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PARTICLE BALANCE IN A TFTR SUPERSHOT

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Particle balance has been studied self-consistently for a TFTR supershot during a relatively steady-state phase of the neutral beam injection. The TRANSP analysis code was used to model plasma parameters within the last closed flux surface, deriving time-dependent plasma profiles from measurements. The poloidal flux surfaces were obtained from TRANSP and an equivalent-filament analysis code. The edge plasma and recycling were modeled using the combined B2/DEGAS code with boundary conditions from the TRANSP modeling. The edge and scrape-off modeling results are compared with measurements of the D_α emission and temperature increases in the inner limiter.

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1 Introduction

The scrape-off plasmas in tokamaks are poorly understood since complicated atomic processes are dominant and since the geometry is complicated. The plasmas are neither poloidally nor toroidally symmetric. Comprehensive measurements and modeling in three dimensions are needed to accurately characterize them. It is important to understand the plasma in these regions for several reasons. The heat and particle fluxes to the first walls are significantly effected by processes occurring in these regions. Also plasma properties in the main plasma region are influenced by these regions. For instance, creation of the enhanced confinement H-mode plasmas [1] and supershots [2] requires control of recycling. Also in DT operation, the flux of tritium to the walls will be partly determined by the scrape-off. The tritium inventory which will be allowed in TFTR for the DT experiments will be very limited, so control of the tritium scrape-off flux would be useful.

This paper gives results from the first 2 dimensional modeling coupling the scrape off plasma and recycling in a TFTR discharge. The discharge studied was a supershot which yielded a high D-D fusion yield and exhibited no MHD, and which had extensive diagnostic coverage. The neutral beam injection (NBI) power was 24.6 MW, the plasma current was ramped up to 1.6 MA, the toroidal field was 5.1 T, the major radius 2.45 m, and the minor radius 0.8 m. The first wall was well conditioned, and a lithium pellet was injected before the NBI to improve the plasma performance [3]. TRANSP modeling of this supershot (#55851) has been described, along with simulations of a DT equivalent [4]. The total numbers of particles within the last closed flux surface (LCFS) are shown in Fig. 1. This paper models the relatively steady-state phase near the end of the NBI (at 3.7 sec). At this time the ohmic heating power was relatively small (0.18 MW). The power radiated from within the LCFS was 7 MW. A substantial amount of power was also radiated from outside the LCFS. The deuterium and electron particle balance, the fluxes

to the limiter, and the recycling of the deuterium from the limiter are discussed. The goal is to increase understanding of the edge, scrape-off, and recycling.

The plasma within the LCFS is divided into a main plasma region and an edge region. The dominant source of electrons and deuterium in the main region is NBI and in the edge region is recycled neutral deuterium from the inner limiter. The region outside the LCFS is the scrape-off region with plasma flowing to the toroidal inner limiter. The TRANSP plasma analysis code is used to model the plasma within the LCFS. The density and temperatures at the boundary between the main plasma and the edge are used as imputs for the B2 code, which computes the two dimensional profiles and flows of electrons and ions in the edge and scrape-off. The source rate of deuterium in the main plasma is

$$S_m = \frac{P_B}{E_B} = 1.5 \times 10^{21} / \text{sec}$$

The recycling source rate, S_{edge}, shown in Fig. 1, is 10^{22} / sec at the time of interest. This source rate is calculated self-consistently from the B2 / DEGAS modeling.

2. Core Plasma Modeling

The central plasma region for the supershot was extensively diagnosed. Measured profiles were used in the TRANSP modeling. Various parameters which were predicted by the model were in good agreement with other measurements. Examples are the neutron emission rate, including its radial profile, the stored energy, and the position of the peak X-ray emission [4].

The TRANSP modeling extends out to the LCFS, but measurements in the plasma edge region (within about 0.1 m of the LCFS) are incomplete or imprecise. The temperature measurements were made along the horizontal midplane. The T_i

measurements from charge-exchange recombination spectroscopy extended from R = 2.5 to 3.0 m, and were extrapolated to the LCFS. The T_e profile was measured by electron cyclotron emission. The signals extended through the plasma center and past the LCFS into the scrape-off region, but the measured values in the edge and scrape-off regions are uncertain since the plasma is less opaque at low density, and since the signal is low at low temperature.

The electron density profile was derived from interferometry along vertical chords. The measurements in the edge are uncertain for several reasons. The scrape-off density contributes to the line integrals, and must be subtracted from the data before Abel inversion. One goal of this paper is to improve our knowledge of this contribution.

The flux surfaces within the LCFS are derived by an equilibrium solver within TRANSP, and those outside the LCFS are derived by an equivalent-filament analysis code. The latter code distributes axisymmetric currents to match measurements of the poloidal field and flux and the total plasma current. Flux contours are shown in Fig. 2 TRANSP uses measured plasma profiles along with its computed particle and energy sources and sinks to compute the transport coefficients such as D_e, χ_e, and χ_i. Profiles are shown in Fig. 3.

