Effect of the Refuelling Profile on the Performance of Divertor Tokamaks

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Abstract

The influence of the refuelling profile on the plasma density and temperature profiles, and on the neutral particle bombardment of the wall is studied using the WHIST tokamak simulation code. Edge refuelling has beneficial aspects for a divertor tokamak of the size of ASDEX or PDX, but central refuelling appears to be better for a reactor size plasma.

I. Introduction

It is well-known that refuelling is necessary in a divertor tokamak for stationary operation. Without replacement of the plasma that flows into the divertor collection chamber, where it is neutralized and pumped away, the density decays on the time scale of the particle confinement time. Various methods for refuelling (e.g. pellet injection, cluster injection, gas puffing) have been proposed. The refuelling method can have a significant impact on the neutral particle flux (and energy spectrum) at the wall. Refuelling methods which produce a particle source peaked near the edge can produce a substantial neutral flux on the wall, but also lead to lower edge temperatures and higher edge density in comparison with particle sources deeper in the plasma.

Without considering the details of the refuelling mechanism, we can model refuelling by an internal source of cold atoms. A fraction of these atoms are immediately ionized and become a cold ion source. The remaining atoms undergo charge exchange and become a source of energetic neutral particles which stream through the plasma and undergo further charge exchange, ionization, or escape the plasma. Both classes of particles, the cold ions and the energetic neutral particles, affect the density and temperature profiles directly through the particle source term and through the transport of energy by the energetic neutral particles, and indirectly through the density and temperature dependence in the plasma transport coefficients. It can be expected that edge refuelling leads to a colder energy spectrum of the neutrals incident on the wall, in comparison to deeper refuelling. It also leads, however, to a greater total flux of energetic neutral particles reaching the wall. Whether the release of impurities from the wall is reduced or increased by edge refuelling depends on the competition between these two effects.

We consider in this report the influence of the spatial profile of the refuelling source on the plasma density and temperature profiles, particularly in the scrape-off zone, and on the flux and energy spectrum of neutral particles incident on the wall. Only poloidal divertors are considered in this work; numerical calculations are presented for a device of the ASDEX/PDX size and for a reactor-size tokamak.

This topic has also been considered to some extent by Mense, et al.[1] and by Haas, Keilhacker, and Lackner.[2] Mense considered the influence of the refuelling profile on the plasma profiles in the ORNL TNS device, but neglected neutral particle effects. Haas considered the neutral particle bombardment of the wall due to various refuelling methods, but only the density profile was obtained self-consistently with the refuelling source. The temperature profiles were prescribed. Neutral particle transport was considered using a simplified one-generation model. Both of the above works, however, treated the physical mechanisms producing the spatial profile of the refuelling source in more detail than considered here. In addition, Haas gave more attention to possible molecular processes in the neutral gas.

II. The Model

The WHIST[3] tokamak simulation code is used to describe the spatial profile and temporal evolution of the plasma. This code solves diffusion equations for the ion density, ion temperature, and electron temperature.

The geometry is assumed to be cylindrical, with variation only in the radial direction, r, being allowed. Toroidal effects are included through the transport coefficients. According to the local value of the collisionality the code assumes either pseudo-classical, trapped electron (2 regimes), dissipative trapped ion, or collisionless trapped particle mode diffusion.[4,5] The diffusion coefficient in the divertor scrape-off layer is taken to be the local Bohm value. The effect of flow parallel to the magnetic field and into the divertor collection chamber is modelled in the one-dimensional transport equations as a radially dependent sink of particles and energy.[6,7]

As indicated in the introduction, the refuelling is modelled as an internal source of cold atoms. The spatial profile is taken to be of the form

$$s(r) = s_o \exp(\delta(r - r_s)/r_s) \qquad (1)$$

or

$$s(r) = s_o (1 - (r/r_s)^2) \qquad (2)$$

for r less than r_s, the separatrix radius. For r greater than r_s, $s(r) = 0$. The input parameter δ determines the degree to which the source is peaked at the separatrix, in the case of Eq. (1). The parabolic case, Eq. (2), provides a contrasting case, where the source is peaked at the center. The coefficient s_o is determined by a feedback routine in such a way that the average density is held constant at the desired value.

A fraction (ionization rate/total reaction rate) of the cold atoms are assumed to be immediately ionized and constitute a cold ion source in the plasma transport equations. The remaining atoms are assumed to undergo charge exchange and become a source of energetic neutral atoms. Their transport in the plasma is calculated using the SPUDNUT routine.[8] This routine solves an integral equation for the neutral particle transport by a matrix inversion technique, rather than by a series in generations. SPUDNUT compares well with ANISN calculations[9] for the TFTR device, and with the FASLAB routine (from ORNL) for both the ISX-B device[10] and a reactor size plasma.[8]

In addition to the internal source of atoms, ten percent of the ion flux into the divertor collection chamber is recycled into the plasma as 5 eV atoms originating from the wall. The effect of energetic particle reflection at the wall is treated using the reflection coefficient, R, of Oen and Robinson.[11] Upon reflection, all energies between zero and the incident energy are assumed to be equally probable. In the ASDEX/PDX case, the remaining fraction, 1-R, of the neutral particle flux incident on the wall is assumed to be absorbed by the wall. In the reactor case, the wall is assumed to be saturated with gas and, therefore, the fraction, 1-R, is returned to the plasma as 5 eV neutral atoms.

