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Shigehisa HITOKI*, Masayoshi SUGIHARA and Shin YAMAMOTO

Department of Large Tokamak Research
Naka Fusion Research Establishment
Japan Atomic Energy Research Institute
Naka-machi, Naka-gun, Ibaraki-ken

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Geometric effects have been investigated on the cold and dense divertor plasma formation. So far, this problem has been discussed only qualitatively. Here the results of numerical calculations are presented quantitatively, with the throat length and the void width as the parameters. Such data will be useful data base for the FER engineering design.

It is concluded that the effectively closed divertor will work better than the open divertor. The closed divertor with no void width forms a cold and dense divertor plasma for a wide range of throat length.

Keywords: FER, Divertor Plasma, Effects of Geometry, Void,
Cold and Dense Plasma, Closed Divertor, Open Divertor, Throat

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* On leave from Mitzubishi Electric Corp., Marunouchi, Chiyoda-ku, Tokyo 100.

FERダイバータプラズマに対する形状効果

日本原子力研究所那珂研究所臨界プラズマ研究部
一木　繁久*・杉原　正芳・山本　新

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低温・高密度ダイバータプラズマ形成に対する幾何形状効果を調べた。この問題は，従来定性的にのみ論じられている。ここでは，数値解析の結果がダイバータのスロート長とボイド巾によって定量的に整理された。こうしたデータは，今後のFER工学設計への有用なベースとなる。

実効的に閉形状のダイバータは，開形状のダイバータよりも定量的によく機能する。ボイドの巾を完全にゼロにすると，低温・高密度のダイバータプラズマが常に形成される。

那珂研究所：〒311-02　茨城県那珂郡那珂町大字向山801-1
＊外来研究員：三菱電機株式会社

CONTENTS

目　次

1. Introduction

Impurity control is one of key problems for the design of the fusion experimental reactor, such as FER in JAERI. Single-null poloidal divertor is employed for a means of impurity control in FER design. Because the cold and dense divertor plasma can be expected to be realized that was observed experimentally in Doublet-III(1),(2), ASDEX(3) and so on. It will reduce the erosion of the neutralizer plate. It is an important problem for the design study of FER whether such a plasma formation can be realized or not.

A qualitative answer to this problem has been given in the previous paper(4), where the dependences on the incoming ion flux and heat flux, and the geometry were investigated. However only a few quantitative discussions were given about the geometric effect. It was shown there that the equilibrium solution for the divertor plasma can have a triple-valued in some range of the incoming ion flux under the condition of fixed incoming heat flux, and that the comparatively large incoming ion flux is needed to realize the high density and low temperature divertor plasma in the case of open divertor. We prefer to the opener divertor structure because of the engineering simplicity. The range of incoming ion flux with which the triple-valued solution occurs was reduced to the narrower range when the divertor geometry was closed. Then it is our primary concern how this solution change in the limiting case where the geometry becomes an extremely closed one. It is one of our purposes of this paper. Second purpose is to obtain more quantitative data set for us to use in the engineering design. There may be some gap between the physical design and the engineering design, where several-centimeters accuracy is required in the latter one. This fact suggests that we need some medium data set to connect with each other.

In modelling the divertor plasma, one fluid momentum equation has been used. It has been suggested that there are some differences between the behaviours of the fuel particles and the fusion produced He particles. It is well known that the neutral particles are largely influenced by the geometry. There might be some correlation between this difference and the geometry. Hence the recycling probability is evaluated for DT and He ions as the functions of the throat length and the void width. Furthermore the range of incoming ion flux for which the triple-valued equilibrium solution occurs is also evaluated as the functions of the throat length and the void width. The model of overall structure is the same as that used in the previous paper(4).

2. Numerical model

Particle, momentum and energy conservation equations are used to calculate the divertor plasma parameters. Three particle conservation equations are solved for D, T and He species. One fluid momentum equation is solved for the plasma with the average mass. Electron and ion energy equations are solved respectively. Sheath electric field is implicitly included through the pressure gradient term in the energy equations. The total incoming ion flux and heat flux, and their profiles are assumed at the throat entrance. Two dimensional plasma density and temperature profiles are outputs of our code parallel and/or perpendicular to the magnetic field projected on the poloidal cross section.(4)

Particle, momentum and energy source terms which treat the ionization and the charge-exchange reactions of neutral particles are obtained from the neutral Mente-Carlo code DICON.(5),(6) Electron-ion collisions and the radiation loss from recycling hydrogen neutrals are taken into account. Diffusion coefficient and the thermal conductivity perpendicular to the magnetic field are neglected, because it is confirmed that they have little effects on the one-dimensional plasma parameters that is averaged over the perpendicular direction to the magnetic field with the diffusion and the thermal conductivity $D_\perp$, $\chi_\perp \lesssim 10^4$ cm^2/sec. The ratio of the poloidal magnetic field to the toroidal magnetic field is selected to $B_p/B_T = 0.1$. Exponential functions for particle and heat flux profiles are selected across the magnetic field at the throat entrance both with 7 cm e-folding lengths.

