# Neutral Transport Calculations for Tandem Mirror Halo Plasmas

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# NEUTRAL TRANSPORT CALCULATIONS FOR TANDEM MIRROR HALO PLASMAS

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# Abstract

An extensive survey of neutral atom transport in typical tandem mirror halo plasmas has been performed using the SPUDNUT code. The calculations are for both with and without reflection of energetic neutrals from the wall. These calculations can be used to provide simple empirical fits of the particle and energy flux of neutrals escaping from the plasma and hitting the wall and of neutrals penetrating the halo and entering the hot plasma. These quantities are of interest in point model halo plasma calculations.

## I. Introduction

It is useful to estimate the neutral atom reflectance, transmissivity, and the average energy of reflected and transmitted neutral particles in research concerning interactions between edge plasmas and walls. A particular application we have in mind is the modeling of halo plasmas for tandem mirror machines. Halo plasmas play an important role in the particle and energy exchange between the hot core plasma and cold neutral gas region near the wall. The SPUDNUT(1) neutral atom transport code has been utilized to calculate the transport of neutral atoms in the halo plasma. The calculations are carried out for representative parabolic and uniform plasma density and temperature profiles. For these calculations the SPUDNUT code has also been revised to better describe neutral atom reflection at the wall. For comparison purposes, we also present the same quantities without wall reflection.

The organization of this report is as follows. Section II of this paper gives a brief description of the revised SPUDNUT code. In Section III we specify the halo plasma parameter profiles which were used in these calculations. The results and discussion are given in Section IV.

## II. Neutral Atom Transport

The SPUDNUT neutral atom transport code(1) calculates the transport of neutral atoms in a finite width plasma slab with arbitrary plasma density and temperature profiles in the direction orthogonal to the face of the slab. The plasma is assumed to be uniform in the other two directions. The atomic interactions considered are ionization by electron and ion impact and charge exchange. Molecular processes are not considered. The original SPUDNUT code considered a single atom (and ion) species; the version used here considers two species (taken to be deuterium and tritium) and was developed by Houlberg and Gordinier.

The atoms are incident on the plasma from one side; their distribution function is taken to be isotropic and monoenergetic with energy $E_0$. The SPUDNUT code solves an integral equation for the charge exchange collision density in the plasma and constructs from it the required quantities, such as the ionization and energy transfer rates inside the plasma, and the flux and energy spectrum of the atoms escaping out each side of the plasma. The SPUDNUT code does not follow generations explicitly, but treats all generations of neutral atoms by inverting the appropriate matrix operator. The finite differencing scheme in SPUDNUT conserves neutral atoms, so the fate of all particles is accounted for.

There is also an option for allowing a solid wall on the same side of the slab as the incident neutral atom flux. Reflection of energetic neutral atoms back into the plasma is considered by dividing the flux reflected from the wall into various energy groups and treating these reflected atoms as additional incident particles with the appropriate energy. This option requires an iterative calculation to achieve a self-consistent result. Convergence is reasonably rapid. The angular effects associated with reflection at the wall are not well represented in this approach, however. The particle and energy reflection coefficients are known to depend on the angle of incidence, whereas we used results for normal incidence.(2) Furthermore, the angular distribution of the reflected particles will differ from the isotropic distribution assumed for the particles incident on the plasma. Including these effects would require a substantial revision to the SPUDNUT code. In addition, the data for angular effects on wall reflection is still somewhat sparse.

The coefficients for wall reflection used are taken from Ref. 2 and are shown in Figs. 1 and 2. It should be noted that the particle reflection coefficient, $R_N$, is the ratio of the reflected particle flux to the incident particle flux, and the energy reflection coefficient, $R_E$, is the ratio of the reflected energy flux to the incident energy flux. Consequently, the mean energy of the reflected particles is $R_E/R_N$ times the mean energy of the incident particles. The data shown is for monoenergetic ion beams incident normally on an iron surface. This data is used in SPUDNUT for all angles of incidence. The deuterium data is also used for reflection of tritium atoms since data for tritium reflection was not given.

## III. Halo Model

The halo model used in our calculations is a slab plasma of width d = 7.5 cm. Calculations are performed for parabolic and uniform profiles. The parabolic profiles take the form

$$T_e(x) = (T_{emax} - T_{emin})[1 - (\frac{x}{7.5})^2] + T_{emin}$$

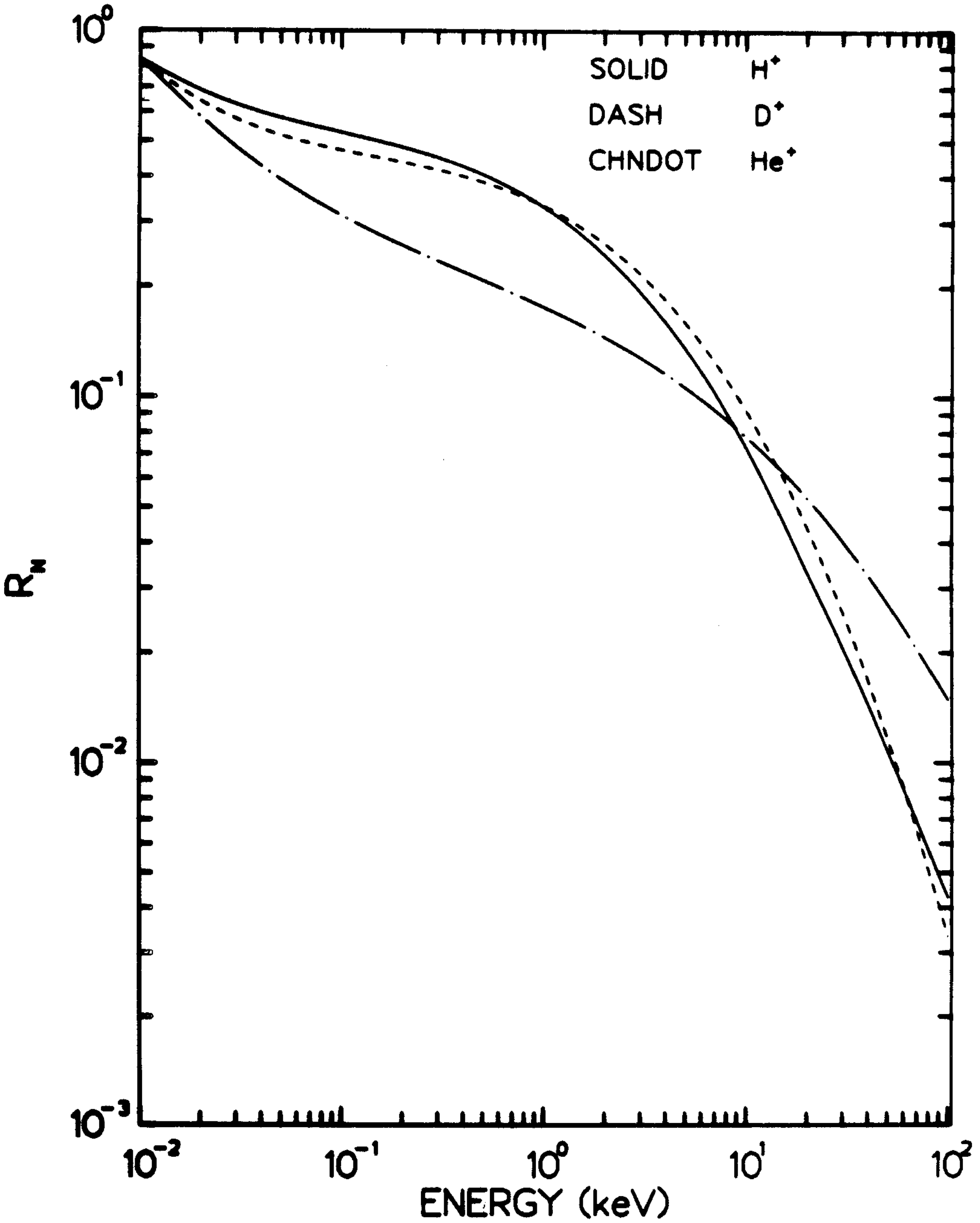
$$T_i(x) = (T_{imax} - T_{imin})[1 - (\frac{x}{7.5})^2] + T_{imin}$$