The radial profile of the "toroidal" plasma current is assumed, rather than calculated self-consistently. For ASDEX/PDX, the assumed profile is

$$J(r) = J_o \, (1 - r^2/r_s^2)^2$$

and, for the reactor case,

$$J(r) = J_o\ (1 - r^2/r_s^2)\ .$$

J(r) is zero in the scrape-off zone.

The procedure is to calculate the plasma parameters as a function of time starting from a given set of initial conditions. The refuelling source (magnitude) is feedback controlled to hold the average ion density at a specified value. The calculation is allowed to go to a stationary state; the results presented in this report are the stationary values.

III. Results of the Simulation

We consider first the results of the simulation of an ASDEX/PDX size tokamak. The following parameters were assumed:

Major radius	165 cm
Separatrix radius	40 cm
Wall radius	44 cm
Toroidal field	28 kG
Plasma current	450 kA
Average density	4.2×10^{13} cm^{-3}

The working gas is hydrogen and ohmic heating is the only energy source. Shown in Figs. 1 and 2 are the density and temperature profiles in the main plasma and in the scrape-off zone for various refuelling profiles. One sees that refuelling strongly peaked near the edge (large δ) leads to a denser and colder plasma in the scrape-off zone, as would be expected. Shown in Table I are the line integral of the electron density in the scrape-off zone, the flux of ions and energy into the divertor collection chamber (normalized to the wall area) and the flux of energetic atoms incident on the wall (the flux of ions to the wall is at least two orders of magnitude smaller). The energy distribution of the neutral particle flux is shown in Fig. 3. Using the sputtering coefficient given by Bohdansky[12] for protons on stainless steel with this energy distribution gives the flux of impurity atoms leaving the wall; this is listed in Table I.

These results show that edge refuelling (large δ) improves the shielding efficiency (increased $\int ndr$), but also increases the gas load for vacuum pumping and increases the total neutral particle flux incident on the wall. Because this flux is colder when δ is large, the impurity production rate does not change much, except in the case of the parabolic refuelling profile, which is a factor of 2 better. The reduced temperature at the separatrix, for edge refuelling, reduces the sputtering rate of the divertor collector plate and the sheath potential. This can alleviate the possibility of unipolar arcs at the collector plate.

The conclusion is that one ought to use refuelling peaked at the edge as much as the vacuum pumping system can handle; this improves the shielding efficiency and can reduce problems at the collector plate without causing a serious increase in the rate of impurity generating at the wall.

We consider next the results for a reactor size plasma. The following parameters were used:

Major radius	1300 cm
Separatrix radius	500 cm
Wall radius	530 cm
Toroidal field	35.7 kG
Plasma Current	14.9 MA
Average Density	4×10^{13} cm^{-3}

The working gas is a 50% D-T mixture, which is treated in the transport equations as a single species with an atomic mass number of 2.5. The primary energy source is alpha heating. The average density, and not the power output, is held constant as the refuelling profile is changed. This is easier numerically, but the general conclusions should not depend strongly on which parameters is held constant. The parameters chosen for the reactor case are taken from the UWMAK-II design,[13] which has a low power density in comparison with later designs.[14,15]

The results for the reactor case are given in Figs. 4-6 and Table II. One sees an interesting effect on the density and temperature profile as the refuelling is peaked more at the edge. The density profile flattens and the temperature profile becomes peaked; this is because the convective energy transport is reduced in the center. Consequently, greater conductive energy transport (and a stronger temperature gradient) is required to remove the energy from the center of the plasma. At the same time the total power output falls, as shown in Table II. This is because of the reduced density in the center, where most of the fusion reactions occur. In contrast with the ASDEX/PDX results, the temperature at the separatrix is rather high, above 1 keV, even for $\delta = 20$. The rate of impurity production at first increases with δ, but then appears to decrease. The parabolic refuelling profile is a factor of 4 better, however. One also sees that a relatively good shielding efficiency ($\int ndr > 10^{13}$ cm^{-2}) can be easily obtained without strongly peaked edge refuelling.

