PSFC/JA-98-12

Comments on Particle and Energy Balance in the Edge Plasma of Alcator C-Mod

M.V. Umansky, S.I. Krasheninnikov, B. LaBombard, J.L. Terry

April 1998

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

To be published in Physics of Plasmas.

This work was supported in part by the U. S. Department of Energy Contract No. DE-AC02-78ET51013. Reproduction, translation, publication, use and disposal, in whole or in part by or for the United States government is permitted.

April 21, 1998

Comments on particle and energy balance in the edge plasma of Alcator C-Mod

M.V.Umansky, S.I.Krasheninnikov, B.LaBombard and J.L.Terry

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Particle balance is examined in a large set of representative Alcator C-Mod diverted plasmas using measurements of neutral gas pressures and ionization source strengths in the main chamber, and parallel plasma flow into the divertor. It is inferred that plasma flow in the scrape-off-layer (SOL) is dominated by transport to the main chamber walls rather than by flow into the divertor. It follows that (i) the effective diffusion coefficient for anomalous cross-field particle transport in the SOL must rapidly grow with distance from the magnetic separatrix to account for the measured density profiles, (ii) a significant fraction of the power from the core plasma can be convected rather than conducted into the SOL, and (iii) the neutral pressure at the outer midplane is governed more by cross-field plasma transport than by wall-plasma separation or divertor/limiter geometries.

email umansky@max.pfc.mit.edu

PACS 52.55.Fa, 52.40.Hf

Some of the main issues for magnetically confined fusion plasmas are the physical nature and magnitude of anomalous transport and contamination of the core plasma due to plasma-surface interaction at the edge. In fusion reactors, the scrape-off layer (SOL) will carry large particle and energy fluxes that must be accommodated by plasma-facing surfaces and yet not cause contamination of the core. In principle, a poloidal magnetic divertor could allow solution to the core contamination problem by physically separating the plasma-wall interaction zone from the confined plasma region and by allowing heat and particles in the scrape-off layer to flow into a remote chamber.[1] In this picture, it is assumed that the cross-field transport of heat and particles to the side wall is weak compared to the parallel transport, causing most of both particles and heat to flow along field lines and into the divertor chamber. In particular, particle balance in the core would be maintained by a back-flux of neutrals from the divertor into the core. However, experimental observations of particle balance in the edge plasma and divertor of Alcator C-Mod suggest that this picture can be overly simplified and in fact violated.

Measurements from both a scanning Mach probe[2] and Doppler spectroscopy[3] indicate that parallel plasma flows into the divertor near the divertor throat have Mach numbers of no greater than $M \approx 0.1$. The main chamber and the divertor chamber communicate through a flux tube of width about $\delta\rho \approx 5$ mm at the midplane level (see Figure 1). This yields an estimate of the total plasma flux entering the divertor chamber, Γ_{div}, for typical C-Mod parameters: upstream plasma density in the SOL $n \approx 10^{20}\ m^{-3}$, electron temperature $T_e \approx 50$ eV, major radius $R \approx 0.6$ m, and the pitch angle $\sin\phi \approx 0.2$:

$$\Gamma_{div} \approx 4\pi R \int_0^{\delta\rho} nV_{\parallel} \sin\phi \, d\rho \approx 4\pi R n V_{\parallel} \sin\phi \, \delta\rho \approx 6 \times 10^{21} s^{-1} \qquad (1)$$

On the other hand, from tomographic reconstructions of D_α emission, the magnitude of the plasma source inside the last-closed flux surface (LCFS) has been estimated to be in the range[4] $S_{core} \sim 10^{21} - 10^{23}\ s^{-1}$. The spatial resolution of the tomography system is insufficient to resolve whether the ionization is truly inside or outside the LCFS and therefore S_{core} may be considered as a lower bound on the total ionization source in the main chamber. When this estimate yields $S_{core} \sim 10^{23}\ s^{-1}$, it is clear that the total ionization source in the main chamber is much larger than the total plasma flux into the divertor. The ionization source in the main chamber is thus balanced by plasma recycling on the main chamber walls rather than by plasma flow into the divertor.

The ionization source S_{core} is largest when the core plasma density is high. Thus, at least at high plasma densities ($n_{core} \gtrsim 10^{20}\ m^{-3}$), the particle balance in the main chamber primarily involves plasma flow to the main chamber walls balanced by radially inward neutral fluxes. Although large recycling fluxes exist in the divertor chamber, they are apparently well separated from the recycling fluxes in the main chamber (see Figure 1).