3. Edge and Scrape off modeling

The B2 code[5] models the electron and deuterium parameters in the edge and scrape-off regions in two dimensions. The plasma is assumed to flow classically along the magnetic field lines and to also flow perpendicular to the field lines with transport coefficients D_e, χ_e, and χ_i which are user specified. The heat convection coefficient is assumed to be 5/2. The transport of and driven by impurities are not included in the B2/DEGAS modeling, except for computing the radiation from the edge and scrape-off, as is discussed below.

The boundary between the main plasma and edge was arbitrarily set at r = a - 0.05 = 0.75 m. The input conditions at the boundary between the main plasma and the edge are gotten from the TRANSP values. For simplicity, we assumed D_e, χ_e, and χ_i to be constants, extrapolating the values computed by TRANSP, as shown in Fig. 3. Also the TRANSP values of n_e, T_e, and T_i were extrapolated as shown in Figs. 4-5. B2 calculates a variation of these profiles along the magnetic flux contours, so the values shown in Figs. 3-4 are specific to the outer midplane.

The boundary condition for B2 at the inner limiter is that the parallel flow is at the sound speed. A user specified fraction R_w of the deuterium striking the limiter is emitted as neutral deuterium. This wall recycling coefficient was chosen to be 0.85 for the results discussed here. The recycling coefficient at the last closed flux surface is different due to the considerable amount of recycling in the scrape-off region. The result for the model discussed here is 0.71.

The ionization of these neutrals is computed approximately by B2. The resulting plasma is input into the DEGAS[6] code, which calculates the neutral deposition more accurately in 3 dimensions. The recycling from the limiter is assumed to be a user specified mix of D^0 and D_2, which was taken to be 100 % D_2 in this study. The DEGAS source distribution is input back into B2, and the process is iterated to improve the accuracy of the model.[7] This more accurate estimation of the S_{edge} can then be input into TRANSP.[8]

The power flow from the core into the edge region implied by the B2 boundary conditions is 17 MW, in agreement with the heating power calculated by TRANSP to be conducted and convected into the edge. Effects of impurity radiation were simulated in B2. Since the dominant plasma impurity is carbon, an empirical fit to carbon radiation[9], proportional to $n_e^2 / T_e^{1.5}$, was used Neither the carbon concentration nor the value of Z_{eff} in the edge or scrape-off regions is known, so we assumed that 50% of the ions were carbon for the radiation estimate. The resulting radiation losses in the edge and scrape-

off were 2.2 MW and 0.8 MW respectively. The total, 3 MW, is low compared with the measured emission. The difference between the heating power and the radiated power, 14 MW, flows to the limiter. The predicted power profiles on the inner limiter, assuming it was axisymmetric are shown in Fig. 6. The total power profile has the characteristic two-humped distribution symmetrically above and below the midplane predicted by exponentially-decreasing flow in the scrape-off.[10]

The flux of deuterium is calculated to be amplified by recycling from the value of 1.1 x 10^{22} / sec flowing into the edge, to 2.8 x 10^{22} / sec into the scrape-off, and further amplified to 5.4 x 10^{22} / sec flowing to the limiter. DEGAS modeling is used to simulate the D_α emission from the recycled deuterium. This emission can be compared with the measured values along five sightlines.[11] The predicted simulation, assuming the limiter was toroidally symmetric, is shown in Fig. 7, along with the measured values.

We investigated the additional effects of charge exchange of recycled neutrals with the beam ions, using DEGAS and the beam ion density and average energy calculated by TRANSP. This effect increases the particle flux to the limiter, however, the effects are predicted to be small for this discharge.

4. Discussion

No probe measurements were possible throughout the scrape-off region of this or similar high power supershots due to the risk of destroying the probes. Measurements have been made in TFTR discharges with lower NBI power (up to 20 MW) and with the limiter less well conditioned.[12] The measured values of n_e and T_e near the outer midplane, 12.5 cm from the LCFS are indicated in Figs. 4-5. It is not possible to probe the scrape-off region in the high recycling region close to the inner limiter.

There are several tests of the accuracy of the B2 / DEGAS modeling. The power flow to the inner limiter is inferred by the change of its temperature after the discharge.

The temperature is measured by an array of 67 active thermocouples on the back face of limiter tiles.[13] From this we infer the total energy flow to the limiter, assuming it is dominated by steady-state flow during the NBI. The heat distribution is fit well by assuming that the heat scrape-off decreases with an exponential which is 1.9 - 2.7 cm at the outer midplane, in approximate agreement with the modeled profiles in Figs. 4-5. This exponential would change along field lines due to the expansion of the flux lines shown in Fig. 2. The heat increase is fit well if the scrape-off power is 15 MW, and if the radiation and charge exchange power gives a uniform background of 10 MW. The scrape-off power is close to the value of 17 MW predicted by the B2 / DEGAS model, however, there are considerable uncertainties in this estimate and arbitrariness in the modeling.