The general conclusion for the reactor case is that a centrally peaked, or perhaps broad, refuelling profile is preferable. It leads to a better power density, through peaking of the density profile, and reduction of the rate of impurity production while yielding a sufficiently dense scrape-off zone plasma for good shielding efficiency. The separatrix temperature is rather high as a result of the large energy flux into the scrape-off zone. This temperature is at, or above, the energy at which the sputtering coeḟficient has a maximum. Consequently, only a drastic reduction in the separatrix temperature would yield a reduced impurity production rate. This can be accomplished by refuelling into the scrape-off zone itself, but with a corresponding increase in the gas handling requirements. This does not appear to be a desirable solution. The high separatrix temperature, however, creates problems for the divertor collector plates.(16) Other means of collecting the particles, and their energy, in the divertor collection chamber are needed.

Table I

ASDEX/PDX Size

δ	$\int ndr$ (cm^{-2})	Divertor Particle Flux ($cm^{-2}\ sec^{-1}$)	Divertor Heat Flux ($watts/cm^2$)	Neutral Particle Flux ($cm^{-2}\ sec^{-1}$)	Impurity Reflux ($cm^{-2}\ sec^{-1}$)
10	1.4×10^{13}	2.8×10^{16}	1.4	8.2×10^{15}	1.6×10^{13}
5	4.7×10^{12}	1.4×10^{16}	1.4	4.9×10^{15}	1.9×10^{13}
1	1.3×10^{12}	5.6×10^{15}	1.1	2.3×10^{15}	1.4×10^{13}
Parabola	8×10^{11}	4.3×10^{15}	1.2	1.3×10^{15}	8.0×10^{12}

Table II

Reactor Size

δ	$\int ndr$ (cm^{-2})	Div. Part. Flux ($cm^{-2}\ sec^{-1}$)	Div. Heat Flux ($Watts/cm^2$)	Neutral Particle Flux ($cm^{-2}\ sec^{-1}$)	Impurity Reflux ($cm^{-2}\ sec^{-1}$)	Alpha Power (Megawatts)
20	5.5×10^{13}	3.1×10^{16}	14	1.0×10^{16}	3.1×10^{14}	523
10	4.3×10^{13}	3.0×10^{16}	20	1.5×10^{16}	3.6×10^{14}	732
5	2.7×10^{13}	3.0×10^{16}	20	1.1×10^{16}	3.2×10^{14}	788
1	1.4×10^{13}	1.6×10^{16}	31	7.1×10^{15}	1.6×10^{14}	1088
Parabola	9.5×10^{12}	1.4×10^{16}	42	4.2×10^{15}	8×10^{13}	1412

References

1. A.T. Mense, W.A. Houlberg, S.E. Attenberger, and S.L. Milora, "Effects of Fueling Profiles on Plasma Transport", Oak Ridge National Laboratory, ORNL/TM-6026 (1978).

2. G. Haas, M. Keilhacker, K. Lackner, "Comparison of Different Refuelling Methods With Respect to Plasma Contamination", Third Int. Conf. on Plasma-Surface Interactions (Culham, UK) (1978).

3. W.A. Houlberg and R.W. Conn, Nuclear Sci. and Eng. 64, 141 (1977).

4. S.O. Dean, et al., "Status and Objectives of Tokamak Systems for Fusion Research", WASH-1295, USAEC, Washington, D.C. (1974).

5. D.F. Düchs, D.E. Post, and P.H. Rutherford, Nuclear Fusion 17, 565 (1977).

6. A.T. Mense and G.A. Emmert, "Simulation of Poloidal Divertors in One-Dimensional Tokamak Transport Codes, Oak Ridge National Laboratory, ORNL/TM-6279 (1978).

7. M. Keilhacker, "Physics of Divertors and the Scrape-Off Layer", Max-Planck-Institut für Plasmaphysik, IPP III/42 (1978).

8. K. Audenaerde, G.A. Emmert, M. Gordinier, "SPUDNUT: A Transport Code for Neutral Atoms in Plasmas", University of Wisconsin, UWFDM-259 (1978).

9. J.G. Gilligan, S.L. Gralnick, W.G. Price, Jr., T. Kammash, Nuclear Fusion 18, 63 (1978).

10. H. Howe, private communication.

11. O.S. Oen, M.T. Robinson, Nuclear Instrum. and Meth. 132, 647 (1976).

12. J. Bohdansky, H.L. Bay and J. Roth, Proc. Seventh Intern. Vacuum Cong. and the Third Int. Conf. Solid Surfaces (Vienna 1977), p. 1509.

13. R.W. Conn, et al. in Plasma Physics Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1974), Vol. 3, 497.

14. R. W. Conn, et al. in Plasma Physics and Controlled Nuclear Fusion Research (International Atomic Energy Agency, Vienna, 1976), Vol. 3, 203.

15. R.W. Conn, G.L. Kulcinski, and C.W. Maynard, "NUWMAK: An Attractive Medium Field, Medium Size, Conceptual Tokamak Reactor", Proc. of the Third Topical Meeting on the Technology of Controlled Nuclear Fusion, Santa Fe, NM, May 9-11, 1978.