In this picture, neutral gas pressure near the walls in the main chamber is determined by the magnitude of the anomalous radial plasma flux. This idea is consistent with observations of main chamber and divertor gas pressures on Alcator C-Mod when a neutral bypass leak in the outer divertor structure was closed: After closure, in L-mode discharges the neutral pressure in the divertor increased by a factor of 2 or more while the pressures in the main chamber decreased by merely 20% in otherwise identical discharges.[2] A stagnant flow scenario with independent main chamber and divertor recycling is a possibility when the divertor becomes opaque to neutrals.[5]

Additional evidence comes from empirical relationships between neutral gas pressures measured at the midplane and ionization source strengths in the main chamber (inferred from D_α spectroscopy). Typical midplane pressures in Alcator C-Mod are in the range 0.03-1.0 mTorr.[6] In steady state, the kinetic flux density of neutral atoms entering the plasma, $\frac{1}{4}n\bar{v}$, must be equal to 1/2 the random flux density of molecules within the gauge. For a LCFS area of $A_{LCFS} \approx 7m^2$, this leads to an estimate of total neutral flux into the plasma per unit gauge pressure:

$$\Gamma_n[s^{-1}] \approx A_{LCFS}\,\frac{1}{2}(n_{D_2}\,\bar{v}_{D_2})_{gauge} \approx 8\times 10^{22}\,P_{D_2}[mTorr]. \qquad (2)$$

From chordal measurements of D_α brightness through the plasma midplane, B_α, the total ionization source in the main chamber can be estimated. Ionization events can occur in a rather broad range of densities and temperatures of the background plasma due to the spatial spread of the ionization zone and variation of conditions from one discharge to another. However the number of ionization per a D_α photon, N_α, does not vary too much and lies between 10 and 100 for plasma densities in the range 0.1-2.0 $\times 10^{20}\ m^{-3}$, and electron temperatures, $20 - 200$ eV.[7] The exact value of N_α within the indicated limits is not critically important for conclusions drawn in the present paper. For a simple estimate it is assumed here that the effective number of ionizations per D_α photon is $N_\alpha \approx 45$ for all discharges. With photon energy, $E_\alpha \approx 2$ eV, and assuming a poloidally uniform distribution of emissivity over a narrow shell at the LCFS, the ion flux leaving the plasma per unit D_α brightness is roughly

$$\Gamma_i[s^{-1}] \approx \frac{1}{2} A_{LCFS}\, B_\alpha\, 4\pi\, N_\alpha\, \frac{1}{E_\alpha} \approx 6 \times 10^{21}\, B_\alpha\, [W/(m^2\, ster)]. \qquad (3)$$

Figure 2 is a plot of the core ion flux estimated from measurements of main chamber D_α brightness using Eq. 3 versus midplane neutral pressure for a set of over 600 discharges. In this data set the plasma current is 0.35-1.1 MA, the core plasma density is 0.7-4.8 $\times 10^{20}\ m^{-3}$ and the toroidal magnetic field is 2.8-7.9 Tesla. The divertor flux shown on the same plot is clearly smaller than the core flux. The divertor flux is estimated for each discharge from measured upstream profiles of plasma density and parallel velocity using Eq. 1 with integration limit $\delta\rho = 10$ mm. One can see that for diverted discharges, the estimated neutral flux in, Γ_n, is close to the estimated ion flux out, Γ_i, over the range of two decades. Systematic differences may be due to reflections of light from the walls that can increase the apparent brightness or due to poloidal non-uniformities in the D_α emissivities. The large discrepancy in limiter discharges shown in Figure 2 exemplifies the latter effect. In this case, the intense, highly localized recycling light from the inner limiter surface is in the view of the detector.

The overall agreement between these two independent diagnostics in diverted discharges lends confidence to the ionization source estimates up to $\sim 10^{23}\ s^{-1}$ in the main chamber.