The power deposition on the limiter inferred by the thermocouples and from IR measurements[14] is not toroidally symmetric. Part of this power is due to the variations of tile position from toroidal symmetry. The limiter is actually a twenty toroidal period poloidal limiter. The variations throughout the 20 bay regions are about 2 mm. These variations impede the direct comparison of the inferred power profile with the predictions in Fig. 6 which are based on the assumption of toroidal symmetry.

The predicted and measured D_α profiles are compared in Fig. 7. There is a factor of two uncertainty in inferring the toroidally-symmetrized profile from the measurements. They are made at one toroidal location in a bay which has a relatively large toroidal field ripple, and the bays were aligned with respect to the toroidal field, so there is uncertainty in the deviation of the bay from toroidal symmetry.

The edge and scrape-off modeling appears consistent with measurements to within a factor of two. Further measurements and modeling in three dimensions would improve the accuracy.

Acknowledgments

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Figures Captions

1) Number of particles within the LCFS and the edge recycling rate in a supershot. The electron density profile $n_e(x,t)$ is symmetrizing from the measured (Abel inverted) profile. The thermal deuterium density, n_D, and the impurity density, n_{imp}, are calculated from Z_{eff}, which is calculated from a visible bremsstrahlung measurement. The beam density, n_{beam}, is calculated from the Monte Carlo neutral beam deposition. The edge recycling rate is given by the B2 / DEGAS modeling.

2) Magnetic flux surfaces. The contours within the LCFS are from the TRANSP modeling with equal spacing of the square root of the normalized toroidal flux. The contours in the scrape off region are unit increments of poloidal flux calculated with an equivalent-filament analysis code.

3) Profiles of the transport coefficients calculated from measurements by TRANSP within the LCFS and those assumed for the B2 modeling in the edge and scrape off regions.

4) Plasma density profiles along the outer midplane from the TRANSP and B2 modeling. The probe result is from a different discharge with relatively high recycling and 20 MW of NBI power.

5) Plasma temperature profiles along the outer midplane from the TRANSP and B2 modeling. The probe result is from a different discharge with relatively high recycling and 20 MW of NBI power.

6) Predicted electron deuterium, and total power flow to the limiter.

7) Profile of the measured D_α along five sightlines through the discharge and the predicted values from the B2 / DEGAS modeling.

