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R.A. Jong, G.D. Porter, R.J. Groebner, C.J. Lasnier, GA Thomson Team

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Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94551

General Atomics
3550 General Atomics Court
San Diego, California 92121

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Effect of ELMs on the SOL plasma in DIII–D

R.A. Jong[†], G.D. Porter[†], R.J. Groebner[‡], C.J. Lasnier[†] and GA Thomson Team[‡]

[†] Lawrence Livermore National Laboratory, Livermore CA 94550, USA

[‡] General Atomics, San Diego CA 92121, USA

Abstract. We have studied the evolution of the edge plasma in VH–mode discharges in DIII–D as the discharge evolves from the ELM-free H–mode phase through the VH–mode phase to the final ELMing H–mode phase, by following the changes in the radial profiles of the density and temperature, in the core plasma near the separatrix and in the scrape-off-layer (SOL) plasma outside the separatrix. The electron density and temperature profiles in the SOL do not show any significant difference between the ELM-free H–mode and VH–mode phases. In the ELMing phase, the density profile broadens during an ELM, forming a high density ($n_e > 1 \times 10^{19}$ / m^3) plateau that extends out into the SOL to the limit of the measurement. This density plateau persists between the ELMs, although the density in the SOL does relax somewhat between the ELMs, with a characteristic time that can be larger than ten milliseconds, much longer than the sonic particle flow time to the divertor plates. The time average density scale length measured at the separatrix increases by about a factor of two after the ELMs begin. This density scale length increases with the ELM background, as measured by the photo-diodes nearest to, but outside the outer strike-point, suggesting that recycling from the divertor targets is supplying particles that maintain the density plateau. The electron temperature profile in the SOL also broadens during an ELM, but relaxes on a much faster time scale and does not persist between ELMs.

1. Introduction

The scrape-off-layer (SOL) plasma in tokamak discharges has been the subject of several recent studies on DIII–D by Watkins *et al* 1995, Watkins *et al* 1994, Jong *et al*, Lippmann *et al*, and Schaffer *et al*. In addition, Hill *et al* studied the effect of ELMs on edge plasma scaling in DIII–D. The density and temperature profiles in the edge region of the plasma and in the divertor region have obvious importance in the study of neutral fueling of the core plasma, impurity penetration of the core plasma, and the transport of particles and energy from the core plasma to the SOL and divertor regions. Here, we shall describe experiments that followed the evolution of the plasma in the scrape-off layer and divertor regions during the quiescent H–mode, VH–mode, and ELMing H–mode phases of high current (1.6 MA), high triangularity, double-null discharges in the DIII–D tokamak.

We have measured the edge and divertor plasmas with a wide array of diagnostics including Thomson scattering for the electron density and temperature, charge exchange recombination (CER) for the ion temperature, a reciprocating probe for midplane electron density and temperature profiles, infrared TV (IRTV) cameras for heat flux distributions on the divertor floor, Langmuir probes for electron temperature and density on the divertor floor, and photo-diodes to measure the D_α light in the divertor. Because of space limitations here, we shall concentrate most of our discussion on the measurements from the multi-pulse

Thomson scattering diagnostic to follow the changes in the radial profiles of the electron density and temperature. We shall also briefly discuss the heat flux profiles measured with the IRTV diagnostic looking at the divertor floor. The whole array of diagnostics are consistent with edge electron density and temperature profiles in the SOL and heat flux profiles in the divertor that do not show any significant difference between the ELM-free H–mode and VH–mode phases. We find that the profiles are significantly broader during an ELM, and that the broad density profiles can persist in the time between the ELMs.