3. Results of numerical calculations

Cold and dense divertor plasma is formed by the strong recycling of neutral particles near the divertor plate, where neutrals emitted from the plate due to the backscattering and the desorption processes are reionized. Thus, it depends on the recycling probability near the plate whether such a cold and dense plasma can be realized or not. The recycling probability is defined as

$$P_{recyc} \equiv \frac{R - 1}{R} \quad , \tag{1}$$

where R is the flux amplification factor of ions between the entrance and the target in the divertor chamber. The results are shown for the cases (A), (B), (S), (C), (D) and (E) as functions of incoming ion flux in Fig. 2 (a), (b), (s), (c), (d) and (e), where we refer the structure of the case (S) as the standard geometry. In the standard case, the throat length is determined by the fact that it is nearly equal to twice value of the mean free path of He particle for electron impact ionization when the electron temperature is 100 eV and the electron density 10^{13} cm^{-3}. The width of divertor plasma is determined by a simple estimation on the width of scrape-off plasma$^{(5)}$.

Dependences of P_{recyc} on the throat length and void width are shown in Figs. 3(a) and (b) when the incoming ion flux is 3×10^{22} s^{-1}. High recycling probabilities of DT can be realized for a wide range of throat length and void width. Recycling probability of He becomes small when the throat length is short and/or the void width is broad. We define the void as the vacuum region without any plasma, although it is not a practical one. When we make a wide range of parameter survey, some inadequate parameters (for example, the plasma density $\simeq 10^{19}$ m^{-3} and the plasma temperature $\simeq$ 20 eV) might be included in modeling the void region. However such a defect of our code does not change the resultant physics. To clarify the characteristics of the void, the total mean free path at the plasma edge as well as on the separatrix line is shown as a function of the coordinate along the magnetic field for the case (S) in Figs. 4 (a) and (b). The mean free path of D neutrals is remarkably short, so that they will be reionized whichever direction they start to fly as shown in Fig. 4 (a). Neutral particles escape into the broad vacuum region more easily in the open geometry than in the closed geometry. This probability also has an effect on the determination of the required pumping speed because the pumping speed is strongly influenced by the pressure of neutral particles. In the closed geometries, (A), (B), and (S), little differences between the behaviours of the fuel ions and He ions can be seen as shown in Fig. 2 (a), (b) and (s).

In the open goemetries (C), (D) and (E), on the other hand, the recycling probability of fuel neutrals is much larger than that of He neutrals as shown in Figs. 2 (c), (d) and (e). Here we notice the behaviours of neutral particles to understand the above difference. There are two typical flight pathes for neutrals. The first is the backflow path to the main plasma along the magnetic field or through the void region. The second is the escaping path into the exhaust duct across the magnetic field. Now we will discuss the first path, for an example, for the case (S).

The difference of the recycling probability between fuel ions and He ions should be important (because, for example, the recycling probabilities 0.95 and 0.98 correspond to the flux amplification factors 20 and 50 respectively). This suggests that the flux amplification of He particles is different from that of fuel particles by a factor of 2.5 at the neutralizer plate. The reason is considered as that the ionization mean free path for He neutrals is longer than that for DT neutrals in the range of temperature from 5 eV to 30 eV(7). Hence the effective length along the magnetic field during which the recycling neutrals are trapped is longer for He neutrals than for DT neutrals. This relation does not change when we take into account the charge-exchange reactions.

Next we will discuss the second path for the same case (S). Neutral particles start to fly from the separatrix line, go across the magnetic field and approach to the exhaust duct. The characteristic length of plasma region perpendicular to the magnetic field is 12 cm. The mean free path of D particles is less than 1 cm near the plate, whereas that of He particles is 8 cm. Thus, He neutrals are apt to escape through the exhaust duct more freely compared with D neutrals. In fact, the ratio of He neutral density to the total neutral density at the duct entrance, becomes nearly 6.5% in this case. The back flow flux for He to the main plasma is 9.1×10^{15} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ and the exhausted flux to the pump is 3.5×10^{16} $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$ for the pumping speed of 2.5×10^{5} ℓ/s.