Particles within the last closed flux surface
and the edge recycling rate

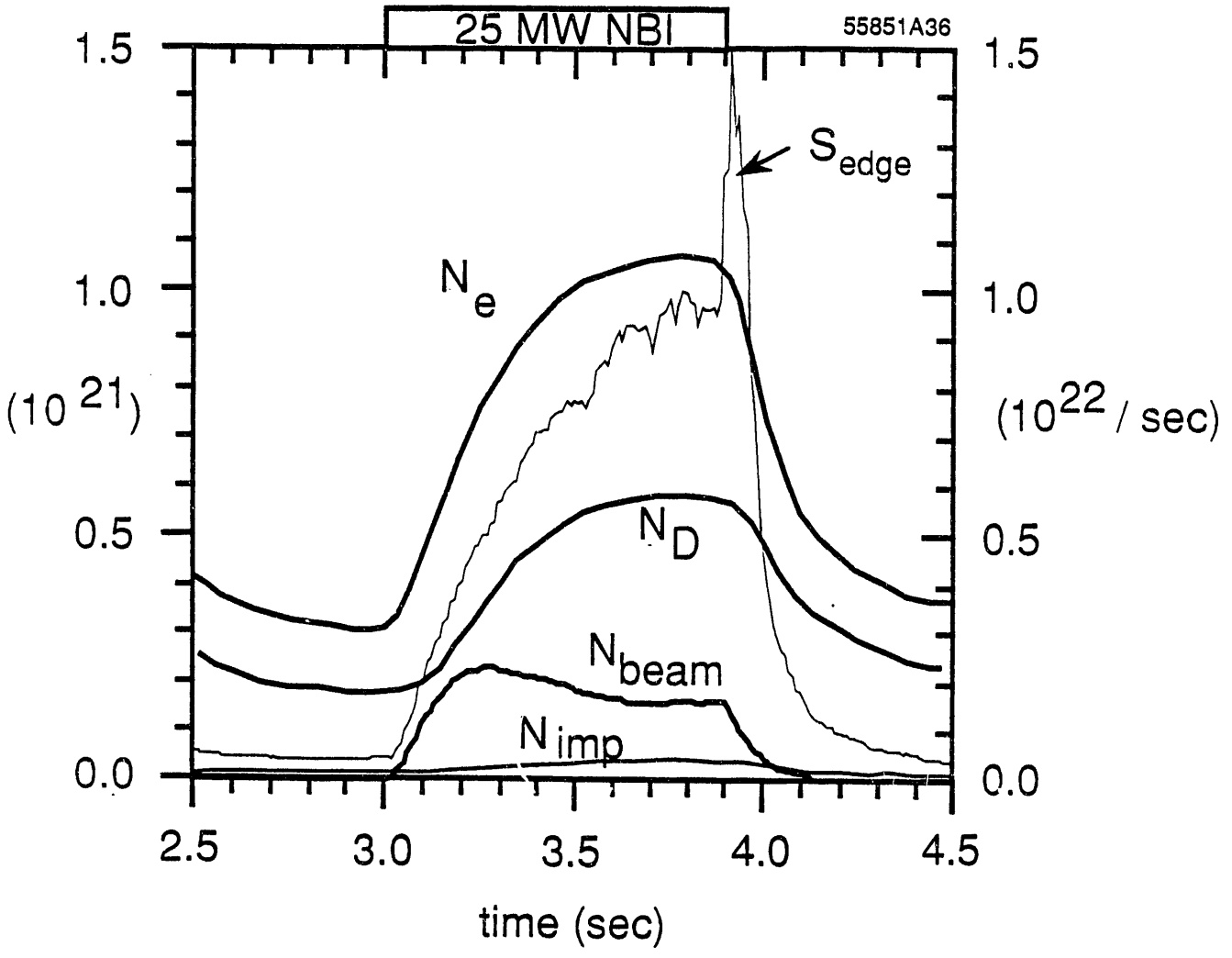

Figure 1

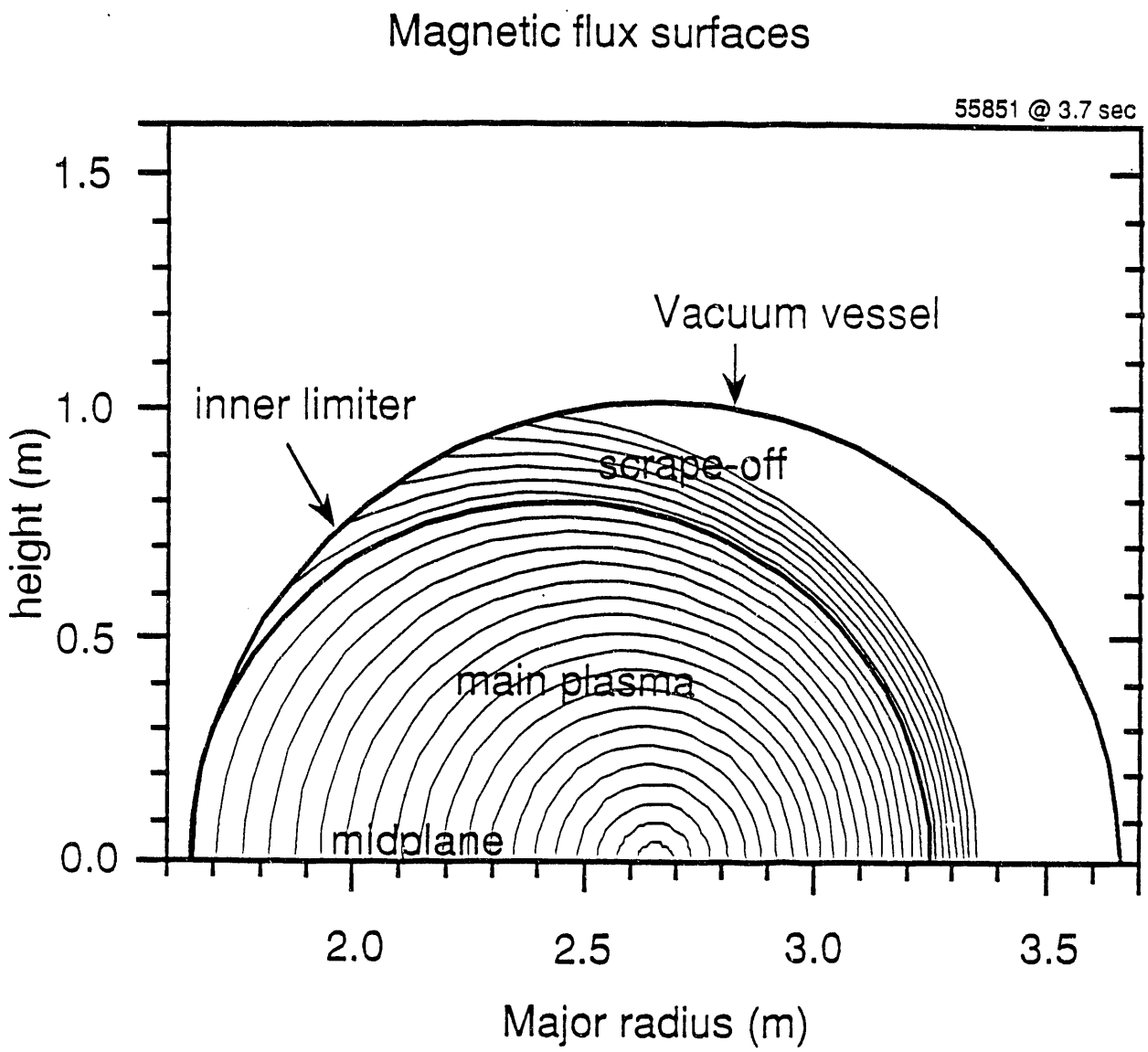
Magnetic flux surfaces
55851 @ 3.7 sec
1.5
1.0
0.5
0.0
height (m)
Vacuum vessel
inner limiter
scrape-off
main plasma
midplane
2.0
2.5
3.0
3.5
Major radius (m)