2. Typical Long-Duration VH–Mode Discharge

The typical high current, high triangularity, double-null discharge we consider is shot number 83618. This is a VH–mode plasma with a long ELM-free period of almost 900 ms, extending from about 2000 to 2877 ms. As seen in figure 1, the ELM-free H–mode transitions to a VH–mode around 2400 ms (i.e. $\tau_{th} / \tau_{DIII-D/JET} \geq 1.6$). This VH phase lasts for about 500 ms, with an energy confinement time enhancement value of up to 2.5 comparedto the DIII–D/JET H–mode scaling). The end of the VH–mode phase is signaled by the event at 2877 ms where the photo-diode signal increases and indicates the onset of ELMs. At the same time, there is a large drop in the plasma pressure as indicated by the drop in the toroidal β (BETAT).
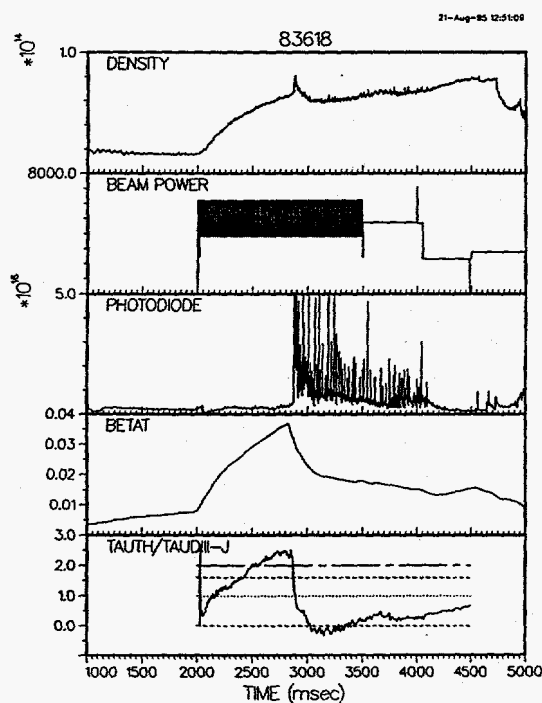

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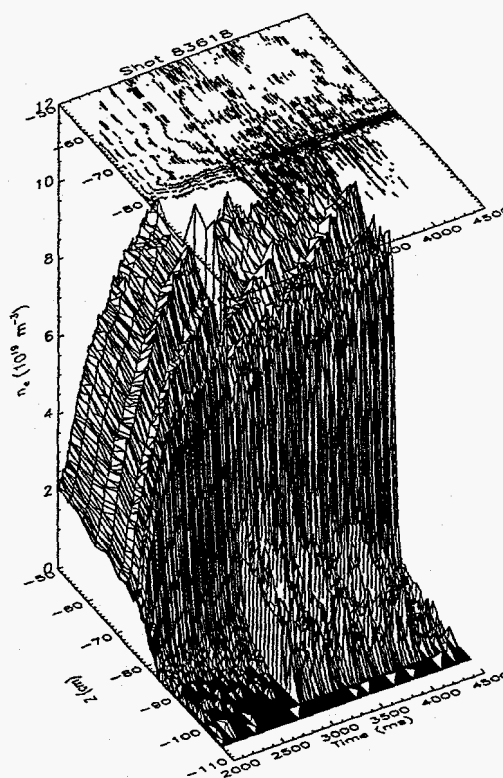<tr><td>Figure 1: Time history</td><td>Figure 2 : Electron density contours</td></tr>
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The 2-D and 3-D electron density contours measured by the multi-pulse Thomson diagnostic are shown in figure 2. There is a dramatic change in the contours at the end of the VH-mode. A density plateau extending out to the limit of the measurement is clearly observed after the onset of ELMs and persists to the end of the discharge In contrast, during the ELM-free period there is no significant density outside the separatrix (around Z=81 cm), and the density is not measurable by the Thomson scattering diagnostic beyond the 90 cm elevation.

The electron density profiles can also be displayed as a function of the distance measured from the separatrix, when mapped to the plasma midplane. We can see the differences in the

profiles during the ELM–free H–mode, VH–mode and ELMing H–mode phases in figure 3. At the 2300 and 2875 ms times during the ELM–free H–mode and VH–mode phases respectively, the SOL density profiles are nearly exponential, with insignificant density outside the separatrix in the SOL. After the onset of the ELMs, the density profile broadens during an ELM and forms a high density plateau extending well into the SOL, with $n_e > 1 \times 10^{19} / m^3$. The density value can persist between the ELMs, often for many laser pulses, which in this case are 6 ms apart.
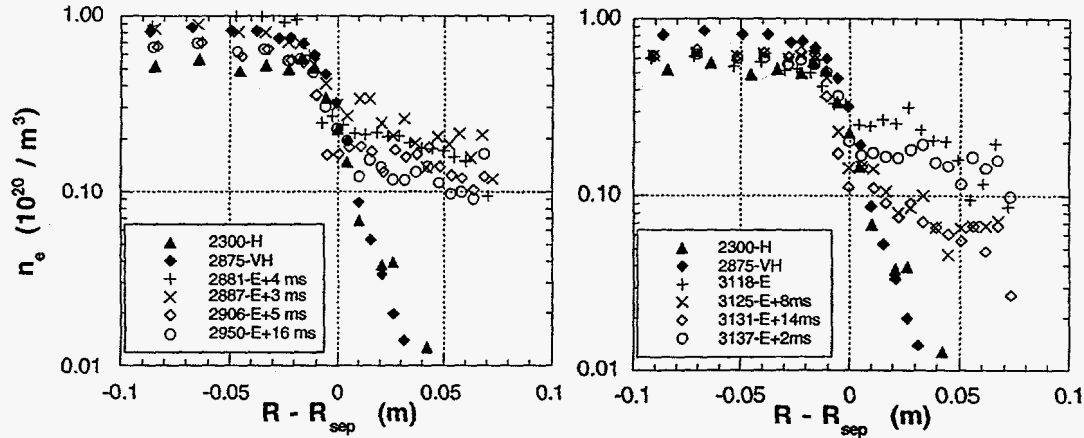

