PPPL--2237

DE85 017688

PARAMETERS OF THE LUMINOUS REGION SURROUNDING DEUTERIUM PELLETS IN THE PLT TOKAMAK

D.H. McNeill, G.J. Greene, and D.D. Schuresko*

Plasma Physics Laboratory, Princeton University,
Princeton, NJ 08544

ABSTRACT

The luminous region of the plasma cloud surrounding deuterium pellets injected into a tokamak is studied spectroscopically. At the time of peak luminosity the average electron density is $2.4 \times 10^{17} \text{ cm}^{-3}$ to within 30% and the temperature is at most 2.0 eV. The intensity ratio of the Balmer alpha and beta light from the pellets, the total number of emitted photons, and the apparent size of the radiating region are consistent with local thermodynamic equilibrium at this temperature and density.

* Permanent address: Oak Ridge National Laboratory, Oak Ridge, TN 37830

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.

In the past decade, experiments have been performed in which pellets of solid hydrogen or deuterium with dimensions of 0.070-4.0 mm and velocities of 90-1300 m/s were injected into tokamak plasmas.¹⁻⁵ Extensive studies have been made of the effect of "interior" plasma fueling using pellets, as opposed to "edge" fueling by recycling and gas puffing, on the confinement properties of discharges, and it has been found that the density of large plasmas can be greatly increased by this means without degradation of confinement. The highest values of the product of the plasma density and energy confinement time in a fusion experiment have been reached in a pellet-fueled tokamak.⁵ An ablating pellet is a unique physical environment: within less than 1 ms, as it enters a large plasma, a solid pellet (molecule density $2-3 \times 10^{22} \text{ cm}^{-3}$), at a temperature of about 10 K, becomes part of a diffuse plasma with an electron density between 10^{13} and 10^{14} cm^{-3} and a temperature on the order of 10^7 K. In the ablation region surrounding the pellet, gradients occur which correspond to these limits over distances of at most a few centimeters. Pellet ablation in large hot plasmas has been studied theoretically,⁶⁻⁹ but no measurements of the properties of the plasma cloud surrounding an injected pellet have been reported previously. The light from pellets is of special importance because it is the only available diagnostic for determining their instantaneous rate of ablation as they enter a plasma.^{1,4,8} In this paper we report spectroscopic measurements of the electron density and temperature in the emitting region of the plasma surrounding pellets injected into a large tokamak and briefly consider the relationship of these results to the properties of the ablating pellets.

Recently, a pneumatic solid hydrogen pellet injection system of the type described in Ref. 10 has been installed on the PLT tokamak.¹¹ In the experiment described here, two solid deuterium pellets were injected at

velocities of 600-800 m/s into each of a series of PLT discharges. The cylindrical pellets, with nominal diameters of 1.2 mm and lengths of 1.5 mm, were fired into the plasma 20 ms apart, beginning roughly 450 ms after the start of the discharge. (In most shots the first pellet broke into two pieces before reaching the tokamak plasma, while the second always remained intact.) Before injection of the pellets, the ohmically heated plasma, with a minor radius of 40 cm and a major radius of ≈ 134 cm, had a comparatively flat density profile with a line average electron density $n_e \approx 2.0 \times 10^{13} \text{ cm}^{-3}$ and a peak electron temperature $T_e \approx 1.5$ keV. The H_α emission from the pellets is monitored with a photodiode and interference filter to measure their lifetime and penetration into the plasma. Figure 1 shows a typical trace of the photodiode H_α signal from a pellet as a function of the time after discharge initiation. The pellet is entirely consumed within 250 μs . The exact shape and fluctuations in the signal vary widely from one shot to the next, but the rapid fall is customary. Data such as that of Fig. 1 show that the pellets moved radially inward a distance of 10-20 cm from the point in the low-density outside edge of the plasma where they began to emit strongly. They reached a region where $n_e \approx 2.2 \times 10^{13} \text{ cm}^{-3}$ and $T_e > 500$ eV before they were completely ablated. Each pellet contained $N_{D_2} \leq 5 \times 10^{19}$ deuterium molecules and the two pellets produced an average density increase of about $2 \times 10^{13} \text{ cm}^{-3}$ in the tokamak, almost doubling the initial density.