Figure 2

Transport coefficients

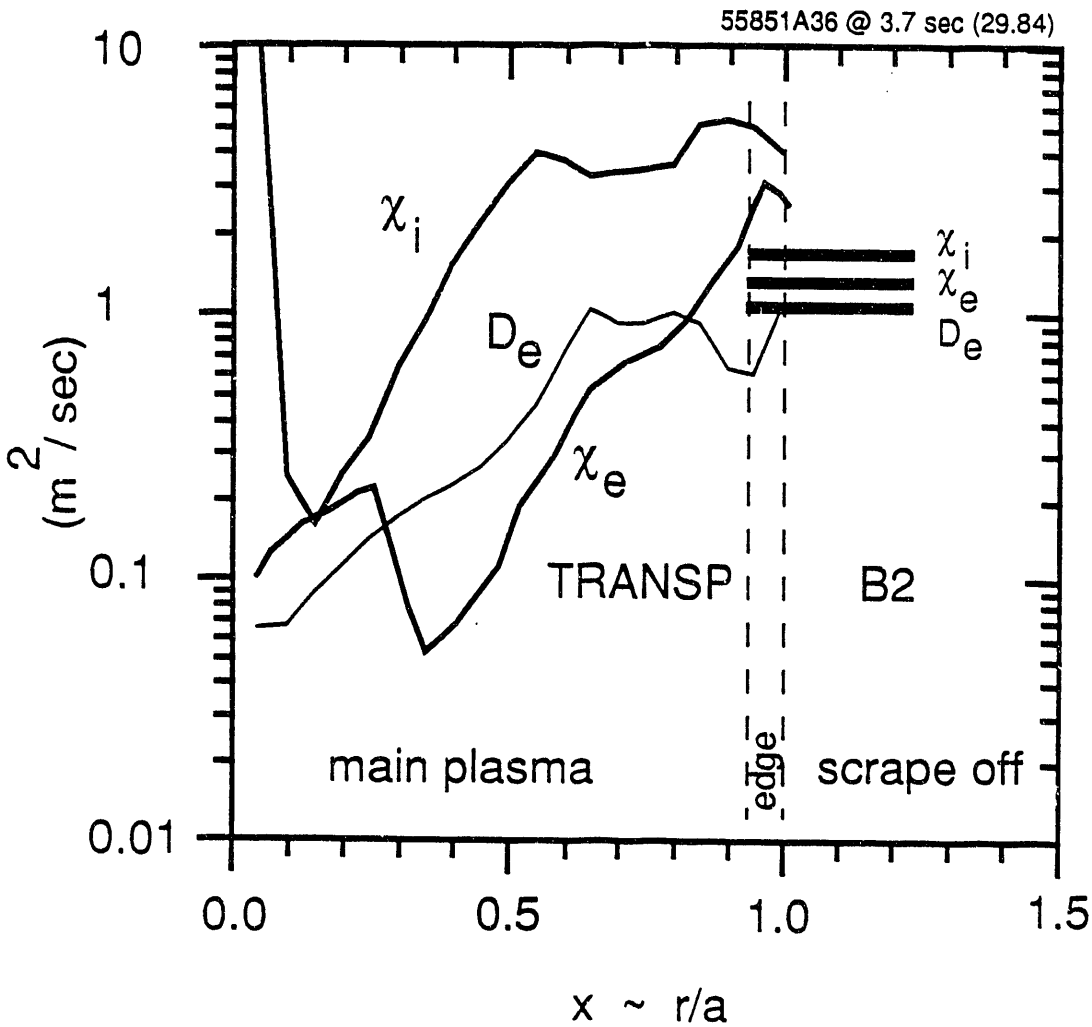

Figure 3

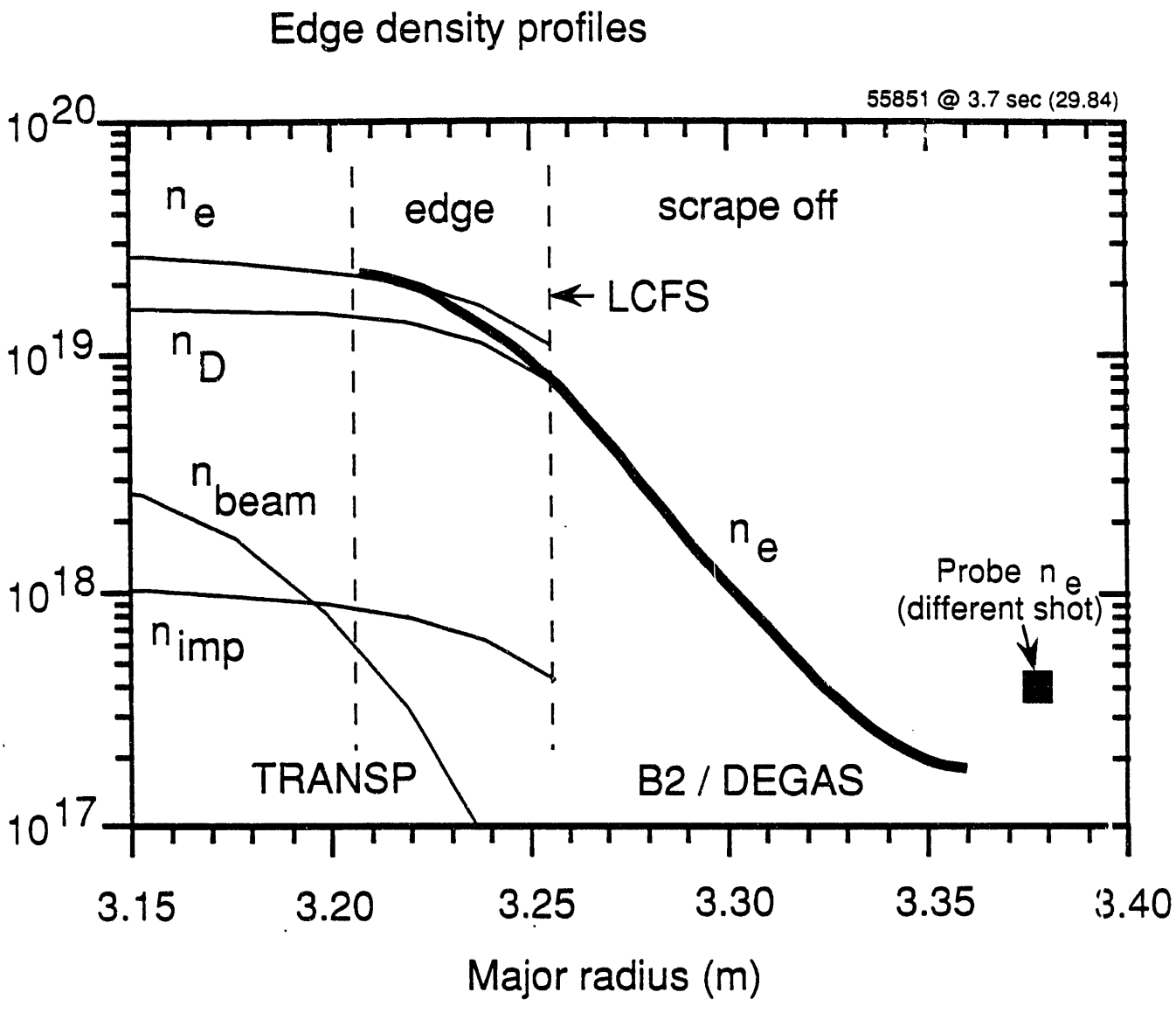