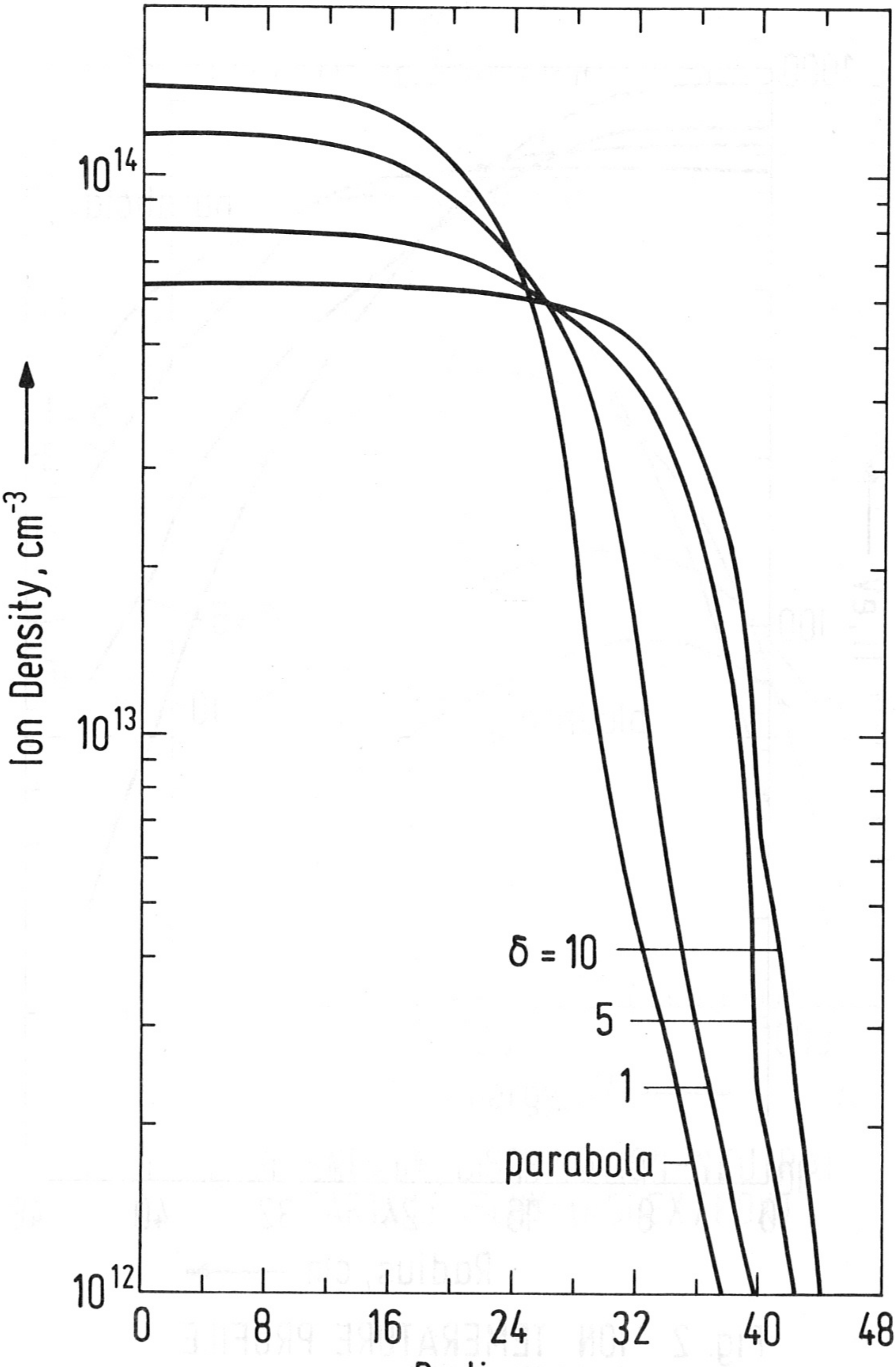

Fig. 1 DENSITY PROFILE (ASDEX/PDX)

