examples of deposition measurements from DIII-D in H-mode and L-mode. The deposition profile that is calculated from the NGS model using the PELLET code [11] and the pellet ablation light mapped onto minor radius are also shown. As was noted before, the ablation light emission and calculated ablation rate have qualitatively similar temporal evolutions. It does not seem likely that a toroidal deflection of the pellet can explain the discrepancy in deposition as the photodetector measuring the emitted light is collimated and a deflected pellet would leave the field of view. Also the radial extent of the measured deposition matches the penetration depth from the emitted light mapped onto the minor radius.

The mechanism responsible for the apparent outward drift of pellet ablatant is hypothesized to be caused by an **E×B** drift that arises from a polarization of the ablatant cloud moving along the curved magnetic field [12] or from a pressure gradient driven effect on the ablatant [13]. The time scale of such drifts for DIII-D are on the order of 10s of μs. In both cases the ablatant would be expected to move in the ∇B (outward radial) direction. Some portion of the pellet ablatant is believed to propagate some 10 cm or more in the ∇B direction and is actually expelled from the plasma confinement region, thus reducing the fueling efficiency.

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 integrating the total number of particles deposited by the pellet, $\int \Delta n_e dV$, and comparing with the measured pellet mass. The fueling efficiency is found to be much lower for shallow penetrating LFS injected pellets [14]. This is consistent with the apparent outward displacement of pellet ablatant that has been seen in deposition measurements. The outward drift for shallow penetrating pellets appears to actually expel a sizeable fraction of the pellet mass from the plasma confinement region leading to lower fueling efficiency. The fueling efficiency for the two examples in Fig. 1 and 2 were 75% and 30% respectively, although for the case in Fig. 2 the density profile continues to build to a larger level suggesting that the deposition process continued after the measurement.

Injection of pellets into H-mode plasmas induces an edge localized mode (ELM) like event 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 [14, 15]. 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. An example of this is shown in Fig. 1a where the collapse in edge density and increase in density in the scrape off layer are labeled "ELM loss". In addition to the apparent ∇B drift of the ablatant, pellet induced ELMs can have an impact on the fueling efficiency.

III. ALTERNATIVE INJECTION LOCATIONS

The drift effect that has been hypothesized to cause the expulsion of pellet ablatant from the plasma should in principle cause ablatant to drift toward the magnetic axis if pellets are injected from the HFS. It was shown on ASDEX-U that pellets injected from the HFS, specifically, the inner wall [13] led to deeper pellet penetration and increased fueling efficiency over that from LFS injected pellets. The density was found to increase strongly, but deposition measurements from the pellets in these experiments have not been available.

The injection of pellets from the inner wall requires a fairly sophisticated curved guide tube arrangement that limits pellet velocity [16]. An alternative injection scheme that may take advantage of ablatant drift in the ∇B direction is injection of pellets vertically inside the magnetic axis. To test this scheme vertical injection lines have been installed on DIII-D and Tore Supra.

The results from Tore Supra [9] with pellets injected from the top at 95° from the LFS do not seem to show any improvement in penetration, deposition, or fueling efficiency using measurements of the density from a multi-chord interferometer. The Tore Supra plasma has a circular cross section and the pellet is not injected significantly inside the magnetic axis. The vertical injection line on DIII-D is installed through a top port that is about 15cm inside the magnetic axis. Since the DIII-D plasma is fairly elongated one might intuitively expect pellets to have shallower penetration in normalized minor radius than from identical pellets on the LFS. Experimentally we see penetration to the same flux surface or deeper, which corresponds to the pellet traversing more plasma than on the LFS. The ELM amplitude from vertical pellets that are injected into H-mode plasmas appear to be smaller in amplitude and indicate higher fueling efficiency than from LFS pellets [15].

The recent addition of a vertical injection port at the top of the DIII-D machine is shown in Fig. 3 and is labeled V+1. The connection to the pellet injector on the horizontal midplane has been made using a 6m long curved guide tube made of thick walled stainless steel. Pellet speeds through this curved guide tube have been limited to just over 500 m/s for intact deuterium pellets.

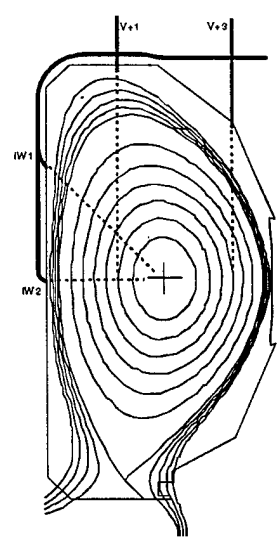

Fig. 3 Layout of DIII-D vacuum vessel and typical plasma flux surface geometry showing the vertical and planned inner wall pellet injection ports.