In the case of the open divertors, the neutrals are apt to escape into the main plasma. Because the void width is broader in the case (C), the throat length is shorter in the case (D) and the geometry is the openest in the case (E), than in the case (S). Hence high concentration of the fuel particles at the plate does not necessarily mean that the fraction of the pumped fuel neutrals is larger than that of He particles, because the geometrical characteristic lengths change. The answer to this problem will be given by more detailed investigation in future.

The fact that the plasma density and temperature near the plate depend strongly on the incoming ion flux is shown for the geometries (A), (B), (C) and (D) in Figs. 5 (a), (b), (c) and (d). As the flux increases, the density increases and the temperature decreases. The double-valued solution$^{(4)}$ appears in the intermediate region of the incoming ion flux, which includes cold and dense solution, and high temperature and low density solution. Only the cold and dense solution remain with further increasing incoming ion flux. Here we arrange the results as functions of throat length and void width with the heat flux fixed 24 MW. The range of the incoming ion flux for which the double-valued solution appears is shown in Figs. 6 (a) and (b). It is observed that the double-valued solution disappears completely when the void width becomes extremely narrow. Two backflow pathes of neutrals exist when the void region is broad; that is, the scrape-off layer and the void region itself. The void region cannot work as the backflow path when we close it. This is the reason why the double-valued solution disappears. Detail physical interpretation is given in the previous paper$^{(4)}$.

4. Summary

We have investigated the geometrical effects on the cold and dense divertor plasma formation. We summarize as follows:

(1) The difference between recycling probabilities of fuel DT particles and He particles becomes $P_{DT}/P_{He}=1.03$, which corresponds to the difference between the flux amplification factors $R_{DT}/R_{He}=2.5$, in the open geometry, under the condition of our calculation. This suggests that we must divide the momentum conservation equation for DT and He.

(2) Our previous paper has indicated qualitatively that the range of the incoming ion flux for the double-valued equilibrium solution to appear is broader in the open geometry (short divertor throat and/or broad void). Quantitative data are obtained here about how to be influenced by the geometry. Double-valued solution disappear when the void width becomes extremely narrow.

In concluding remarks, we will have to consider how to control to close the effective geometry. One simple way is using a movable buffer to prevent the backflow of neutral particles.

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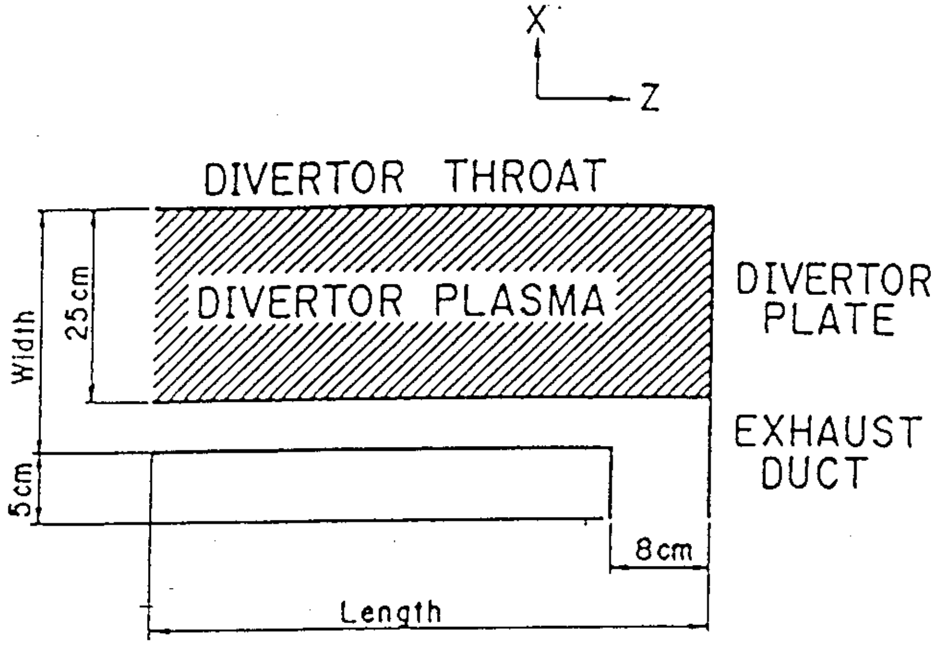


Case	Length (cm)	Width (cm)
A	50	25
B	75	30
S (standard)	50	30
C	50	50
D	25	30
E	25	50

closed ↑ ↓ open

Fig. 1 : Various geometrical configurations to investigate the divertor peformance.