Figure 4

$R_{wall} = 0.85$

Edge temperature profiles

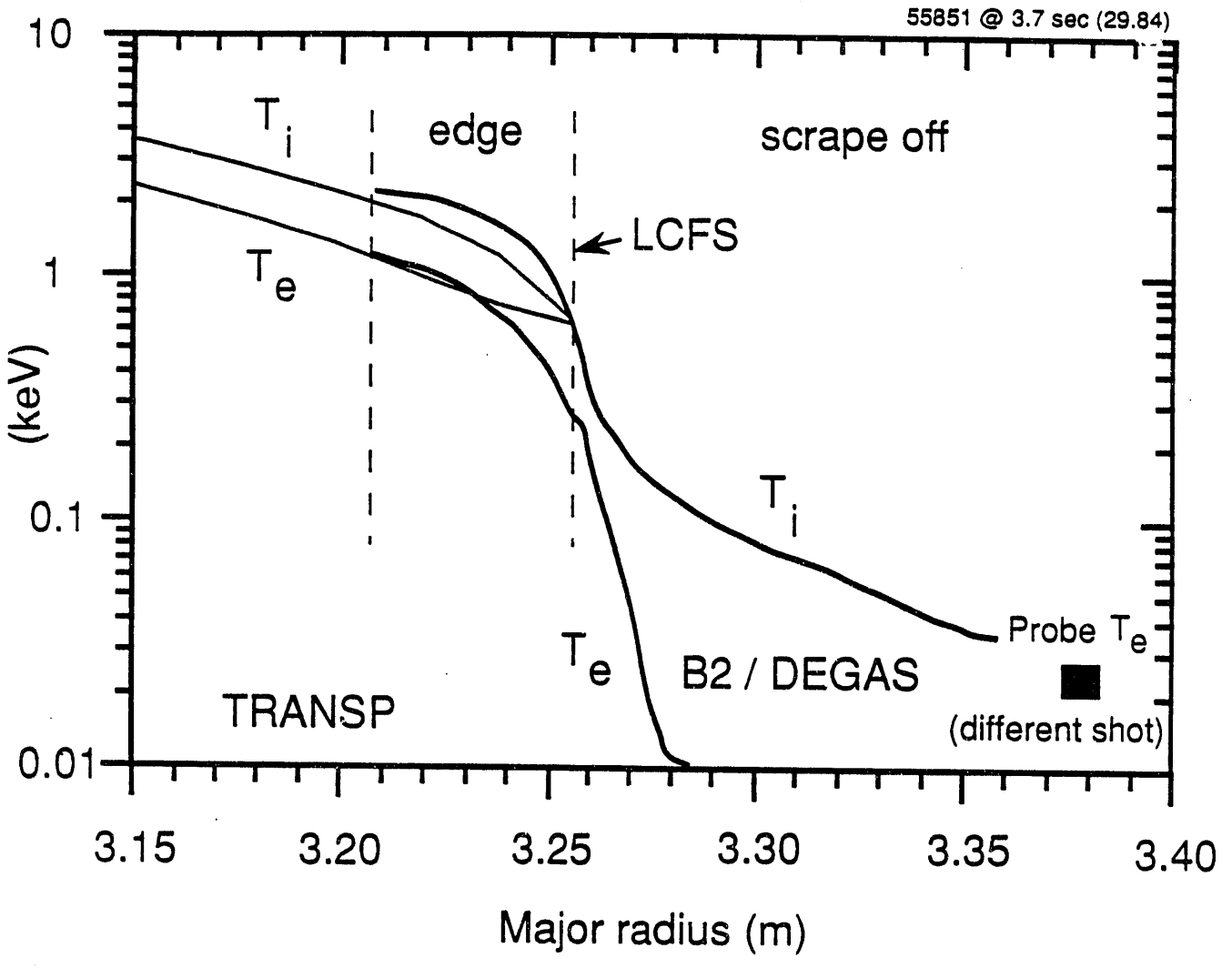

Figure 5

Power deposition on