$$n_i(x) = (n_{imax} - n_{imin})[1 - (\frac{x}{7.5})^2] + n_{imin}$$

$$n_e(x) = \sum_i n_i(x) \qquad (i = D, T) .$$

The neutral atoms are incident from the right (x = 7.5 cm) with an energy $E_0$. Those escaping to the left (x < 0) are assumed to be absorbed in the core

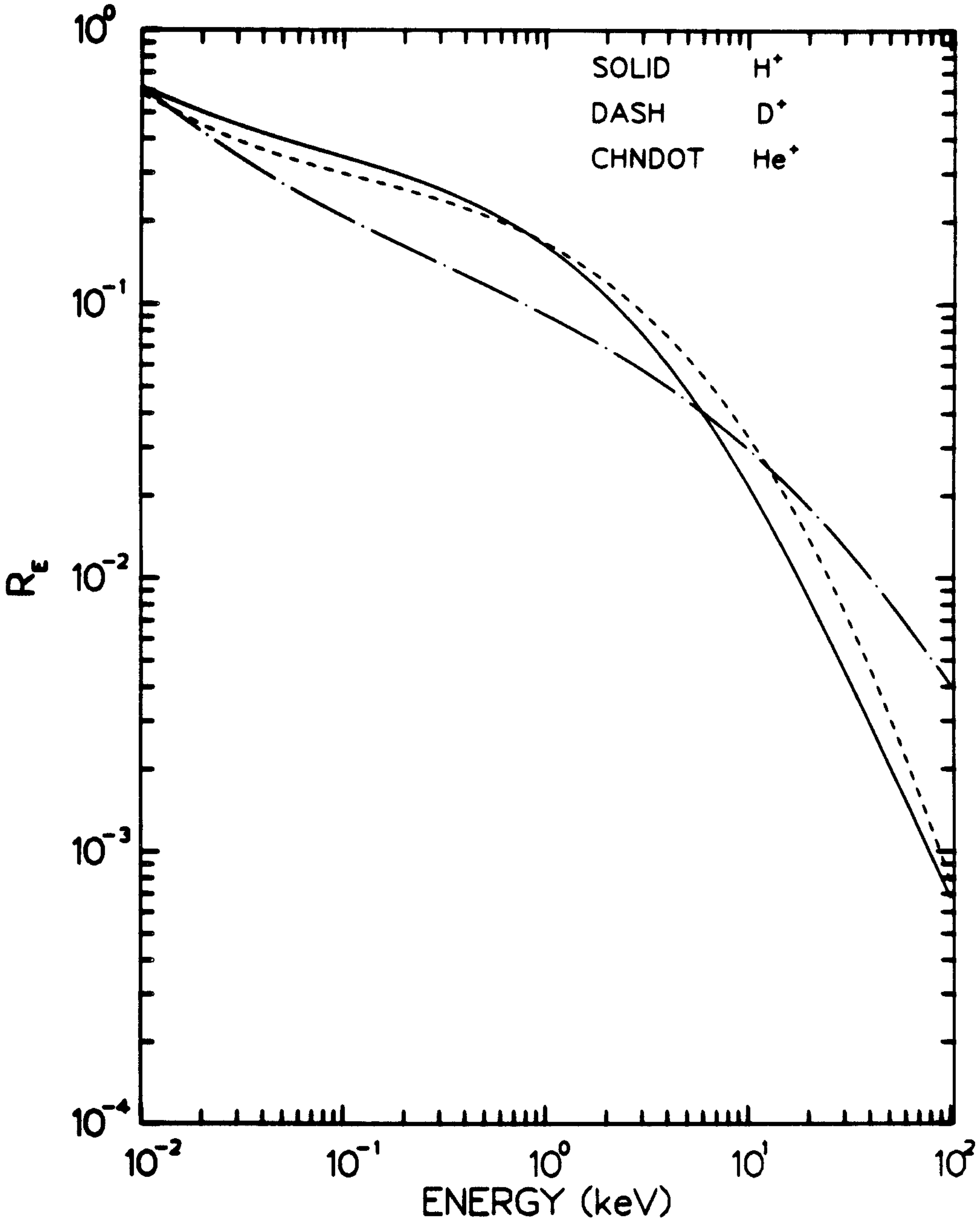
Fig. 1



Particle Reflection Coefficient for $H^+$, $H_2^+$, $He^+$ on Fe

Fig. 2

Energy Reflection Coefficient for $H^+$, $H_2^+$, $He^+$ on Fe



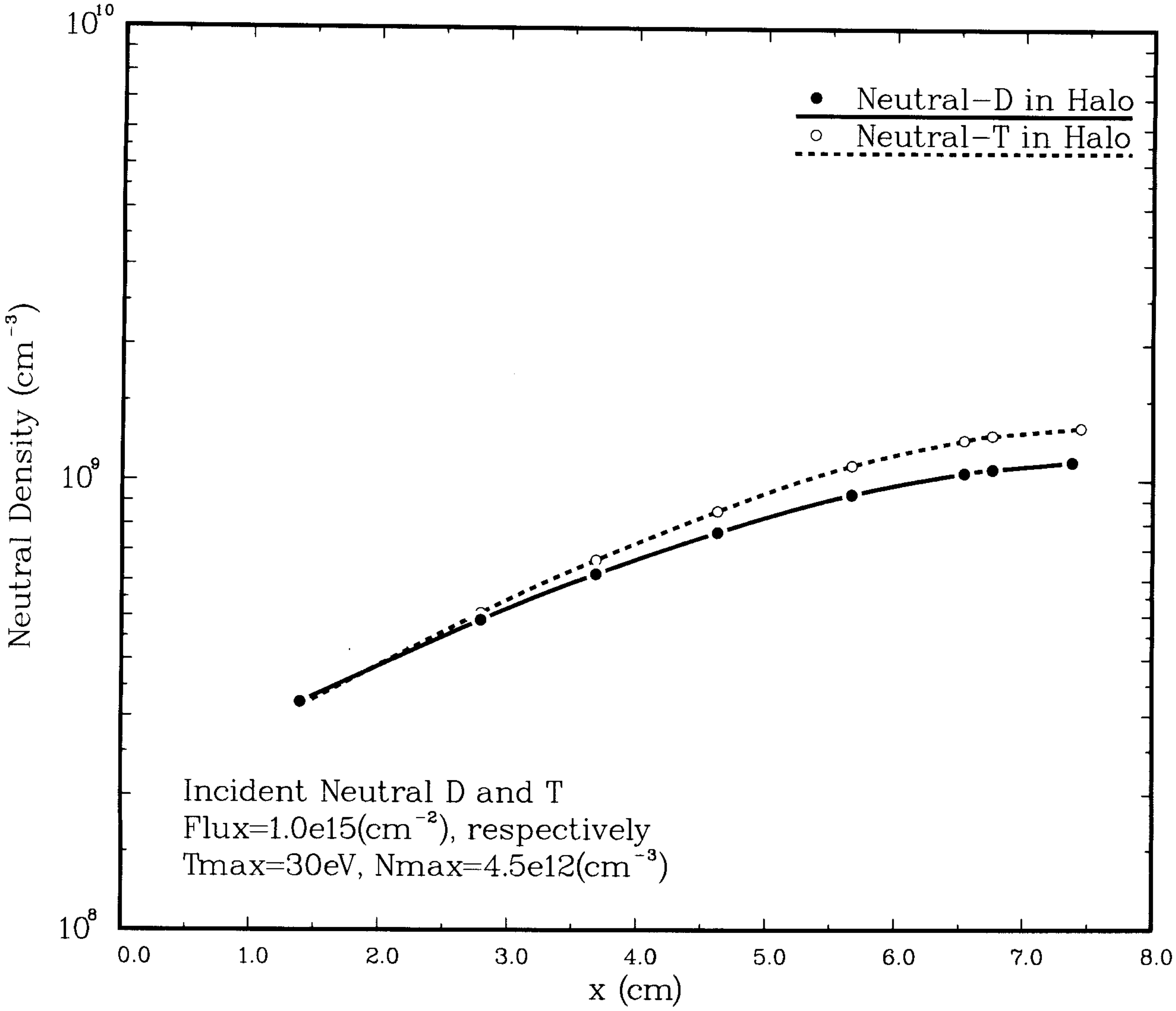
plasma and not return to the halo. For the calculations in this report, we take $T_{emin} = T_{imin} = 3$ eV, $n_{imin} = 0.05\ n_{imax}$. The halo plasma is assumed to be 50% deuterium and 50% tritium everywhere.

## IV. Results and Discussion

We present our results for neutral transport in the halo plasma in terms of the plasma reflectance, R, and the plasma transmissivity, T, for neutral atoms. The reflectance is defined here as the ratio of the flux of neutrals escaping to the right to the flux of cold neutrals incident from the right. Note that this incident flux does not consider the flux of neutrals reflected from the wall and therefore reincident on the plasma. We treat this as a form of "internal" neutral atom recycling. With this definition, the reflectance R can exceed unity because an atom can escape the plasma and be reflected back by the wall several times. The transmissivity, T, is defined here as the ratio of the flux of neutrals escaping to the left to the cold atom incident flux. The transmitted flux includes not only the uncollided part of the incident cold atom flux, but also the flux of neutrals which have undergone interactions in the plasma. We simply count all neutrals escaping to the right. We also present the mean energy of the reflected (by the plasma) and transmitted neutrals.

Figure 3 shows the neutral atom density profile in the halo plasma for a parabolic plasma density and temperature profile; the ion density is $4.5 \times 10^{12}\ \mathrm{cm}^{-3}$ and the temperatures are 30 eV at $x = 0$. The neutrals are incident with an energy of 5 eV. The tritium atoms are attenuated more than the deuterium. This leads to the differing neutral density profiles for deuterium and tritium. Figures 4 and 5 show the reflectance and transmissivity, respec-

Fig.3 Neutral Atom Density Profiles In Steady State



Incident Neutral D and T
Flux=1.0e15($cm^{-2}$), respectively
Tmax=30eV, Nmax=4.5e12($cm^{-3}$)