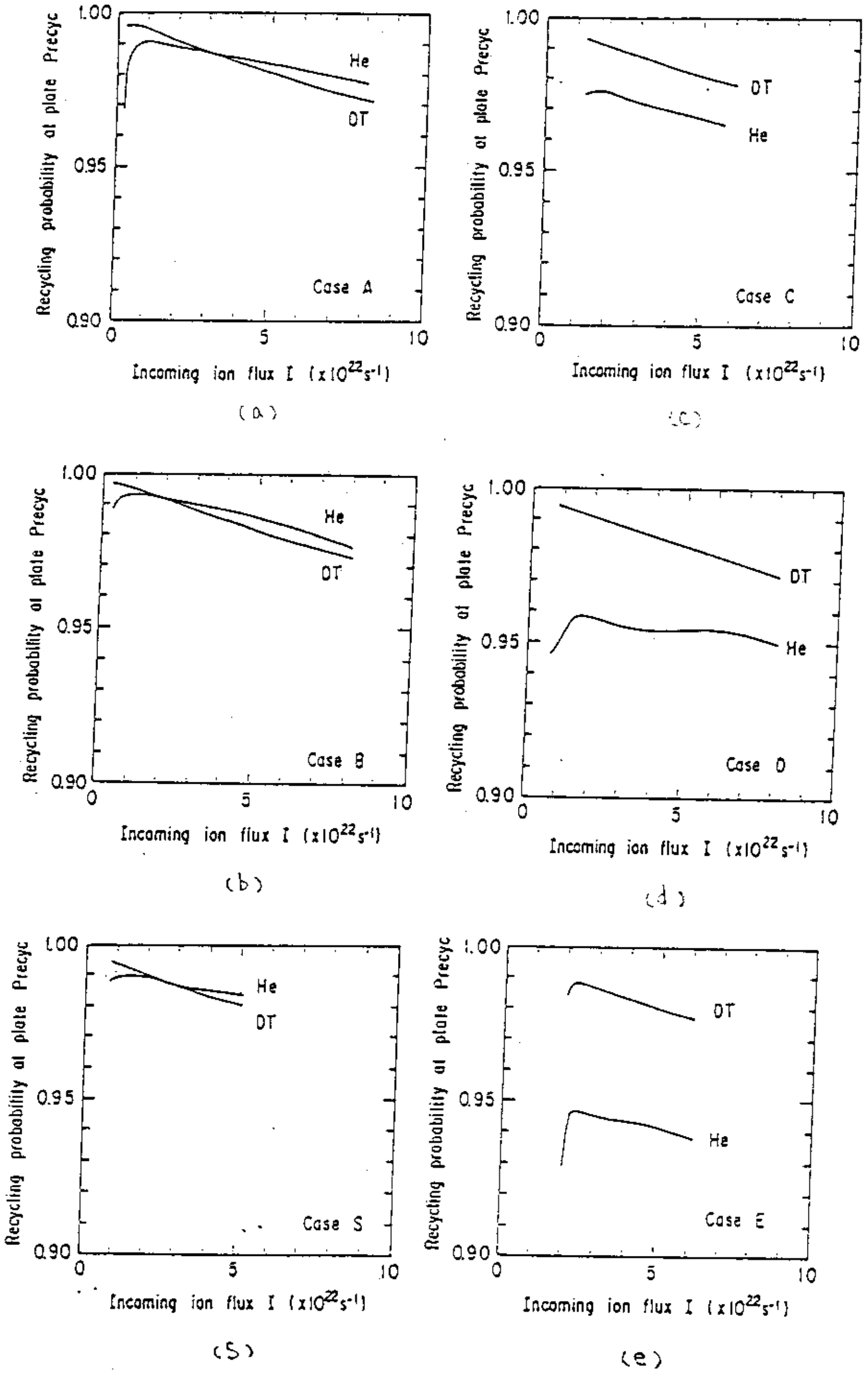


Fig. 2 : Recycling probability at plate, P_{recyc}, is shown as a function of incoming ion flux for the cases (A)-(E).