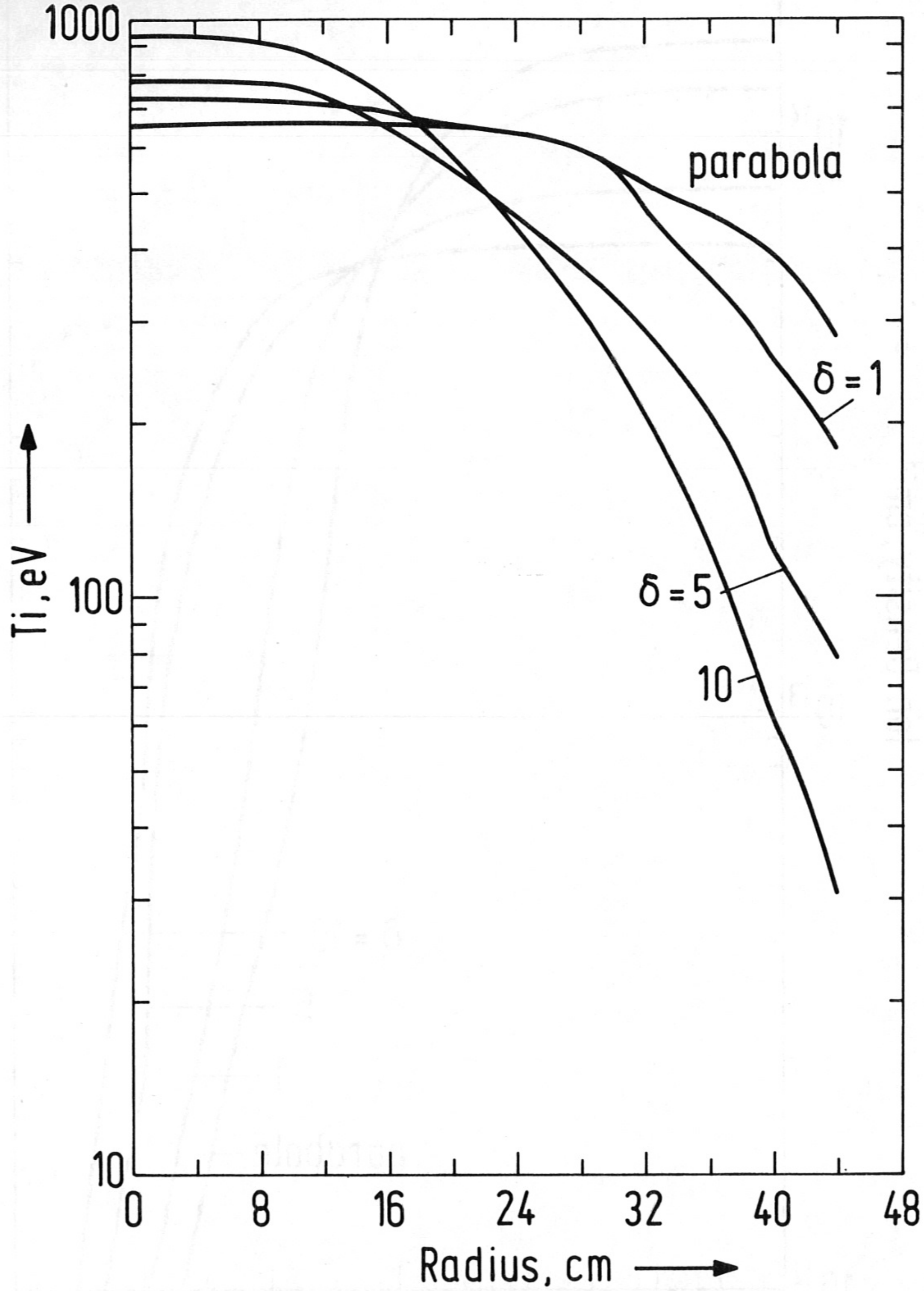

Fig. 2 ION TEMERATURE PROFILE (ASDEX / PDX)