Accepting that the particle flow in the main chamber SOL at high densities is primarily radial, one is led to some important conclusions about anomalous cross-field particle transport in the SOL. If one assumes that the radial plasma transport in the SOL can be characterized by an effective diffusion coefficient then the positive curvature of the SOL plasma density profile (see Figure 3) requires an effective plasma diffusion coefficient that grows rapidly with the radial coordinate. This is similar to what has been previously found in modeling of ASDEX-Upgrade.[8]

It is observed in all types of Alcator C-Mod discharges that the local cross-field density e-folding length increases with distance from the LCFS.[2] Figure 3 clearly illustrates this point, showing a nearly flat density profile for radial coordinates greater than 5 mm. Since volume recombination is negligible in these main chamber SOL plasmas ($T_e > 10$ eV), the radially-outward plasma flux must be lowest near the separatrix ($\rho = 0$ mm) and increase towards the wall. In order to drive even a constant flux, the effective cross-field diffusion coefficient must increase by more than an order of magnitude over the SOL profile.

The spatial resolution of the D_α measurements is insufficient to determine how many ionizations occur inside the LCFS rather than in the SOL. However, the ionization mean free path for warm neutrals in the SOL is on the order of 1 cm which is comparable to the width of the SOL. Therefore recycling neutrals have a significant probability of ionizing inside the LCFS. Modeling studies of Alcator C-Mod with the UEDGE transport code[9] employing a fluid neutral description show that as much as 30% of the ionizations can occur inside the LCFS. If the fraction of neutrals penetrating inside the LCFS is $\xi \approx 0.3$ then for the total ionization source in the main chamber, $S_i \lesssim 10^{23}\ s^{-1}$, the plasma flux from the core is $\Gamma_{core} \approx \xi S_i \lesssim 0.3 \times 10^{23}\ s^{-1}$.

Then the effective diffusion coefficient, $D_\perp$, can be estimated near the separatrix from the e-folding length of the density profile, $\lambda_n \approx 3mm$ and plasma density $n \approx 10^{20}\ m^{-3}$ as

$$D_\perp \approx \frac{\xi S_i / A_{LCFS}}{n/\lambda_n} \lesssim 0.1 m^2/s. \tag{4}$$

For H-mode plasmas, $D_\perp$ is apparently smaller at the LCFS (assuming ξ is the same) since similar values of S_i are inferred but the slope of the density profile near the separatrix is by a factor of 2 or more steeper.

Far from the LCFS, the magnitude of effective cross-field diffusivity can greatly exceed the Bohm level. Such strong growth of $D_\perp$ suggests that the cross-field transport mechanism is not diffusive at these locations. It is more likely that the transport mechanism is convective in nature, perhaps involving a rapid transport of unstable plasma flux tubes towards the wall surfaces.

These observations indicate that the neutral pressure at the main chamber wall is not always a parameter that can be controlled by conventional means such as neutral baffling in the divertor, active pumping in the divertor, or increased LCFS-wall separation distances in the main chamber. Rather, neutral pressures at the outer midplane can be governed more by the cross-field plasma transport in the SOL. The lack of a direct external control of the midplane neutral pressure has important implications for a fusion reactor regarding charge-exchange sputtering of the first-wall, tritium gas inventory, and the auxiliary power needed to achieve the H-mode confinement in presence of high neutral pressure.

Although the SOL particle transport picture is significantly altered by these observations, the energy transport picture is relatively unaffected. Most of the energy flux coming into SOL from the core is transported to the divertor by the parallel electron heat conduction. For a typical discharge with radial electron temperature profile at the scanning probe location of $T \approx T_{sep} \exp(-\rho/\lambda_T)$, with $\lambda_T \approx 3$ mm, classical electron parallel heat conductivity, $\kappa_{\|} \propto T_e^{5/2}$, poloidal connection length between the probe and the nearest target plate, $\Delta L_c \approx 0.3$ m, major radius R ≈ 0.6 m, and pitch angle $\sin\phi \approx 0.1$, one can estimate the conducted heat as:

$$P_{cond} \approx \frac{2}{7}\kappa_{\|}(T_{sep})\,\frac{T_{sep}}{\Delta L_c}\,(\sin\phi)^2 4\pi R\lambda_T \approx 0.6MW \times \left(\frac{T_{sep}}{50eV}\right)^{3.5} \qquad (5)$$

For Alcator C-Mod T_{sep} is typically in the range 40-60 eV implying the conducted power in the range 0.4-1.2 MW which is consistent with the range of powers entering SOL.