the (symmetrized) limiter

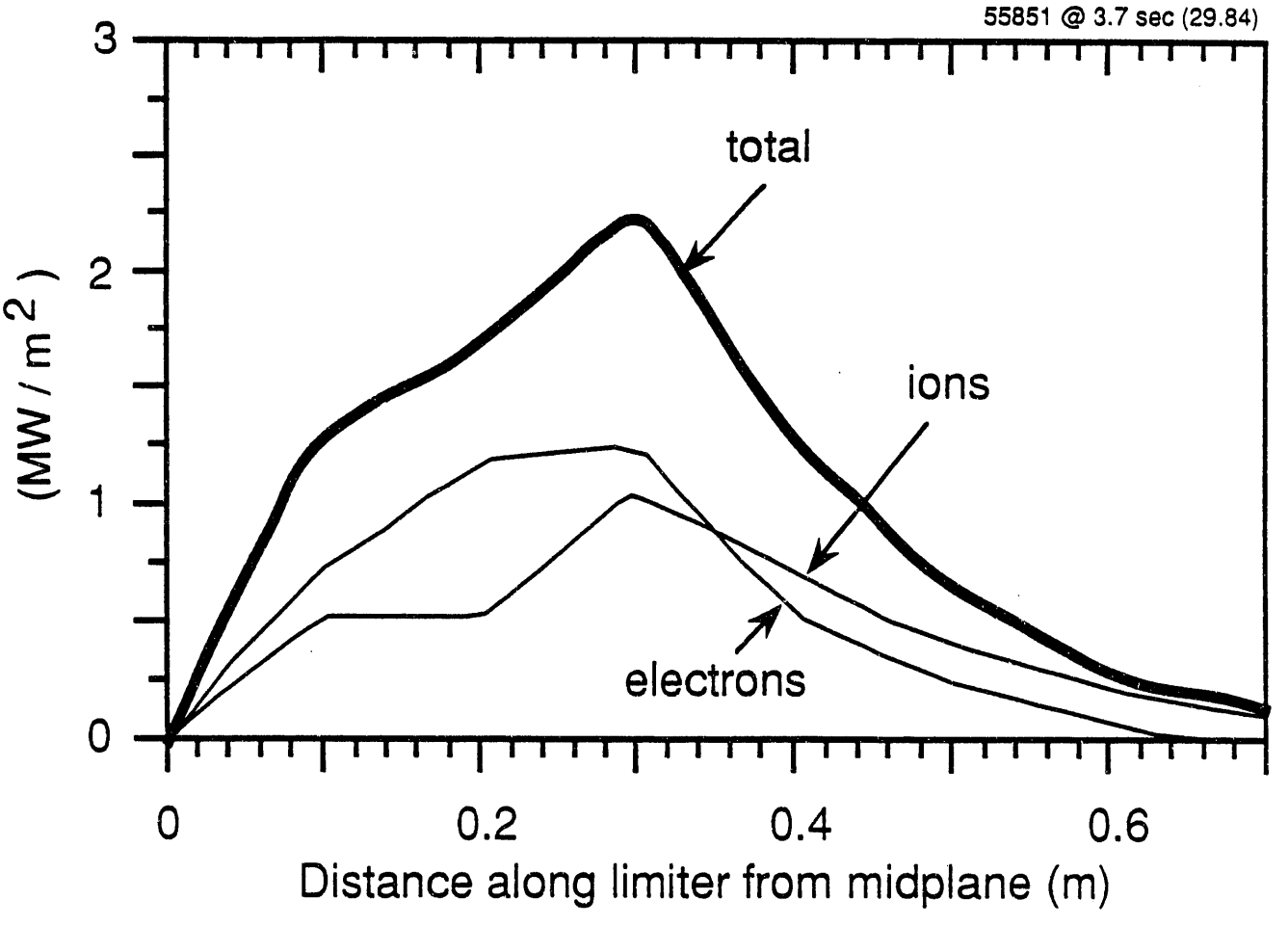

Figure 6

Measured D_α and prediction from B2 / DEGAS modeling