Figure 3 : Electron density profiles in ELM–free H–mode (2300 ms)
VH–mode (2875 ms) and at various times between the ELMs

In the time period immediately after the end of the VH–mode (2881-2950 ms), the ELMs are rapid and large. The measured density plateau values remain above the $1 \times 10^{19} / m^3$ level and there is very little density profile relaxation in this period. Later in the ELMing H–mode phase when the ELMs are smaller and more isolated, we can see the density profile relax between the ELMs. In figure 3, we also show the density profile variation after an ELM at 3118 ms. The profiles for the time at 3118 ms (during the ELM) as well as for the later profiles at 3125, 3131, and 3137 ms demonstrate the profile relaxation between ELMs. The times 3125 and 3131 are 7 ms and 14 ms after the peak of the ELM at 3118 ms, and the density values for these profiles have dropped by about a factor of 3 relative to the value at 3118 ms. The 3137 ms profile is 2 ms after the peak of the next ELM, and the density value has decreased only slightly from the 3118 value. See figure 4 for a plot of the laser pulse times relative to the ELMs shown in the photo-diode signal. While the density relaxes more rapidly between these smaller, less frequent ELMs, the profile in the SOL still does not revert to it's narrower, pre-ELM shape.

The temporal variation in the SOL thickness is clearly shown by the plot of the density scale length in figure 5. The density scale length mapped to the midplane is defined in terms of the separatrix values of density and density gradient as

$$L_n = n_e /(dn_e/dr) .$$

The scale length is plotted versus time in figure 5 along with the ELM background signal from the upper photo-diodes closest to, but outside the outer divertor strike points. Here, the ELM background is obtained by a linear fit to the photo-diode signal over a span of 100 ms, with the excursions due to the ELMs removed.

The time average density scale length appears to correlate with the background photo-diode signals near the outer strike point. Because of the 100 ms averaging time used in the algorithm for the ELM analysis, the ELM background signal from the upper photo-diode,

PHD02UP, in figure 5 is effectively shifted to larger times by up to 100 ms. However, we can see that during most of the ELM-free H–mode period from 2200 to 2400 ms, and the VH–mode phase from 2400 to 2875 ms, the density scale length is constant at around 0.008 m and the photo-diode signal is correspondingly low.

When the ELM activity starts after 2877 ms, the density profiles are modulated by the ELM activity. This modulation, in conjunction with the uncontrolled time of the laser pulse relative to the time of occurrence of the ELM, can produce the apparent scatter in the scale length, L_n, seen after 2900 ms in figure 5. We are measuring the density at times during an ELM and also at various times during the density relaxation phase between ELMs, so the density scale length can change from laser pulse to laser pulse. However, the average value increases to about 0.013 m in the time span from 2900 to 3500 ms, concurrent with the increase in the photo-diode signals. In the period from 3500 to 3800 ms, the background photo-diode signal and the average scale length decrease together.

In the ELMing H–mode phase, the average value of the density scale length increases by about 65% over the VH–mode and ELM-free H–mode value. The correlation of the density scale length with the photo-diode background signal suggests that the recycling from the divertor is supplying particles to support the density
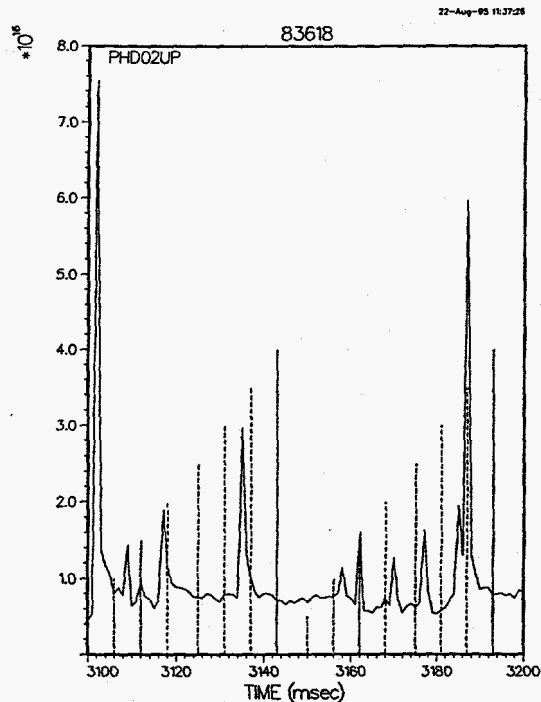