One can also see using $T \approx 50$ eV and Γ_{div} from Eq. 1 that the parallel plasma flow plays almost no role in the transport of thermal energy:

$$P_{conv} \approx \frac{5}{2}T\Gamma_{div}\,\frac{\lambda_T}{\delta\rho} \lesssim 0.1MW \qquad (6)$$

If the plasma source in the main chamber, S_i, is as high as $10^{23}\ s^{-1}$ then a significant part of energy can be convected rather than conducted across the LCFS. For the fraction of neutrals penetrating inside the LCFS $\xi \approx 0.3$ the plasma flux from the core is $\xi S_i \lesssim 0.3 \times 10^{23}\ s^{-1}$. For a separatrix temperature of $T_{sep} \approx 50\ eV$, the convected energy flux from the core can then be estimated as

$$P_{out} \lesssim \frac{5}{2}\xi S_i T_{sep} \approx 0.6MW, \tag{7}$$

which can be a significant fraction of total energy flux from the core. This probably explains why there are no H-mode data points in Figure 2 for midplane pressures above $\approx$ 0.5 mTorr.

It has been generally assumed that in a tokamak with a divertor both particles and energy flow from the core into the divertor chmaber. In Alcator C-Mod however this is apparently not the case. Here plasma flows in SOL primarily to the main chamber walls while for the energy transport it is probably still true that the energy is transported into the divertor chamber (possibly by the electron heat conduction mechanism). The particle balance in the main chamber is maintained by a back-flux of recycling neutrals from the main chamber walls into the core. The radial profile of plasma density in SOL implies that the effective plasma diffusion coefficient grows very rapidly across SOL towards the wall which is a strong indication for a radial plasma transport mechanism different from diffusion. The energy convected from the core into SOL with the radial flow of plasma can account in some discharges for a large fraction, maybe most, of the total energy coming from the core into the SOL.

Acknowledgements

This work is supported by U.S. Department of Energy Contract No. DE-AC02-78ET5103 and grant DE-FG02-92ER-54109.

References

[1] F.Wagner and K.Lackner, in "Physics of Plasma-Wall Interactions in Controlled Fusion", p. 931, D.E. Post, R.Behrisch Eds. (1986).

[2] B. LaBombard, J.A. Goetz, I. Hutchinson, D. Jablonski, J. Kesner, C. Kurz, B. Lipschultz, G. M. McCracken, A. Niemczewski, J. Terry, A. Allen, R.L. Boivin, F. Bombarda, P. Bonoli, C. Christensen, C. Fiore, D. Garnier, S. Golovato, R. Granetz, M. Greenwald, S. Horne, A. Hubbard, J. Irby, D. Lo, D. Lumma, E. Marmar, M. May, A. Mazurenko, R. Nachtrieb, H. Ohkawa, P. O'Shea, M. Porkolab, J. Reardon, J. Rice, J. Rost, J. Schachter, J. Snipes, J. Sorci, P. Stek, Y. Takase, Y. Wang, R. Watterson, J. Weaver, B. Welch, S. Wolfe, *J. Nucl. Mat.* **241-243**, 149 (1997).

[3] J.L.Weaver, B.L.Welch, H.R.Griem, J.L.Terry, J.E.Rice, B.Lipschultz, B.LaBombard, C.S.Pitcher, S.Wolfe, E.S.Marmar, D.A.Pappas, *Bull. Amer. Phys. Soc.* **42**, No. 10, P. 1908, (1997).

[4] C.Kurz, *PhD Thesis*, Massachusetts Institute of Technology (1995).

[5] Pitcher, C.S., Stangeby, P.C. *Plasma Physics and Controlled Fusion*, **39**, no.6, p.779-930 (1997)

[6] A.Niemczewski, I.H. Hutchinson, B. LaBombard, B. Lipschultz, G.M. McCracken, *Nucl. Fus.* **37**, 151 (1997).

[7] L.C.Johnson and E.Hinnov, *J.Quant.Spectrosc.Radiat.Transfer*, **13**, 333, (1973).

[8] H.-S. Bosch, J.Neuhauser, R.Schneider, A.Field, A.Herrmann, G.Lieder, W.Junker, C.S.Pitcher, D.Reiter, B.Braams, *J. Nucl. Mat.* **220-222**, 558-562 (1995).

[9] T.D.Rognlien, J.L.Milovich, M.E.Rensink and G.D.Porter, *J. Nucl. Mat.* **196-198**, 347-351 (1992).