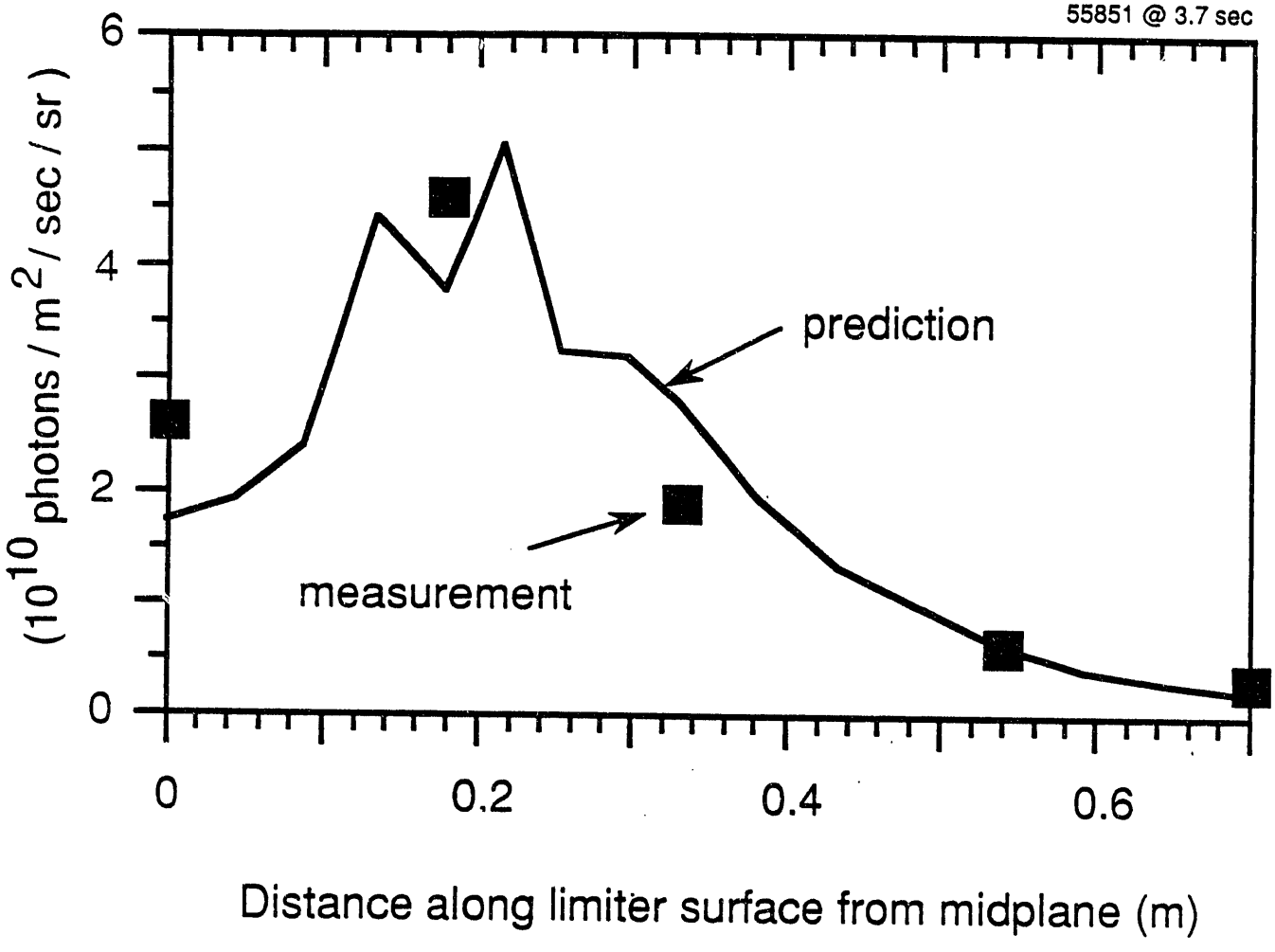

Figure 7

(29.10 & 29.28)

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