# Fig.4 Reflectance versus Integrated Line Density

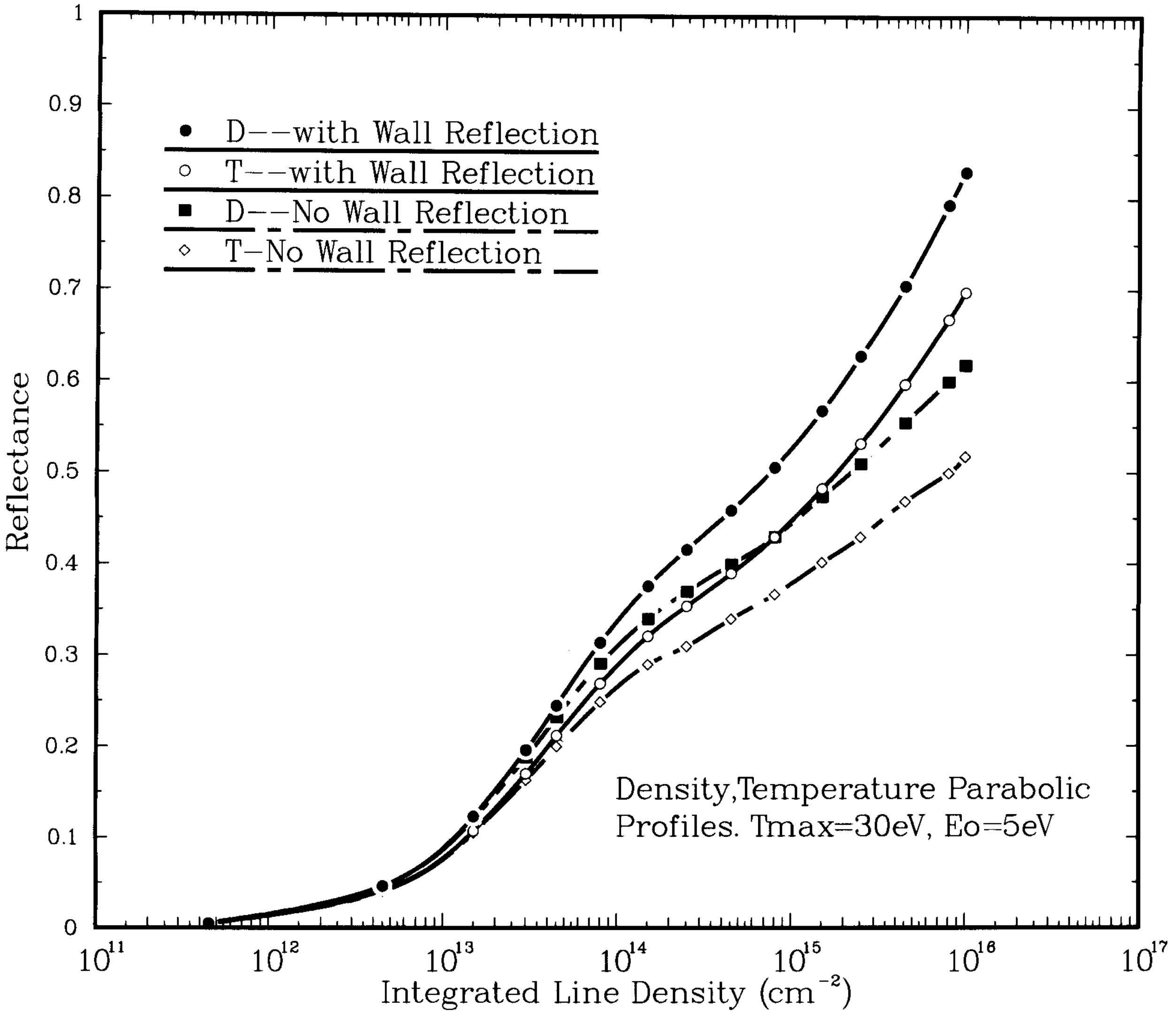
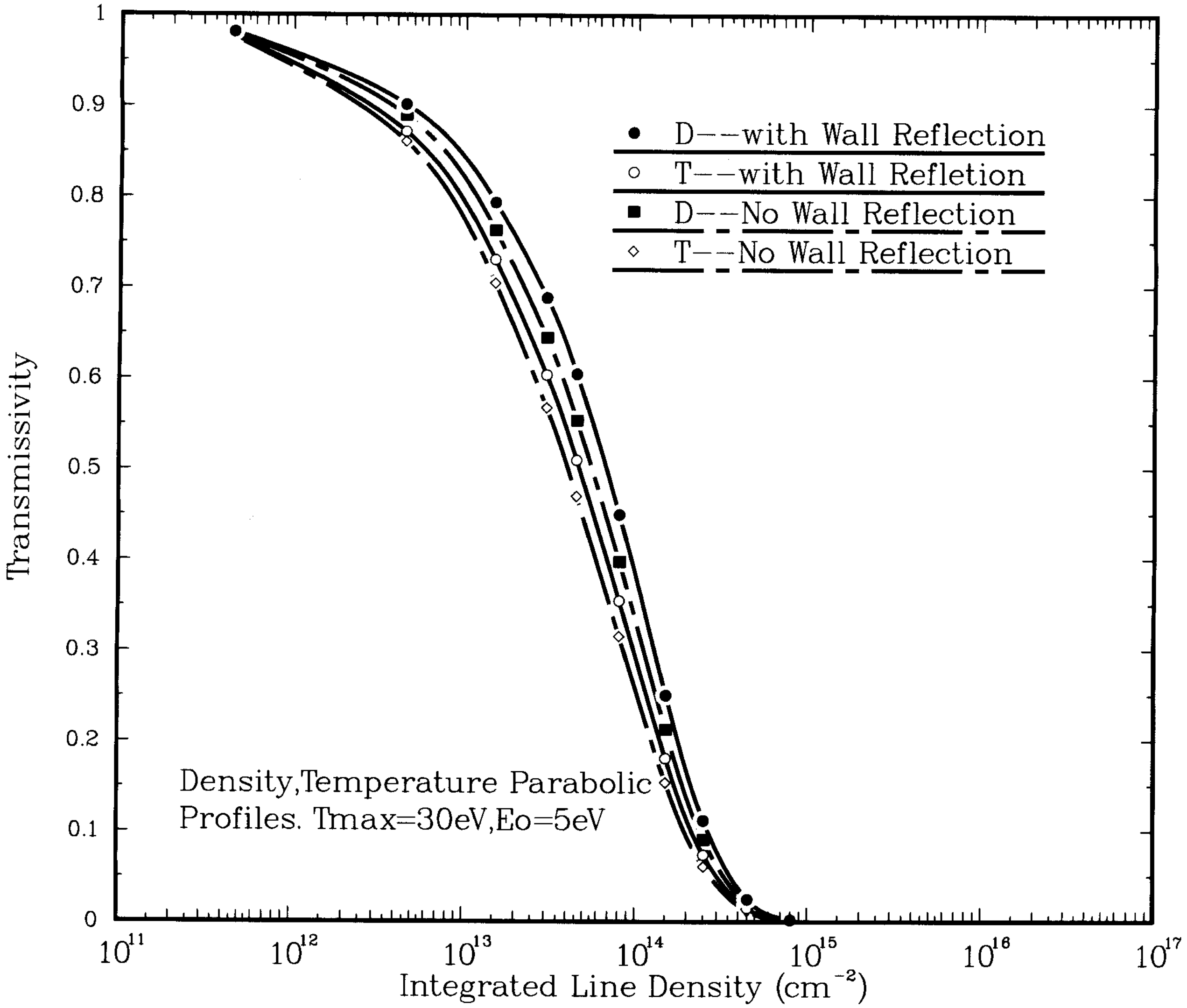