In this experiment, light from the pellets, reflected off the inside wall of the vacuum vessel, was viewed by a fiber optic cable which carried the signal out of the machine area. Spectral profiles of the deuterium Balmer beta

(H_{β} , 486.0 nm) and alpha (H_{α} , 656.1 nm) light from the pellets were taken with the aid of two detectors. A spectral scan was made using a 50-cm grating monochromator with an approximately triangular passband of 0.3 nm full-width half-maximum (fwhm). Part of the light from the fiber optic cable was split off by a glass beam splitter and passed through a 15 nm fwhm interference filter centered at the H_{α} wavelength. The broadband monitor was used to normalize the narrowband signal from the monochromator which was tuned in wavelength from shot to shot. Photomultipliers with amplifiers were used on both channels and the signals were recorded on oscilloscopes and/or CAMAC transient recorders (sampling rate 10-40 kHz).

Figure 2 shows the normalized signal from the monochromator in the neighborhoods of the H_{α} and H_{β} lines at the time of peak luminosity from the pellets. The plotted points are averages of from 2 to 12 values obtained by dividing the monochromator signal at a given wavelength separation $\Delta\lambda$ from the line center by the broadband monitor signal. The data of Fig. 2 have been calibrated relatively using a tungsten-halogen standard lamp and the apparent continuum background has been subtracted. The error bars denote unbiased estimates of the standard deviation about the plotted mean. The H_{α} and H_{β} profiles were obtained in sequences of about 20 and 30 similar discharges, respectively. Data were taken on both sides of the line centers, but no systematic asymmetry was found in the lineshapes. Over the entire sequence of discharges the spectral profiles obtained from the two (or three, since in most cases the first pellet was broken in two) groups of pellets overlap within the measurement errors, and all pellets are included in the average values of Fig. 2.

The ratio of the intensities of the H_{α} and H_{β} lines from the pellets, i.e., of the areas of the respective profiles in Fig. 2, is 3.7 (or slightly less), while the corresponding ratio for the PLT plasma is above 4.5. At the time of peak pellet luminosity the broadband H_{α} monitor signal from the pellets was over 200 times that from the PLT plasma and would have been relatively larger if the pellets had been viewed directly by the fiber optic cable.

Both the H_{α} and H_{β} lines from the pellets are substantially broadened.¹² For $\Delta\lambda > 0$ the profiles of Fig. 2 can be interpreted readily in terms of Stark broadening in a uniform plasma.^{13,14} The solid curves in Fig. 2 are Stark broadened H_{α} and H_{β} profiles for $n_e = 2.4 \times 10^{17} \text{ cm}^{-3}$ and $T_e = 20000 \text{ K}$ interpolated from the tables of Griem.¹³ (The computed profiles are fairly insensitive to the temperature. The H_{β} profile for $T = 5000 \text{ K}$ differs from the $T = 20000 \text{ K}$ profile at small $\Delta\lambda$ and is shown in Fig. 2 by a dotted curve.) At $\Delta\lambda = 0$ the relative scatter in the normalized signal is much larger than at other wavelengths for both lines. (Other data than that shown here confirm this behavior for H_{β} .) This large scatter and the "filling in" of the Stark profile at the line centers seem to be caused by emission from regions where the density is much lower, such as tiny pellet fragments which vaporize without forming a dense plasma cloud or deuterium gas which enters the plasma edge along with the pellet. The monochromator signal also rises earlier at $\Delta\lambda = 0$ than for $\Delta\lambda \geq 1 \text{ nm}$, suggesting that a weak, narrow central peak develops before the pellets begin to emit strongly. (This precursor may be caused by release of gas from the pellet as it moves through the discharge edge before a dense ablation cloud has developed.) Nevertheless, the observed lineshapes for $\Delta\lambda \geq 1 \text{ nm}$ are in good

agreement with Stark broadening theory and yield the same density for both Balmer lines. The estimated error in the average value $n_e = 2.4 \times 10^{17} \text{ cm}^{-3}$ is 30% for the three groups of pellets together. The line profiles obtained separately for the three groups show qualitatively that n_e at the time of peak luminosity was lowest for the first fragment of the first pellet and highest for the second (intact) pellet.