Initial results from pellets injected 15 cm inside the magnetic axis through the vertical port

show a deeper density deposition depth than expected as shown in Fig. 4. The calculated penetration depth and deposition is shallower than that for LFS injected pellets, however the initial data shows a deeper deposition than even the LFS calculation. If the vertical pellet follows a straight trajectory it can just reach a minor radius of ρ = 0.4. From Fig. 4 it can be seen that the density perturbation from the pellet reaches to ρ = 0.2 leading to speculation that the ablatant drifts toward the magnetic axis. A calculation of the density evolution using a 1 m^2/s diffusivity does not change the profile fast enough in the 2 ms following ablation to explain the discrepancy in deposition profiles.

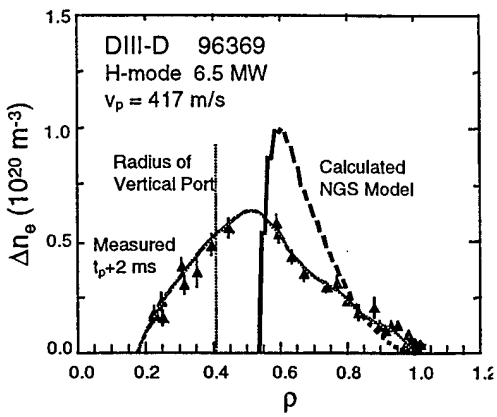

Fig. 4 Measurement of pellet deposition from a vertical 2.7mm pellet on DIII-D compared with the calculated deposition from the NGS model.

The fueling efficiency of these vertically injected pellets appears to be better than LFS injected pellets despite a factor of 2-3 lower injected velocity. The measured D_α light perturbation on both the lower and upper divertor locations is smaller for the vertically injected pellets, possibly indicating a reduced expulsion of pellet mass from the pellet induced ELM and from any outward drift of the ablatant.

The future plan for pellet injection on DIII-D is to install curved guide tubes inside the machine under the tiles to the inner wall, labeled IW1 and IW2 in Fig. 3. These tubes are being installed in order to examine HFS injection and to compare with both the ASDEX-U results [13] and with those obtained from the installed vertical injection port. The three-barrel DIII-D pellet injector will be able to inject pellets from the LFS, HFS and vertical ports during the same plasma discharge.

The obvious advantage of vertical injection over inner wall HFS 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 probably limit the pellet speed to about 300 m/s because of the fairly sharp bend radius that the tube must make. A spherical torus device that has no room for inner wall guide tubes is another application where vertical injection inside the magnetic axis may be beneficial.

IV. DISCUSSION

It is hypothesized that a radial outward drift of the ablatant occurs during the process of the pellet mass symmetrization along the field lines. The mechanism may be an **E×B** drift from polarization of the ablatant or a toroidal drift of a high-pressure plasmoid. 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 especially apparent in shallow penetrating pellets. The ∇B drift is the motivation for attempting vertical injection inside the magnetic axis and for attempting HFS injection from the inner wall.

The initial results from vertical injection of pellets inside the magnetic axis on DIII-D look very promising for increased penetration depth and fueling efficiency. A reduced ELM magnitude from the vertical pellets is observed that is believed to be partially responsible for improved fueling efficiency. This is presumably related to the asymmetric nature of the ideal ballooning mode that is believed to be related to the ELM activity. For a reactor sized device where the pellets may not penetrate far beyond the ELMing region, these alternative injection schemes may enable much higher fueling efficiency than LFS injected pellets since most of the LFS pellet would probably be ejected by the ELM. LFS injected pellets may remain useful in such a device for triggering ELMs to limit the edge pressure and heat flux on the divertor.

One of the possible limitations of HFS pellet injection is the required use of curved guide tubes that reach to the inner wall. Laboratory tests of pellet survivability have shown that there is a limited velocity for a given bend radius that is in some cases lower than predicted by simple yield stress models of solid deuterium [15]. Pellet speeds in excess of 1000 m/s will not likely survive the curved guide tubes for HFS injection in a reactor device. The penetration depth of pellets from the

NGS model and from the international pellet database for LFS injection is a weak function of the pellet speed ($\lambda \propto v_p^{1/3}$) [2,3,4], so it remains to be seen how serious a limitation this presents. The benefits of higher fueling efficiency and lower ELM magnitude may compensate for a lower pellet speed.