Fig.5 Transmissivity versus Integrated Line Density



tively, for this parabolic plasma profile versus the integrated line density. Both properties increase somewhat with wall reflection and depend strongly on the integrated line density. Figure 6 shows the effect of the incident neutral energy on the reflectance and the transmissivity. As expected, the transmissivity increases and the reflectance decreases with increasing incident energy. In Fig. 6 wall reflection is included. Figures 7 and 8 show the effect of changing the plasma temperature on the reflectance and transmissivity. The reflectance increases and the transmissivity decreases with increasing plasma temperature. The strongest dependence is on the integrated line density, however.

Figures 9 and 10 show the reflectance and transmissivity versus integrated line density for a uniform plasma profile. There is a considerable difference between the results for the uniform and parabolic profiles. Note that the reflectance approaches a constant value in the uniform profile case, but continues to rise in the parabolic profile case. This is because, at high line density, the neutrals can only penetrate a short distance into the halo. In the parabolic model the temperature there is near $T_{min}$, which is 3 eV in these calculations. Consequently, there is little ionization of these neutrals; charge exchange dominates and this leads to enhanced reflectance.

Figure 11 shows the average energy of the neutrals transmitted, $\langle E^T \rangle$, through the halo, and reflected, $\langle E^R \rangle$, by the halo versus integrated line density for parabolic profiles and with wall reflection. As expected, the average energies approach the average particle energies corresponding to "boundary" ion temperatures as the integrated line density increases. If the integrated line density is low, then $\langle E^r \rangle \rightarrow 3/2\ T_{imax}$ and $\langle E^T \rangle \rightarrow E_0$.

Fig.6 Reflectance and Transmissivity versus Incident Energy

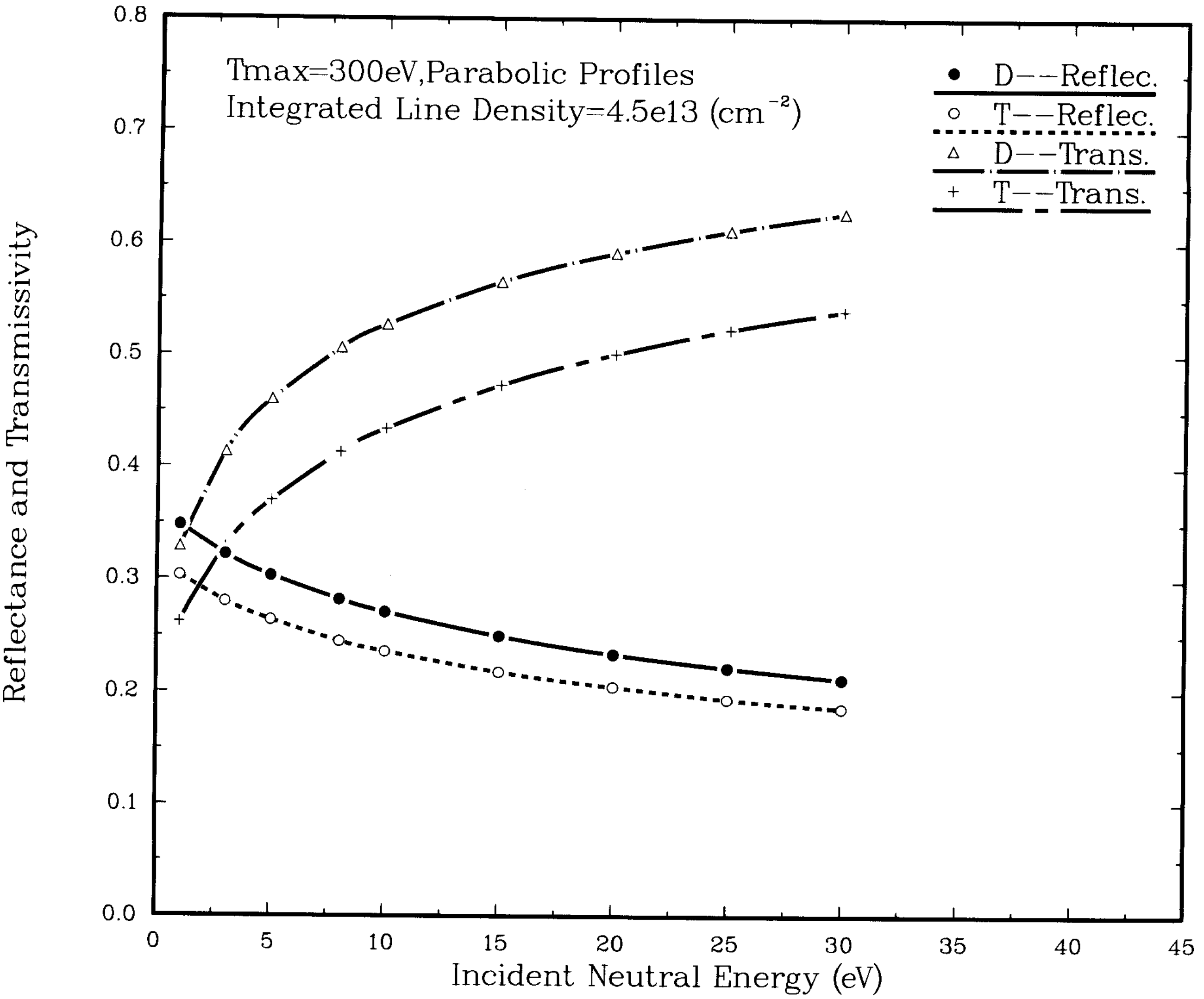
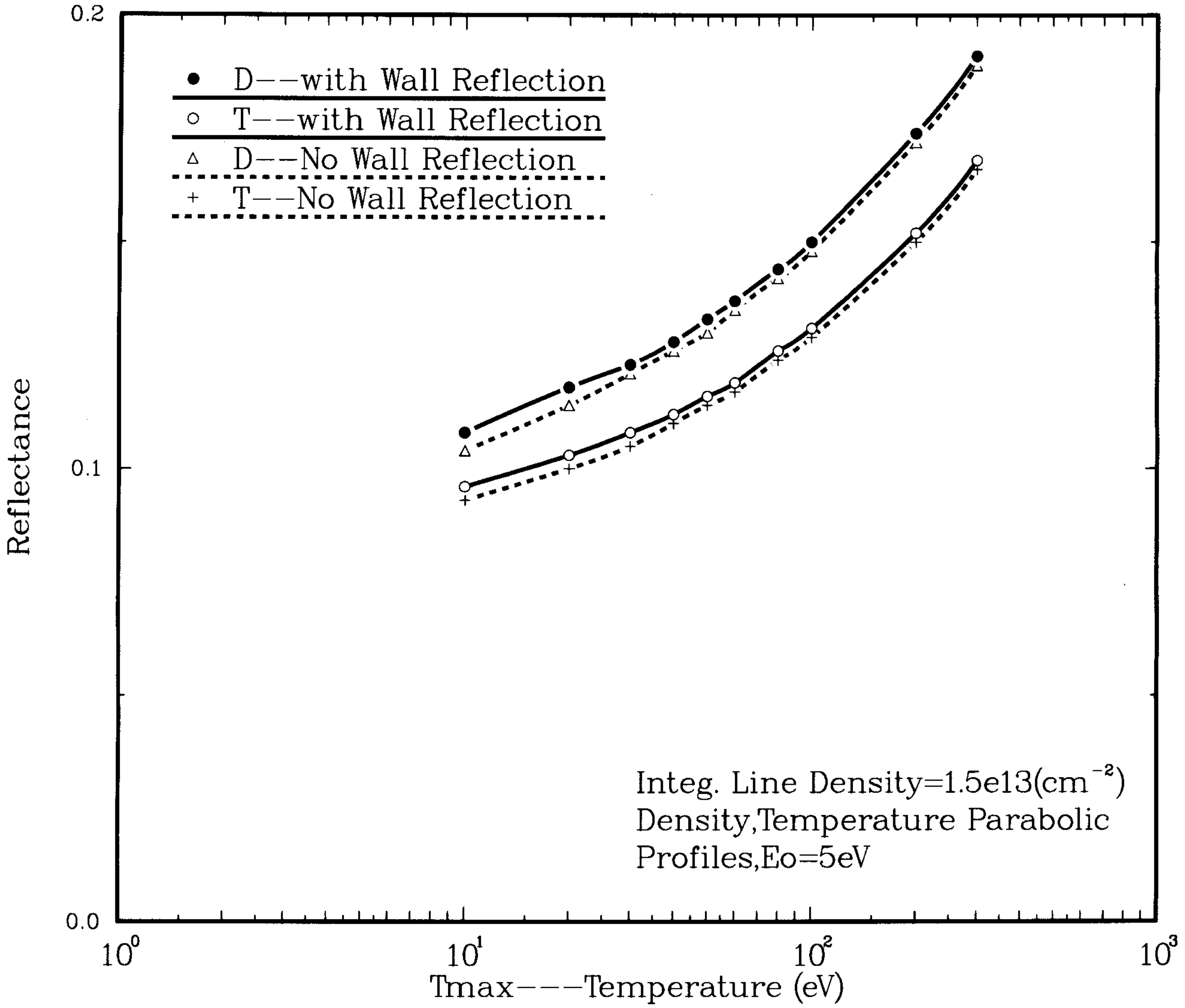