Figure 4 : Photo-diode signal and Thomson laser pulse times for ELMing period around 3118 ms.

plateau in the SOL. The ELMs produce a transient plasma in the SOL which supplies the power to ionize the recycled particles to sustain the broad density profiles between the ELMs.

The corresponding scale length of the electron temperature (not shown here), also increases during an ELM. Because of th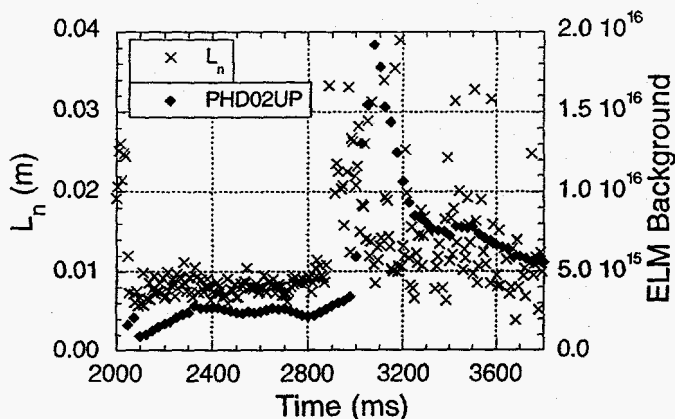e rapid conduction of the electron power to the divertor on the open field lines and the absence of a power source in the divertor for the electrons, the relaxation of the T_e scale length to its quiescent phase value is much quicker than for the density scale length. Hence, while the average value of the T_e scale length we calculate during the ELMing H–mode phase is larger, the lower bound of the scale length is nearly the same as is was in the ELM-free period. Overall, the T_e scale length is about one half of the density scale

Figure 5 : Density scale length and background photo-diode signal for shot 83618. VH–mode extends from ~2400 to 2877 ms.

length.

The measurement of the divertor heat flux profile for the shot discussed here lacks the time resolution necessary to determine the heat flux profile between the ELMs. What we effectively measure is the heat flux over a time span that includes several ELMs. Experiments with data taken at a higher sampling rate to give the behavior between ELMs are scheduled for a later time. However, the data does show that the maximum in the peak power and total power to the divertor both occur at the end of the VH–mode. The peak power and total power remain at elevated values until shortly after about 3000 ms, at which time the VH–mode ending event is over, and a normal ELMing H-mode discharge follows.

During the quiescent phases of the discharge, the FWHM of the outer power peak is about 10 cm and very slowly increasing. When the ELMs begin, the width almost doubles for a period of less than 100 ms, and then drops back to a level above the pre-event value. The width continues to increase, until later in the ELMing H-mode phase, it is again about double its value in the VH–mode and ELM-free H–mode phases, consistent with a wider SOL plasma during the ELMing plasma phase.

3. Summary

The vast array of diagnostics that view the SOL and divertor plasmas in the DIII–D tokamak indicate that the SOL plasma density is nearly exponential in the quiescent H–mode and VH–mode phases, and becomes broader by forming a high density plateau during ELM activity in high current, high triangularity, double-null plasmas. The broad SOL density profile persists between the ELMs, albeit with some density relaxation to lower values. The source of particles maintaining the broad density profile appears to be recycling from the divertor floor as indicated by the correlation of the SOL density with the D_α light at the divertor strike points. Unlike the case of the density, where recycling or gas feed can support a broad density plateau in the SOL in the presence of the ELMs, there is no source of power to maintain a broad electron temperature profile in the SOL during the period between the ELMs. Consequently, the electron temperature profile which also broadens during an ELM, does not persist between the ELMs. The heat flux and density profiles measured on the divertor floor are also broader after the appearance of ELMs when compared to the VH–mode and ELM-free H–mode profiles.

Acknowledgments

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