Injection of pellets vertically inside the magnetic axis has the attractive feature of making high speed pellets possible if the injector is positioned above (or below) the tokamak using a straight guide tube. If the apparent advantage of vertical injection is proven, it may indeed be more beneficial than HFS injection from the inner wall, which will have a limited pellet injection velocity. A study to see which fueling method yields the highest fueling efficiency is planned on the DIII-D tokamak in the near future.

In conclusion, pellet deposition measurements in tokamak plasmas from pellets injected on the LFS seem to universally indicate an outward expulsion of pellet mass during the ablation and symmetrization process. Recent experiments on DIII-D have permitted very accurate measurements of the pellet deposition and show a strong outward expulsion that appears to be reduced with vertical injection inside the magnetic axis. 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.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support and assistance of the DIII-D operations group at General Atomics and the Plasma Fueling Group at ORNL. Work supported by U.S. Department of Energy under Contracts DE-AC05-OR9622464 and DE-AC03-89ER51114.

REFERENCES

1. S. L. Milora, W. A., Houlberg, L. L. Lengyel, V. Mertens, "Pellet Fuelling," *Nucl. Fusion* **35** 967 (1995).

2. S. L. Milora, C.A., Foster, "A Revised Neutral Gas Shielding Model for Pellet-Plasma Interactions ," IEEE Trans. Plasma Sci. **PS-6** 578 (1978).

3. P. B. Parks, R. J. Turnbull, "Effect of Transonic Flow in the Ablation Cloud on the Lifetime of a Solid Hydrogen Pellet in as Plasma," *Phys. Fluids* **21**, 1735 (1978).

4. L. R. Baylor, A. Geraud, et al., "An International Pellet Ablation Database," *Nucl. Fusion* **37**, 445 (1997).

5. L. R. Baylor, G.L. Schmidt, et al., "Pellet Fuelling Deposition Measurements on JET and TFTR," *Nucl. Fusion* **32**, 2177 (1992).

6. D. K. Mansfield, et al., "Local-Density Increment from an Ablated Deuterium Pellet in the TFTR Tokamak," *Phys. Rev. Lett.*, **66**, 3140 (1991).

7. L. Garzotti, B. Pegourie, et al., "Neutral gas and Plasma Shielding Scaling Law for Pellet Ablation in Maxwellian Plasmas," *Nucl. Fusion* **37**, 1167 (1997).

8. L. R. Baylor, et al., "Pellet Injection into H-mode Plasmas on DIII-D," in Controlled Fusion and Plasma Physics (Proc. 22th Eur. Conf.) Vol. 19C, 133 (1995).

9. A. Geraud, J. F. Artaud, "Vertical pellet injection experiments on Tore Supra," to be published in Controlled Fusion and Plasma Physics (Proc. 25th Eur. Conf.) (1998).

10. T. Carlstrom, et al., "Design and Operation of the Multipulse Thomson Scattering Diagnostic on DIII-D," *Rev. Sci. Intrum.* **63** 4901 (1992).

11. W. A., Houlberg, S.L. Milora, S.E. Attenberger, "Neutral and Plasma Shielding Model for Pellet Ablation," *Nucl. Fusion* **28**, 595 (1988).

12. V. Rozhansky, et al., "Evolution and Stratification of a Plasma Cloud Surrounding a Pellet," *Plasma Phys. Control. Fusion* **37**, 399 (1995).

13. P. T. Lang, et al., "High-efficiency Plasma Refuelling by Pellet Injection from the Magnetic High-Field Side into ASDEX Upgrade," *Phys. Rev. Lett.*, **79**, 1478 (1997).

14. P. T. Lang, et al., "Pellet Fuelling of ELMy H Mode Discharges on ASDEX Upgrade," *Nucl. Fusion* **36**, 1531 (1996).

15. L. R. Baylor, T. C. Jernigan, R. Maingi, A. Mahdavi, "Fueling efficiency of pellet injection on DIII–D," submitted for publication in *J. Nucl. Matl.*

16. S. K. Combs, et al., "High-Field-Side Pellet Injection Technology," these proceedings.

M98003586

Report Number (14) ORNL/CP--98520
CONF-980606--

Publ. Date (11) 199806
Sponsor Code (18) DOE/ER, XF
UC Category (19) UC-420, DOE/ER

19980707 007

DTIC QUALITY INSPECTED 1

DOE