Fig.7 Reflectance versus Halo Temperature



## Fig.8 Transmissivity versus Halo Temperature

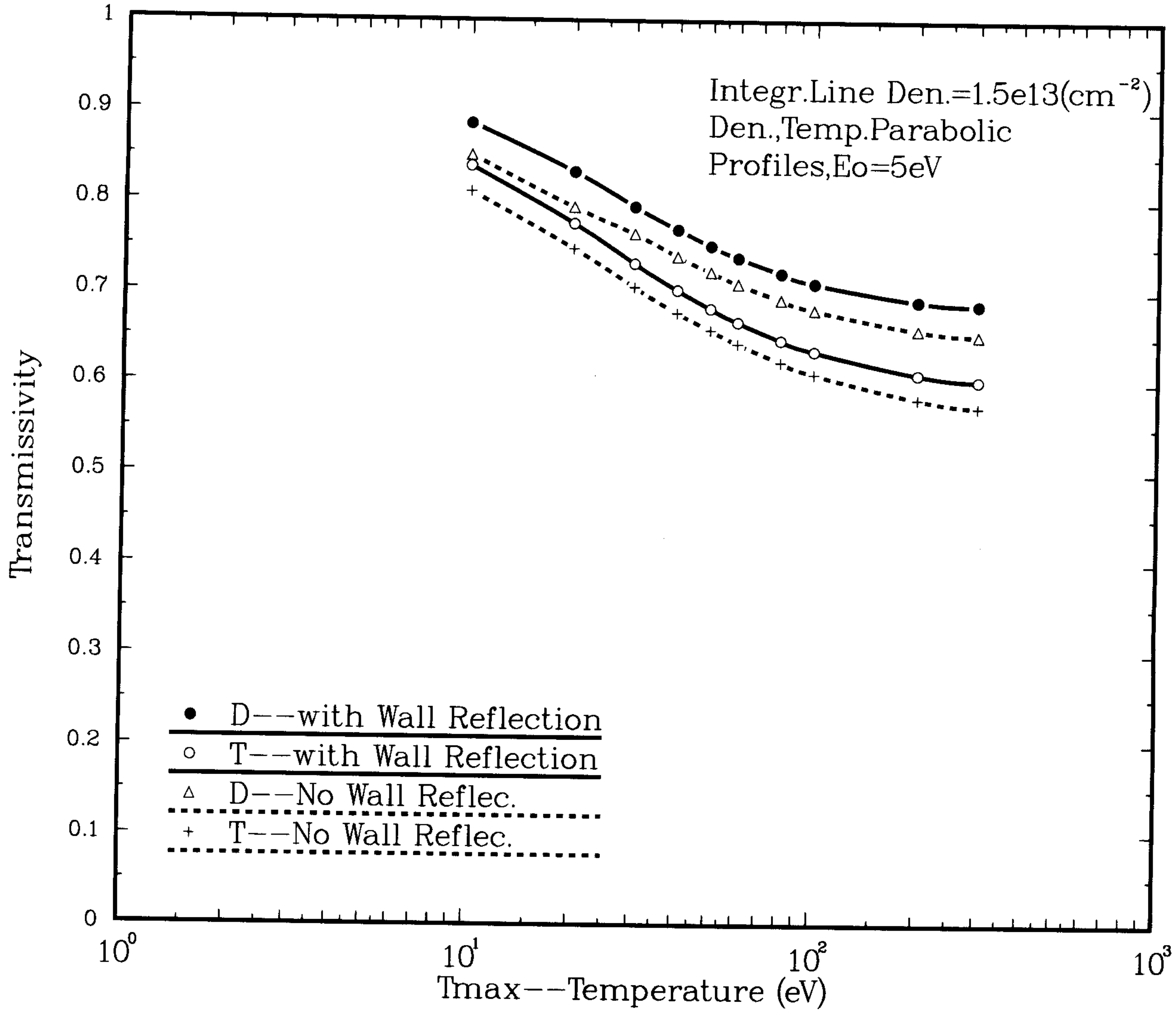


Fig.9 Reflectance versus Integrated Line Density

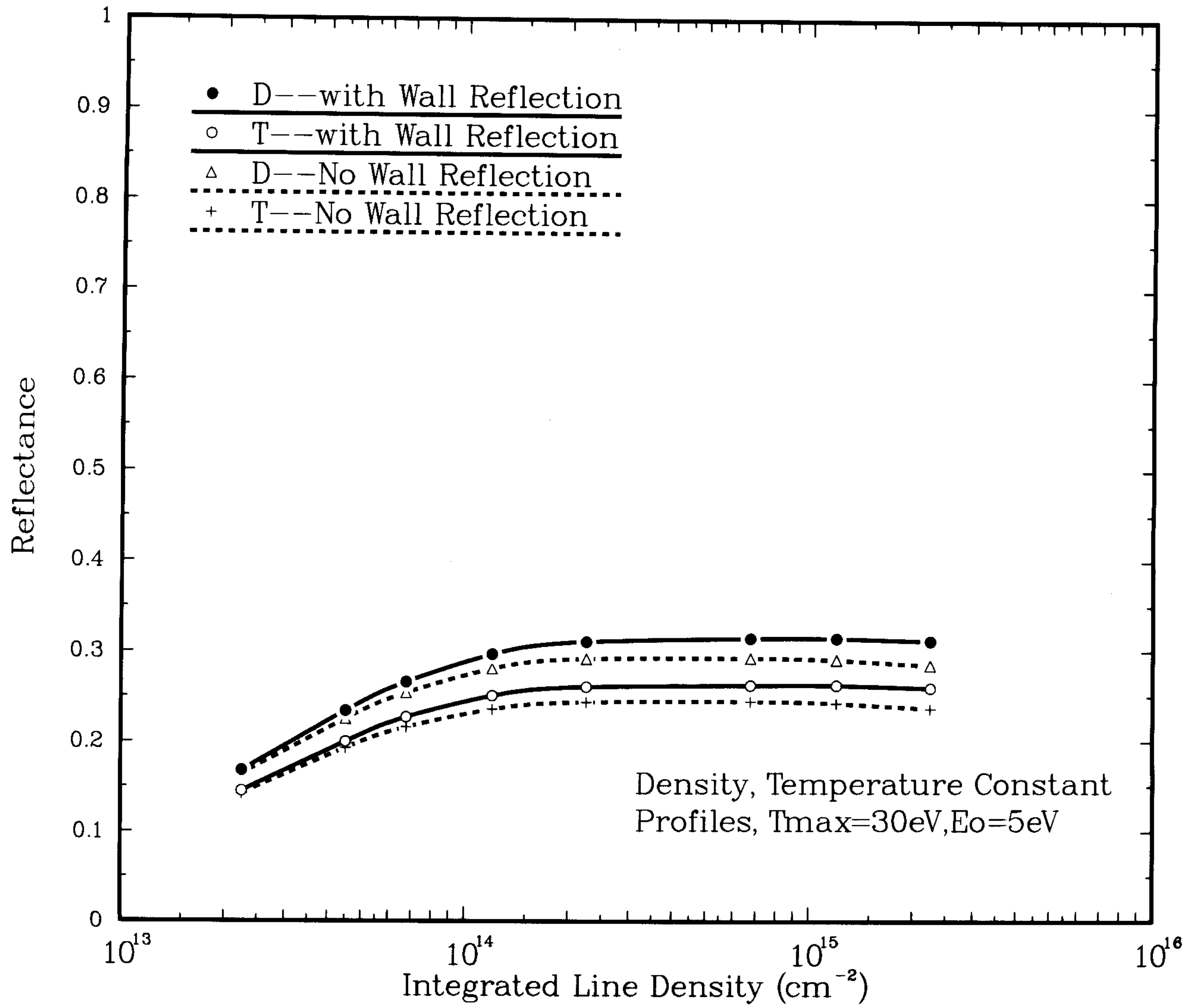