The background continuum was estimated by making measurements 30 nm or more from the centers of both lines. The background levels in the plots of Fig. 2 are ≈ 0.020 for H_α and ≈ 0.012 for H_β . By using the observed ratio of the total line intensity to the continuum intensity over a fixed interval it is possible to determine the temperature of the emitting region.¹⁴ The maximum temperature of the emitting region is 1.5–2 eV (17000 K and 23000 K from the H_β and H_α profiles, respectively, where the first value is more accurate with an estimated error of about 20%). This is an upper bound on the temperature of the emitting region, since (i) molecular line emission, for example, may contribute to the apparent background level, and (ii) this method is based on the assumption that the continuum emission comes from the same volume as the line emission. At $\approx 100 \mu\text{s}$ before the time of peak luminosity, when the intensity is about a fifth of the maximum (cf. Fig. 1), the H_β spectrum away from the line center corresponded to an electron density and temperature that were within a factor of two of their values at the time of peak luminosity. Because of the wide scatter in the signal from one shot to the next, a polychromator would be needed for reliable measurement of the time evolution of the line profiles from injected pellets.

A first step in understanding these results may be taken by assuming that the emitting region is in local thermodynamic equilibrium (LTE)¹⁴ with the measured $n_e = 2.4 \times 10^{17} \text{ cm}^{-3}$ and $T_e = 1.5 \text{ eV}$, but not opaque to Balmer alpha and beta emission (except possibly near the line centers). According to the Saha-Boltzmann formula for ionization equilibrium,¹⁴ the densities of deuterium atoms in the $n=3$ and $n=4$ states are $n_3 = 2.6 \times 10^{14}$ and $n_4 = 3.0 \times 10^{14} \text{ cm}^{-3}$, respectively. When the photon emission rates are converted to intensities, these densities, along with the transition probabilities A_{32} and A_{42} for the H_α and H_β transitions, give an intensity ratio for these lines of 3.4, which is close to the observed value, 3.7. Assuming that these parameters for the emitting region of the pellet cloud are the same throughout the time it radiates most strongly ($\tau_{em} \approx 100 \text{ } \mu\text{s}$; cf. Fig. 1) and that the pellet emits $\approx 0.02 H_\alpha$ photons per atom,⁴ gives an emitting volume $V_{em} = 0.04 N_{D_2} / (n_3 A_{32} \tau_{em}) \approx 1.8 \text{ cm}^3$. Photographs suggest that pellet ablation can be highly asymmetric; however, for simplicity we shall assume symmetry, in which case this volume could be a sphere or a shell centered at the pellet core. In particular, a shell with a radius of about 2 cm and a thickness of 0.036 cm is consistent with the steep temperature and density profiles which theoretically should exist in an ablating pellet^{6,7,9} and with time-exposure photographs of pellets in PLT. This radius is comparable to the ionization radius obtained in the neutral shielding model of Parks, Turnbull, and Foster.⁷ The ablatant temperature computed in the ionization front model of Gralnick⁶ is similar to the emitting-region temperatures measured here. Spatial or temporal fluctuations in the electron density and temperature of this region would cause changes in the densities of excited neutral atoms and contribute to

the intensity fluctuations seen in Fig. 1.

Knowledge of the localized rate of deposition of new particles from a pellet is of crucial importance for understanding the pellet's effect on a plasma. The primary technique used to estimate the rate of ablation of an injected pellet and determine its depth of penetration is to record the line emission from the pellet as it moves in the plasma.^{1,4,8,9} In early experiments this diagnostic was used under the assumption that the number of H_{α} photons emitted per ablated atom is constant, independent of the temperature of the emitting region, so that the H_{α} intensity of the pellet is proportional to the rate of pellet ablation (and ionization).^{1,4} This assumption is approximately true for an isolated atom or molecule released and fully ionized in a large, uniform, low-density plasma with an electron temperature $T_e > 25$ eV. For H atoms this process would yield about 0.07 Balmer alpha photons per ionization event; however, this ratio increases rapidly with decreasing temperature. Existing theories of pellet ablation rates all show some disagreement with observed H_{α} signals from pellets entering plasmas.^{3,4,9} Model calculations of the correlation between the rates of pellet ablation and H_{α} emission have been made using a collisional-radiative model.⁹ In these calculations it was assumed that the charged particle density in the emitting region of the pellet cloud is comparable to the density in the surrounding tokamak plasma, and that the temperature in the emitting region is on the order of tens of eV (so that ionization and excitation are dominated by the primary electrons of the discharge plasma). We have shown that neither assumption is correct. More detailed studies may show that the emission rate, size, and other properties of the pellet cloud must be explained in terms of a

flux of cold neutrals moving outward into a nonequilibrium plasma, especially in rf and ohmic heated discharges. On the other hand, we have shown that LTE in the emitting region at the measured values of T_e and n_e yields satisfactory agreement with the average behavior of ablating pellets in an ohmically heated plasma. If the emitting region of the plasma cloud around a pellet is in LTE throughout the pellet's lifetime, then it may be possible to justify the H_α ablation diagnostic theoretically. The observations reported here should aid further analysis of the relationship between the instantaneous H_α emission rate and the rate of release of particles from a pellet into a plasma.