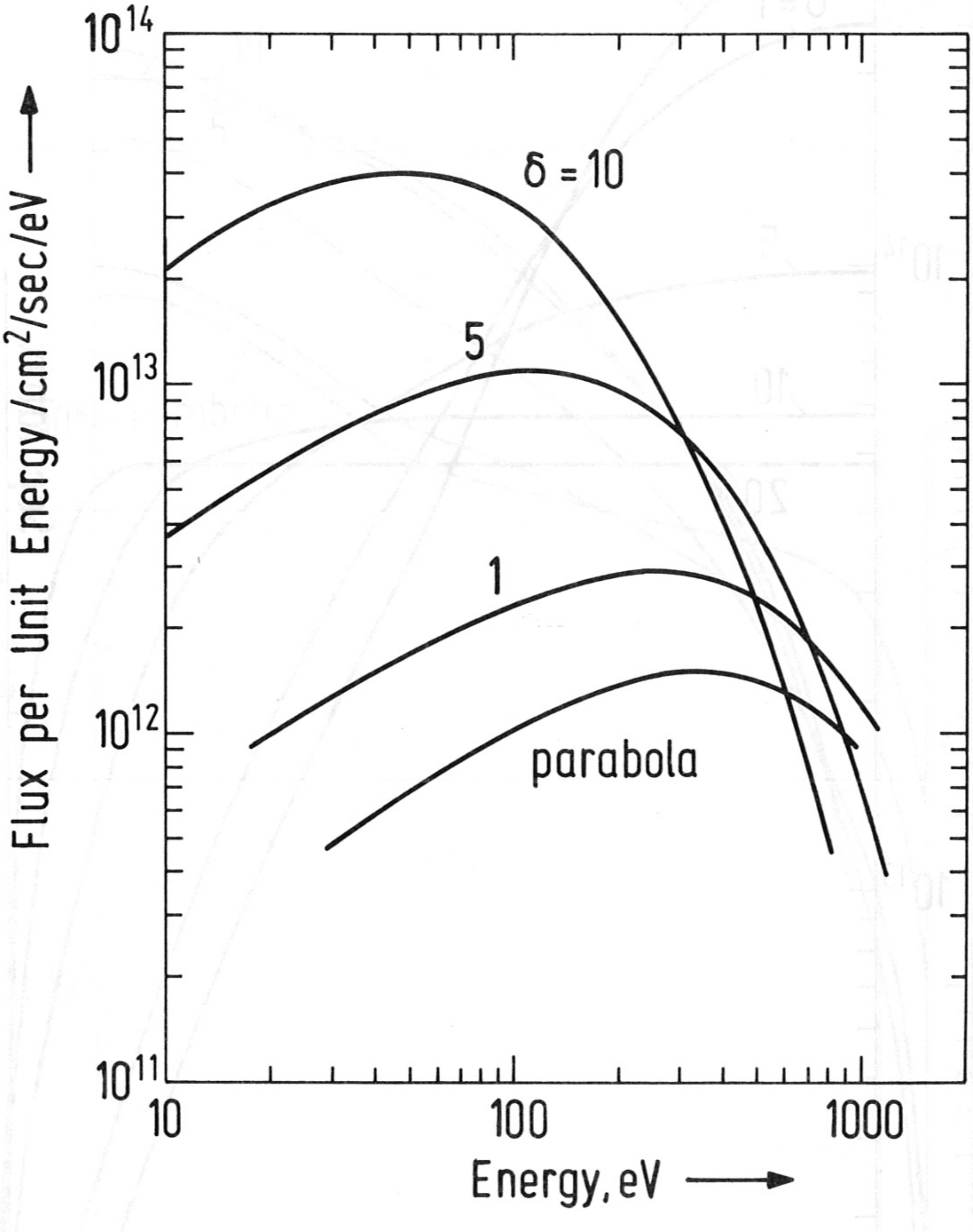

Fig. 3 ENERGY DISTRIBUTION-NEUTRAL PARTICLE FLUX-(ASDEX/PDX)