Fig.10 Transmissivity versus Integrated Line Density

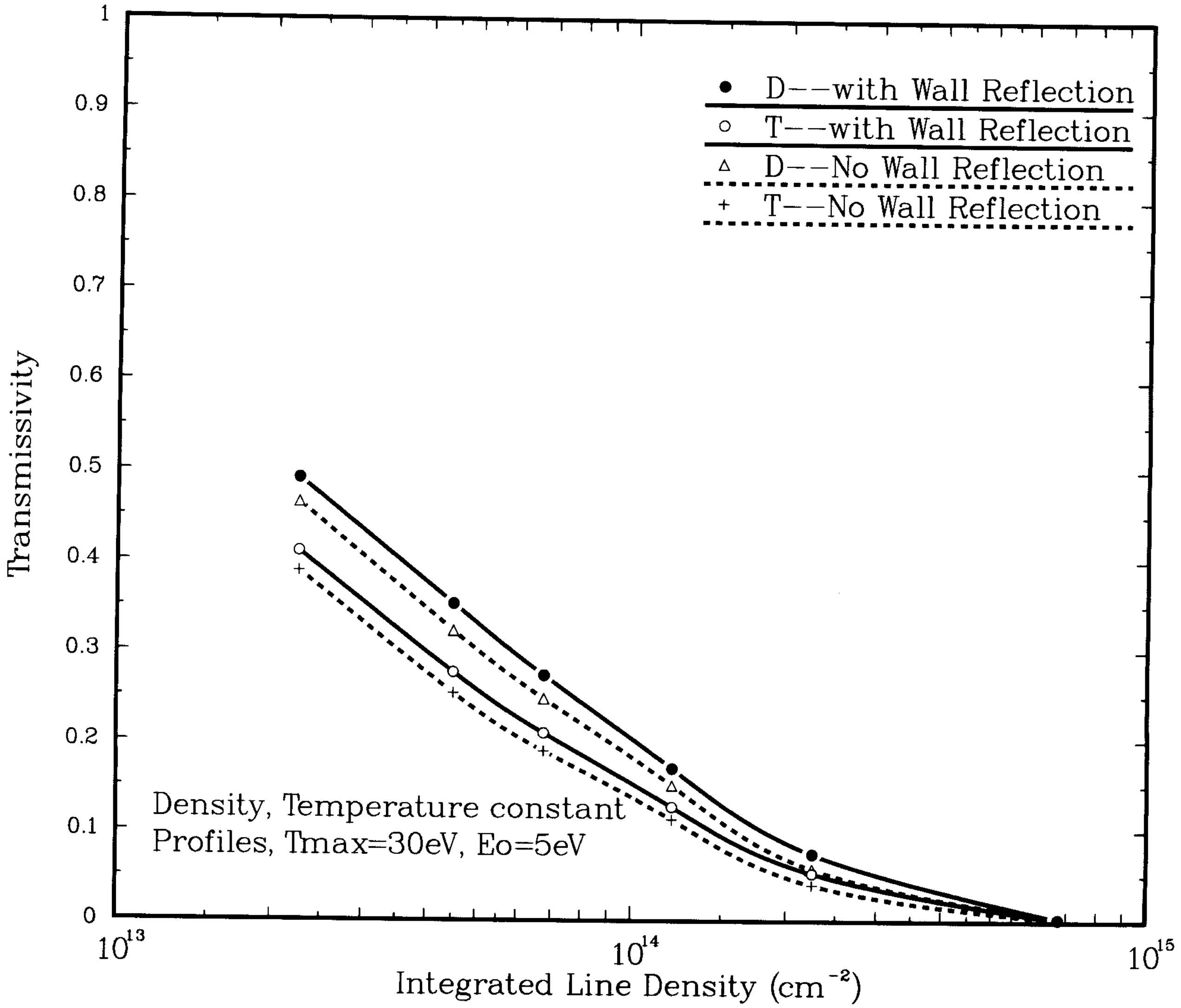
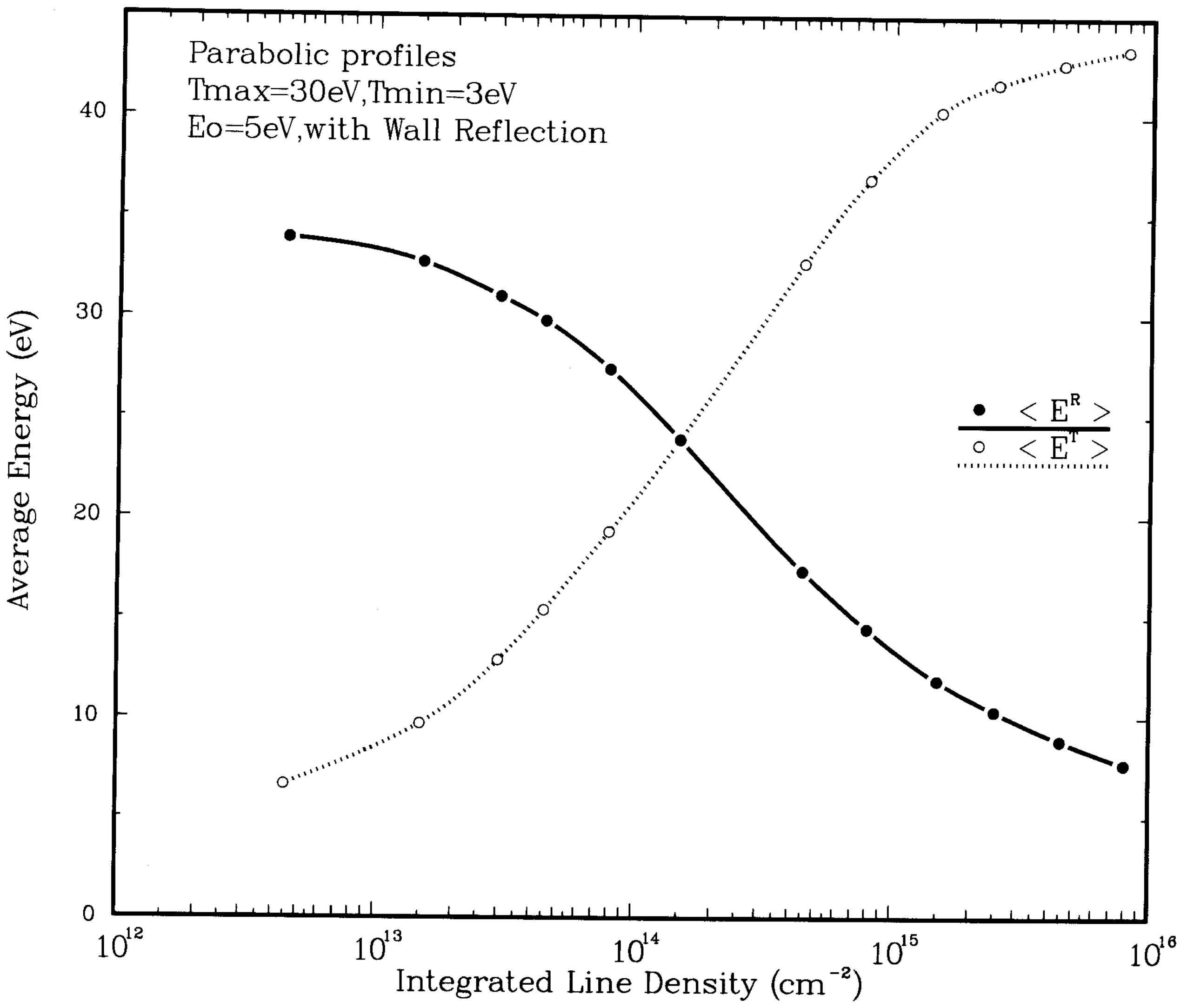


Fig.11 Average Energy of
Reflected and Transmitted Neutrals



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