Figure captions

Figure 1: The wall geometry shown has the features of Alcator C-Mod divertor: closed box divertor with narrow throat. The dashed line defines the separation between main and divertor chambers. The shaded area shows flux tubes through which the two chambers can communicate via poloidal flow. Recycling in the main chamber and divertor occurs independently (indicated by arrows), particularly in high density plasmas, $n_{core} \gtrsim 10^{20}\ m^{-3}$.

Figure 2: Core ion flux Γ_i derived from midplane D_α brightness using Eq. 3 is plotted against midplane pressure. The top secondary axis indicates the values of Γ_n from Eq. 2. The dashed line is the estimated balance line where $\Gamma_i = \Gamma_n$. Divertor flux derived from experimental profiles and Eq. 1 is shown by cross symbols. H-mode and L-mode data from both diverted and inner-wall limited discharges are shown. These data indicate that the main chamber recycling fluxes greatly exceed the flux into the divertor, $\sim 3 \times 10^{21} s^{-1}$.

Figure 3: Typical experimental plasma density profile in Alcator C-Mod.

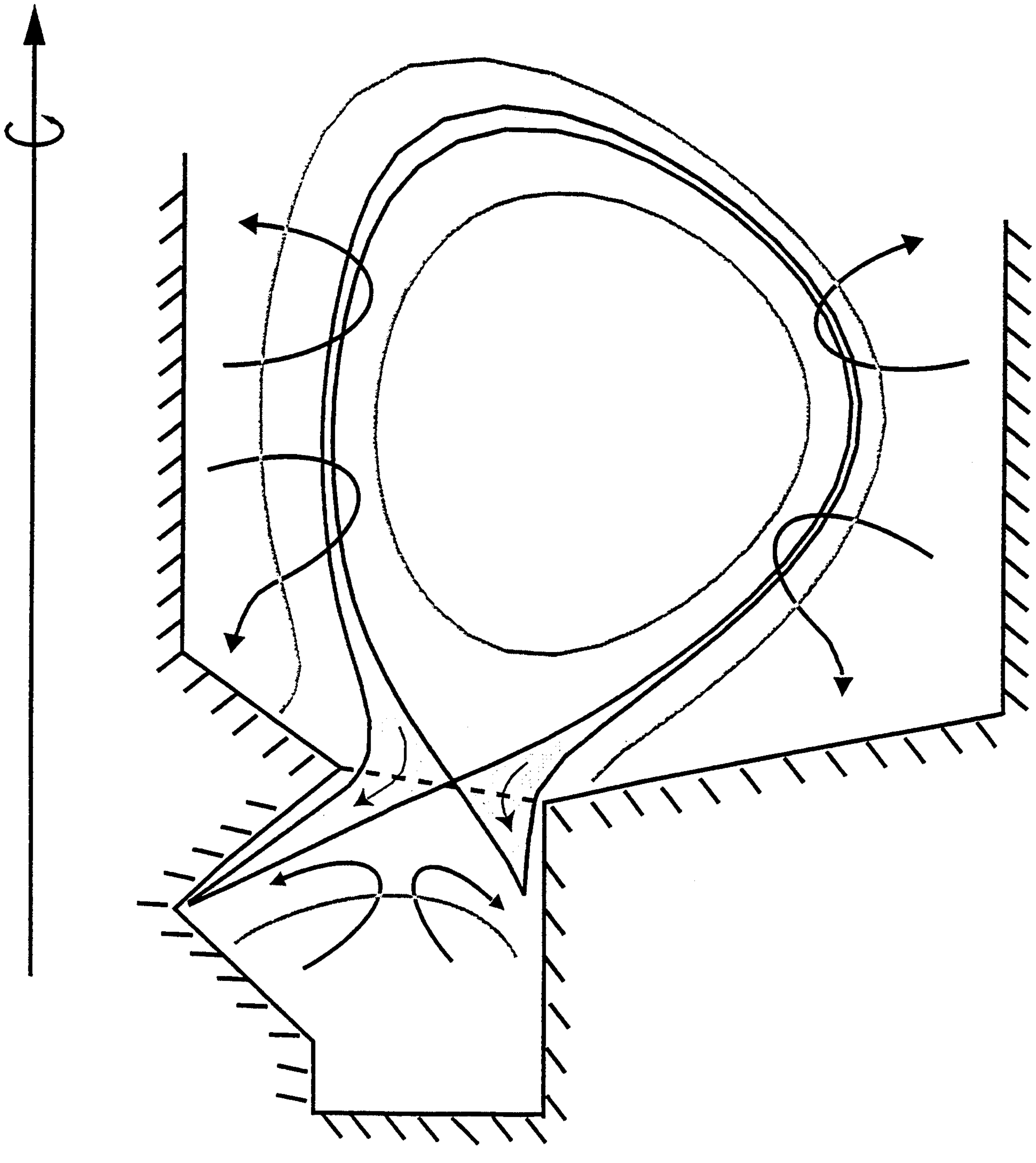

Fig. 1

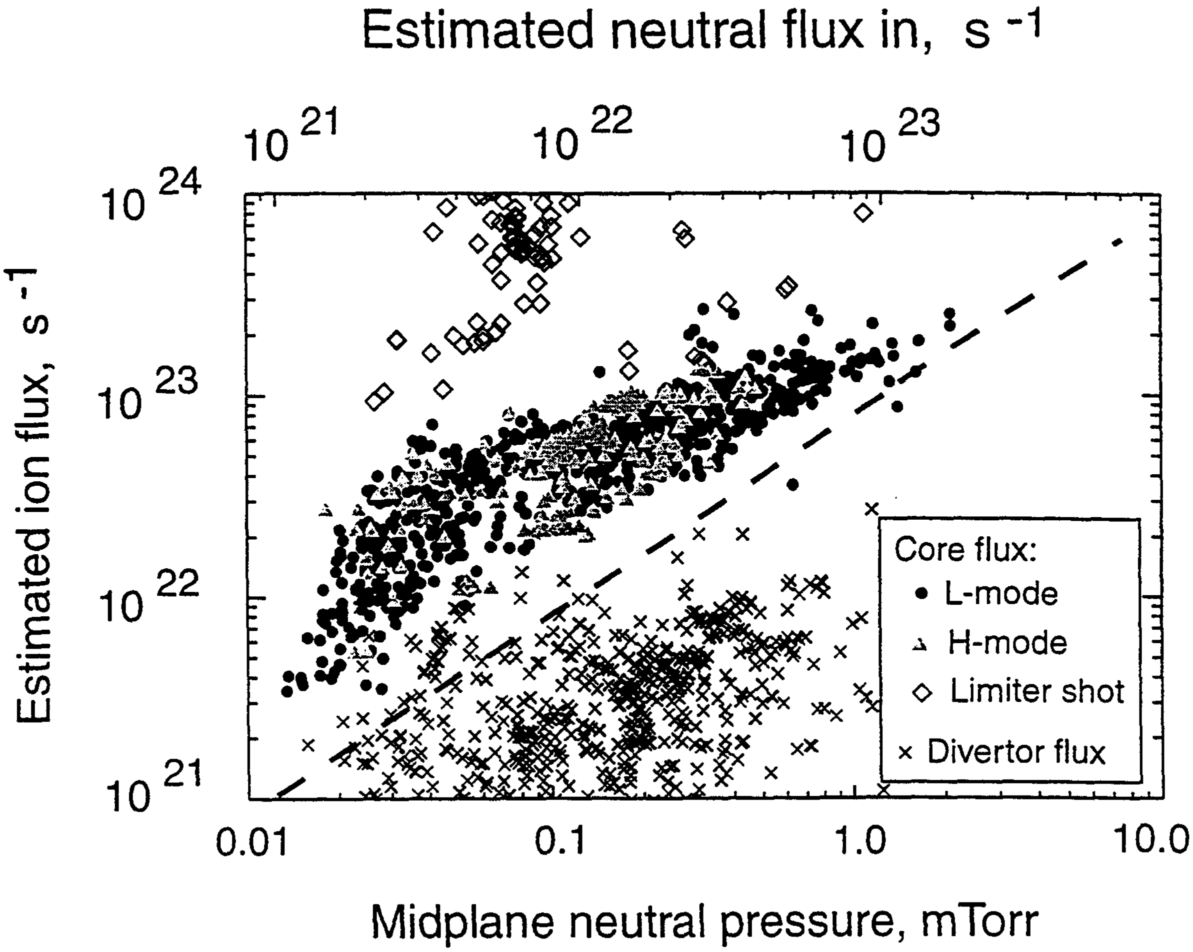
Estimated neutral flux in, s -1
10 21
10 22
10 23
Estimated ion flux, s -1
10 24
10 23
10 22
10 21
0.01
0.1
1.0
10.0
Midplane neutral pressure, mTorr
Core flux:
● L-mode
▵ H-mode
◇ Limiter shot
× Divertor flux