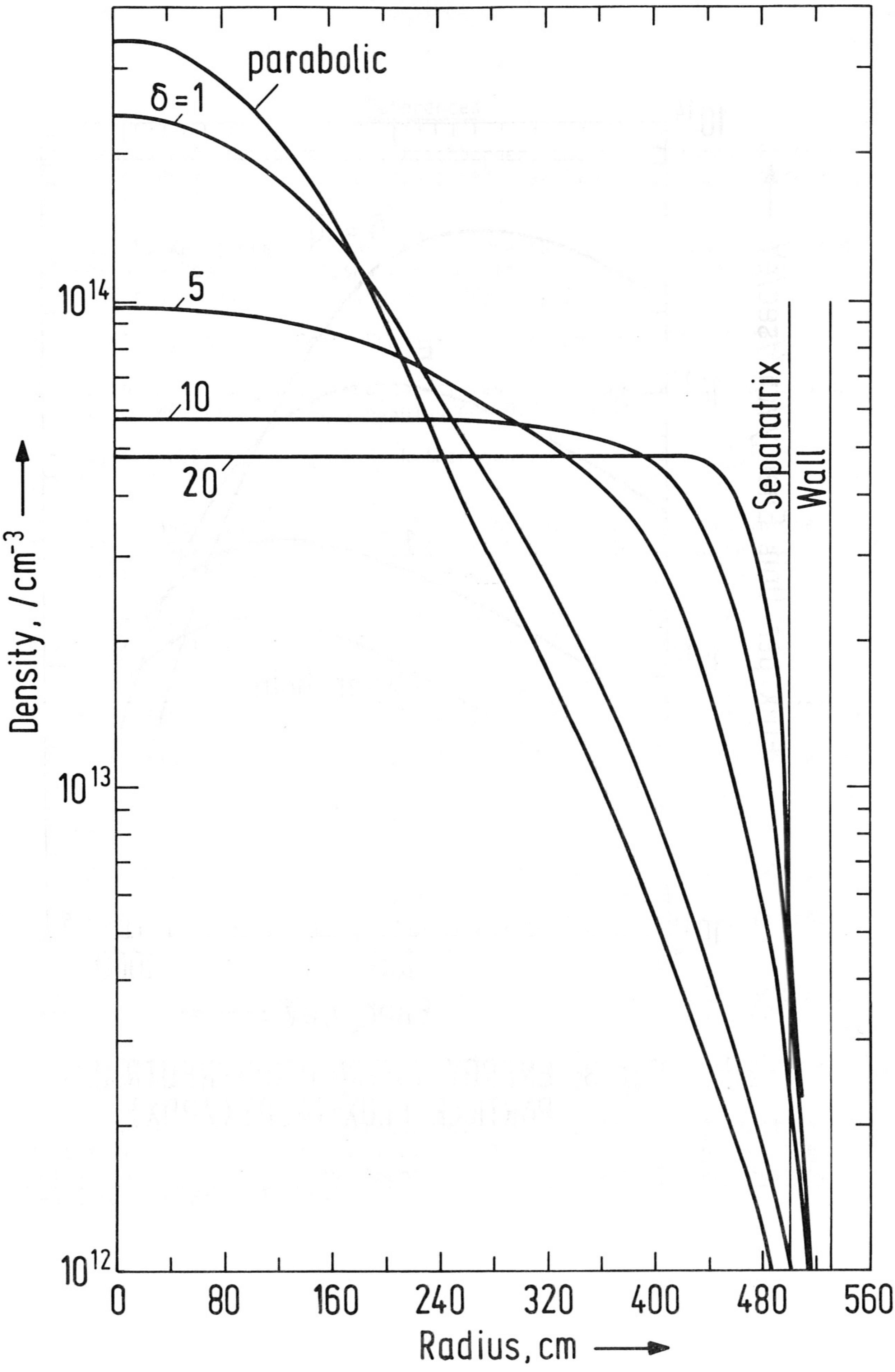

Fig. 4 DENSITY PROFILE (REACTOR SIZE)