Special thanks to J.C. Hosea, D.Q. Hwang, and S.L. Milora for their interest in this experiment. This work has been supported by the U.S. Department of Energy, contract No. DE-AC02-76-CHO3073.

REFERENCES

- ¹ C.A. Foster *et al.*, Nucl. Fusion 17, 1067 (1977).
- ² C.T. Chang, L.W. Jorgensen, P. Nielsen, and L.L. Lengyel, Nucl. Fusion 20, 859 (1980).
- ³ S.L. Milora, J. Fusion Energy 1, 15 (1981).
- ⁴ S.L. Milora *et al.*, Nucl. Fusion 20, 1491 (1980).
- ⁵ M. Greenwald *et al.*, Phys. Rev. Lett. 53, 352 (1984).
- ⁶ S.L. Gralnick, Nucl. Fusion 13, 703 (1973).
- ⁷ P.B. Parks, R.J. Turnbull, and C.A. Foster, Nucl. Fusion 17, 539 (1977).
- ⁸ C.T. Chang and K. Thomsen, Nucl. Fusion 24, 697 (1984).
- ⁹ B.V. Kuteev, A.P. Umov, and L.D. Tsandin, Fiz. Plazmy 11, 409 (1985).
- ¹⁰ D.D. Schuresko *et al.*, J. Vac. Sci. Technol. A 1, 959 (1983).
- ¹¹ E. Mazzucato *et al.*, in: Proceedings of the Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1985), Vol. 1, p. 433.
- ¹² Observations made in 1983 of pellets injected into the ISX-B tokamak showed that the H_{α} line was significantly broadened. An interference filter centered 11 nm off the line center was used. (C.E. Bush, personal communication)
- ¹³ H.R. Griem, Spectral Line Broadening by Plasmas (Academic Press, New York, 1974).
- ¹⁴ H.R. Griem, Plasma Spectroscopy, (McGraw-Hill, New York, 1964).

FIGURE CAPTIONS

Fig. 1. The signal from the photodiode monitor during injection of a pellet into PLT (sample rate 100 kHz).

Fig. 2. Spectral scans of the Balmer alpha and beta line emission produced by pellets injected into PLT. The solid curves are computed Stark broadening profiles for $n_e = 2.4 \times 10^{17} \text{ cm}^{-3}$ and $T = 20000 \text{ K}$. The dashed curve on the lower plot corresponds to $T = 5000 \text{ K}$.

FIG. 2

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Plasma Res Lab, Austro Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. O. Palumbo, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakaraka, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Sachynski, MFB Technologies, Inc., CANADA
 Chalk River, Nucl Lab, CANADA
 Zhengwu Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, Academia Sinica, CHINA
 Dr. Peter Lukac, Komenskeho Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-SPP, FRANCE
 AM Dupas Library, AM Dupas Library, FRANCE
 Dr. Tom Mui, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. S.K. Trehan, Panjab University, INDIA
 Dr. Indra Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chavda, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Vikram Univ, INDIA
 Dr. B. Dasgupta, Saha Inst, INDIA
 Dr. P. Kaw, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Ouperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Clelia De Palo, Assoc EURATOM-ENEA, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. Y. Yanato, Toshiba Res & Dev, JAPAN
 Dirac, Dept. Eg. Tokamak Dev. JAERI, JAPAN
 Prof. Nobuyuki Inoue, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigeru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Saburo Itoh, Kyushu University, JAPAN
 Dr. D.I. Choi, Adv. Inst Sci & Tech, KOREA
 Tech Info Division, KAERI, KOREA
 Bibliothek, Pan-Inst Voor Plasma, NETHERLANDS
 Prof. B.S. Liley, University of Waikato, NEW ZEALAND
 Prof. J.A.C. Cabral, Inst Superior Tech, PORTUGAL
 Dr. Octavian Petrus, ALI OJZA University, ROMANIA
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Plasma Physics, Nucor, SO AFRICA
 Fusion Div. Library, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of Umea, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. V.T. Tolok, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Kyutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Institute Gen. Physics, USSR
 Prof. T.J.M. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universitat, W. GERMANY
 Nuclear Res Estab, Jülich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Bibliothek, Inst Plasmaforschung, W. GERMANY
 Prof. R.K. Janev, Inst Phys, YUGOSLAVIA