Fig. 2

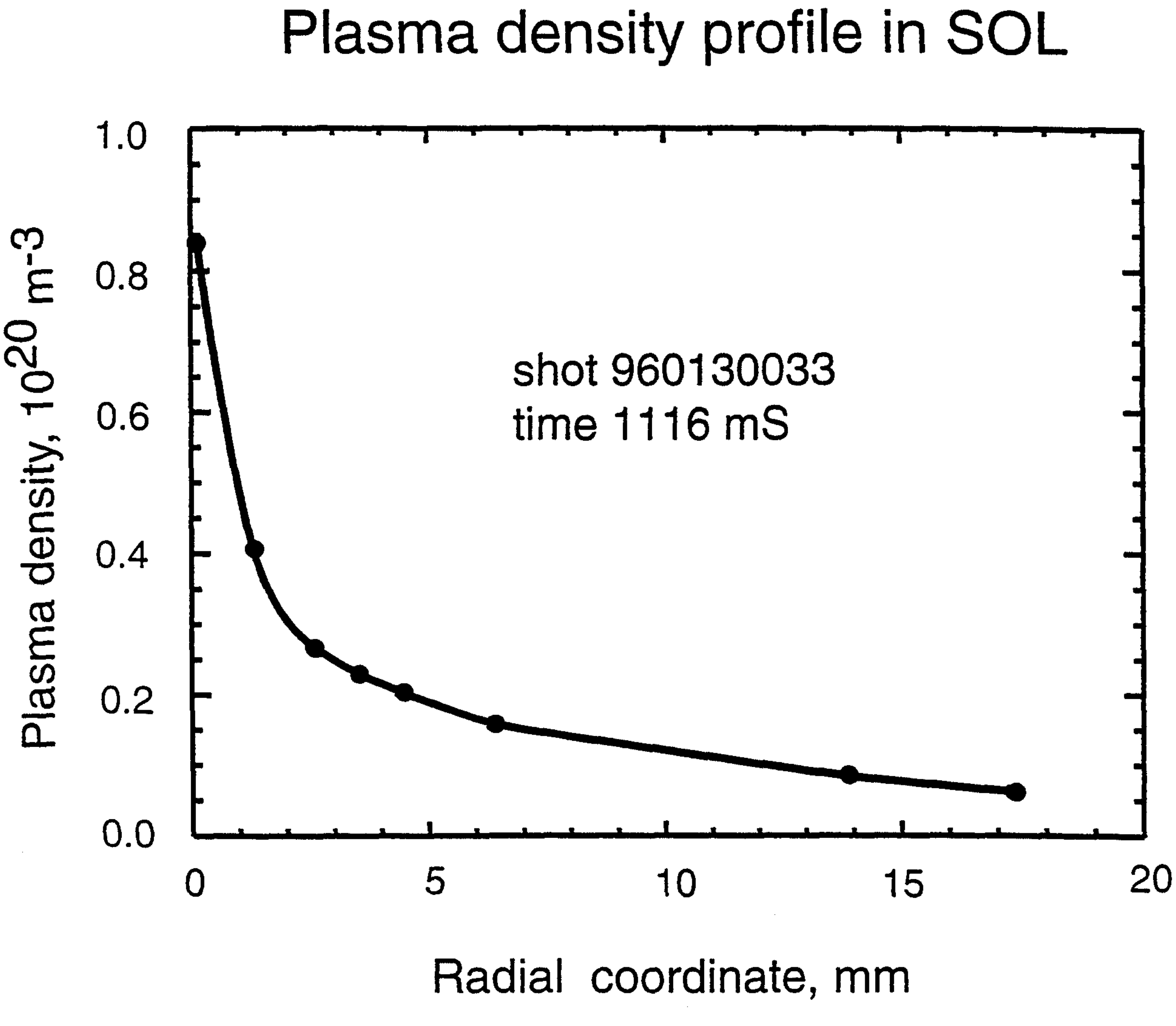
Plasma density profile in SOL

Fig. 3