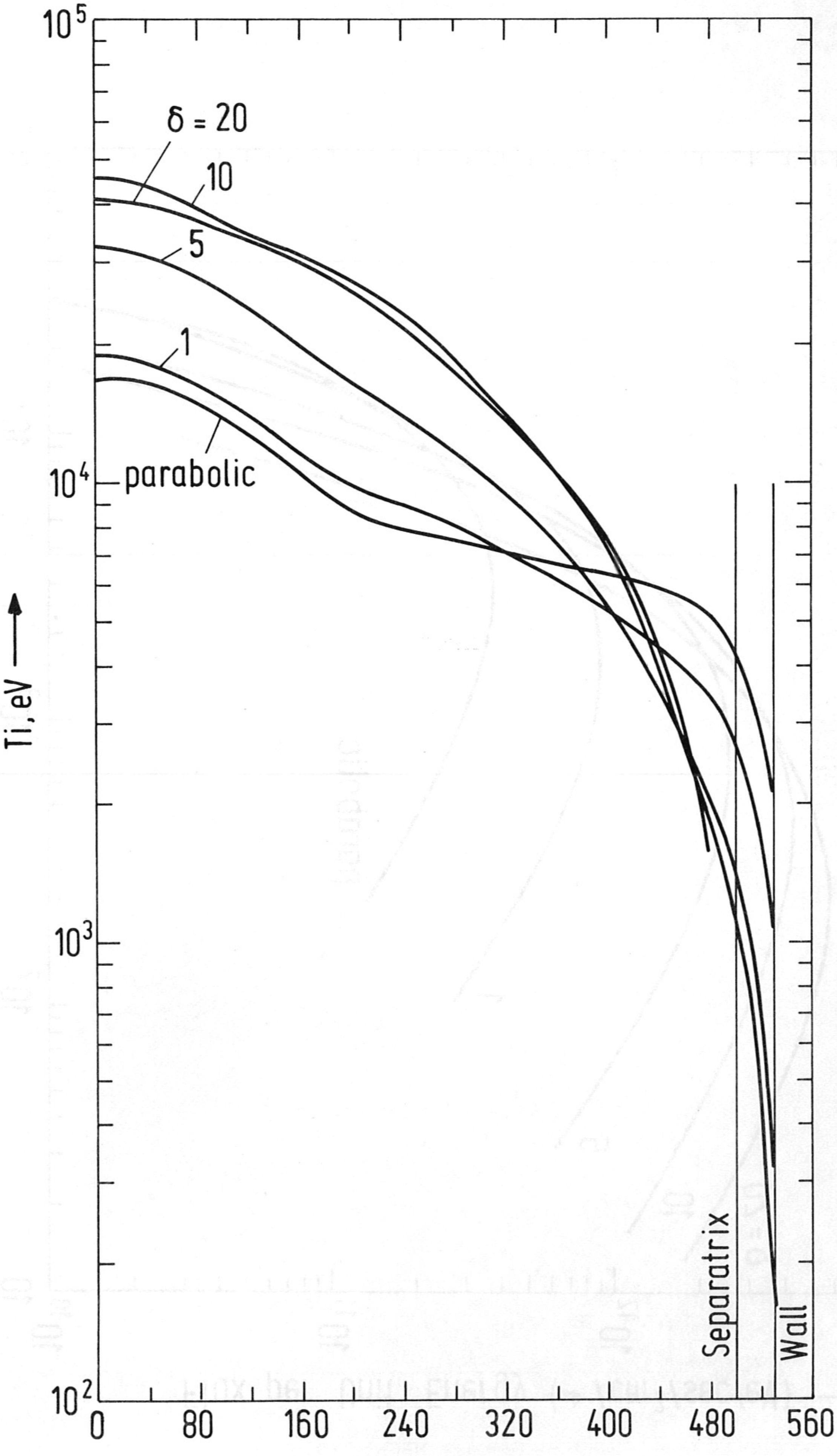

Fig. 5 ION TEMPERATURE PROFILE (REACTOR SIZE)

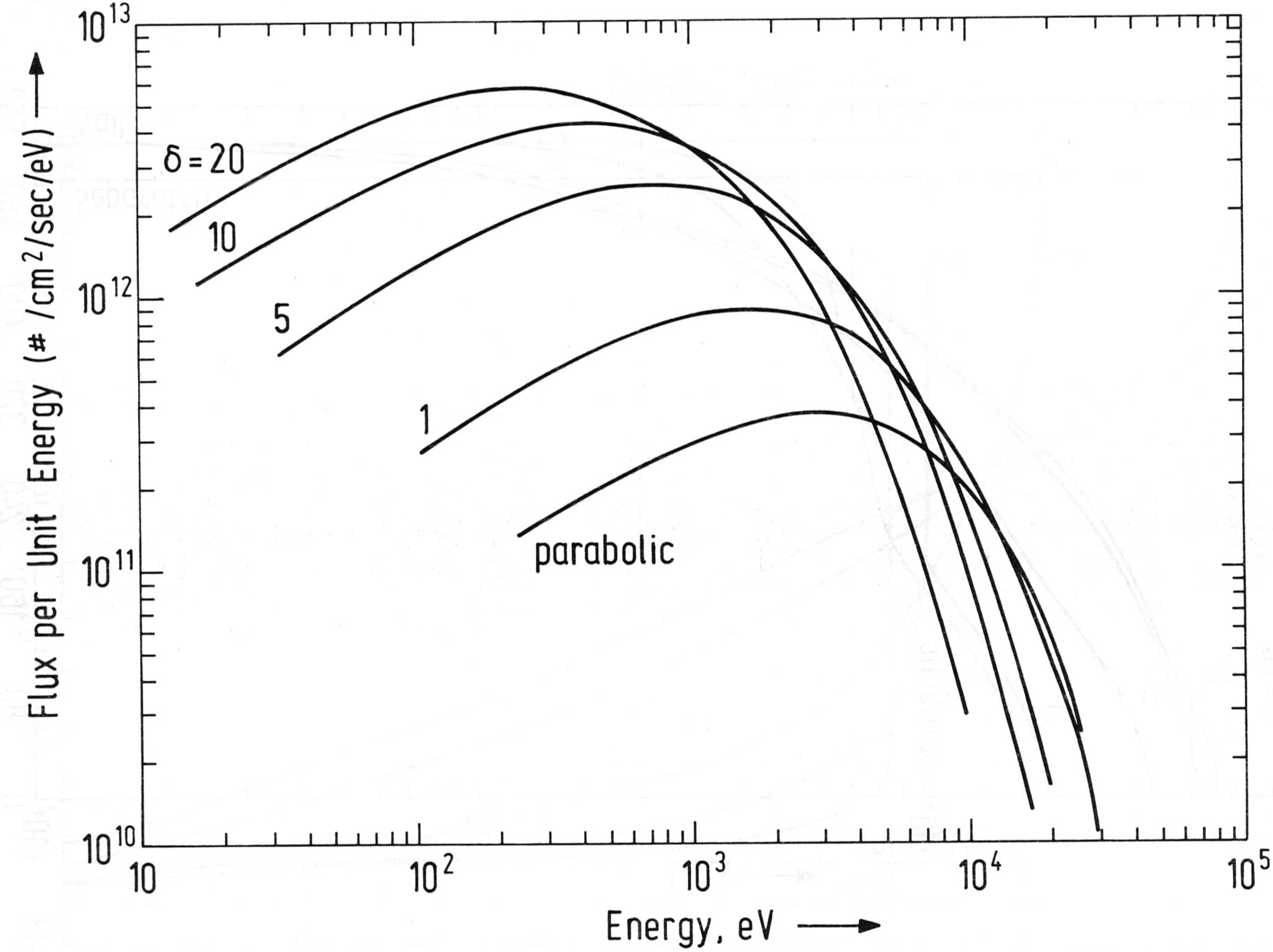

Fig. 6 ENERGY DISTRIBUTION NEUTRAL PARTICLE FLUX (REACTOR SIZE)