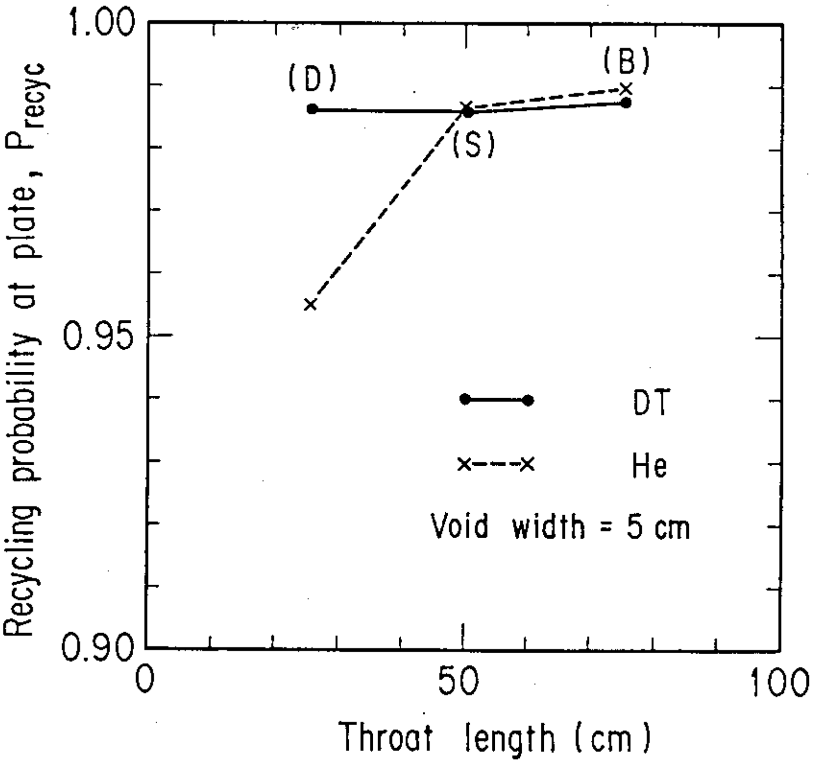
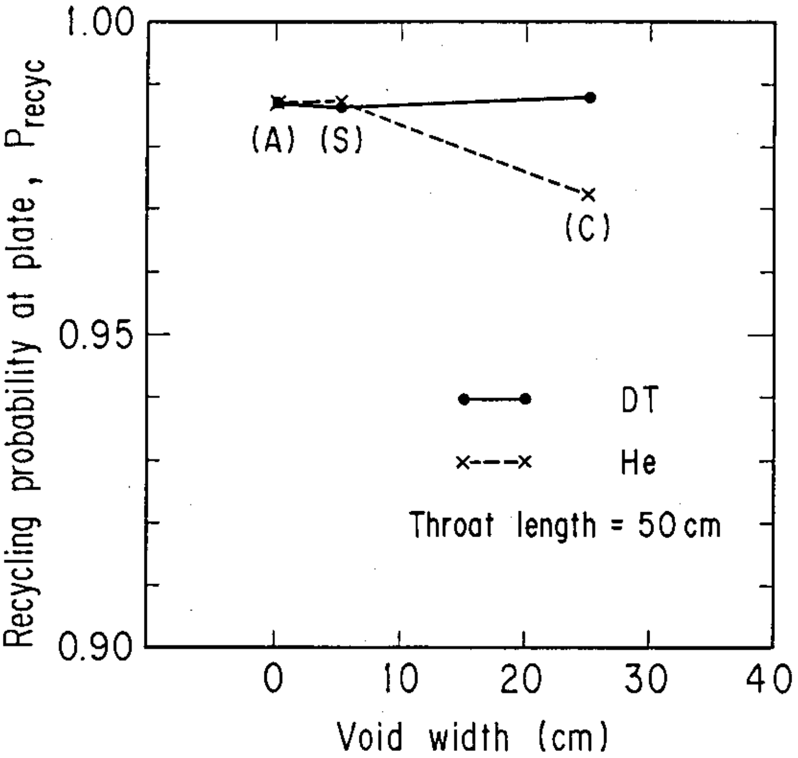


Fig. 3(a): Recycling probability at plate, P_{recyc}, is shown as a function of throat length. Incoming ion and heat fluxes are 3.0×10^{22} s^{-1} and 24 MW.



(b): Recycling probability at plate, P_{recyc}, is shown as a function of void width. Incoming ion and heat fluxes are 3.0×10^{22} s^{-1}, and 24 MW.

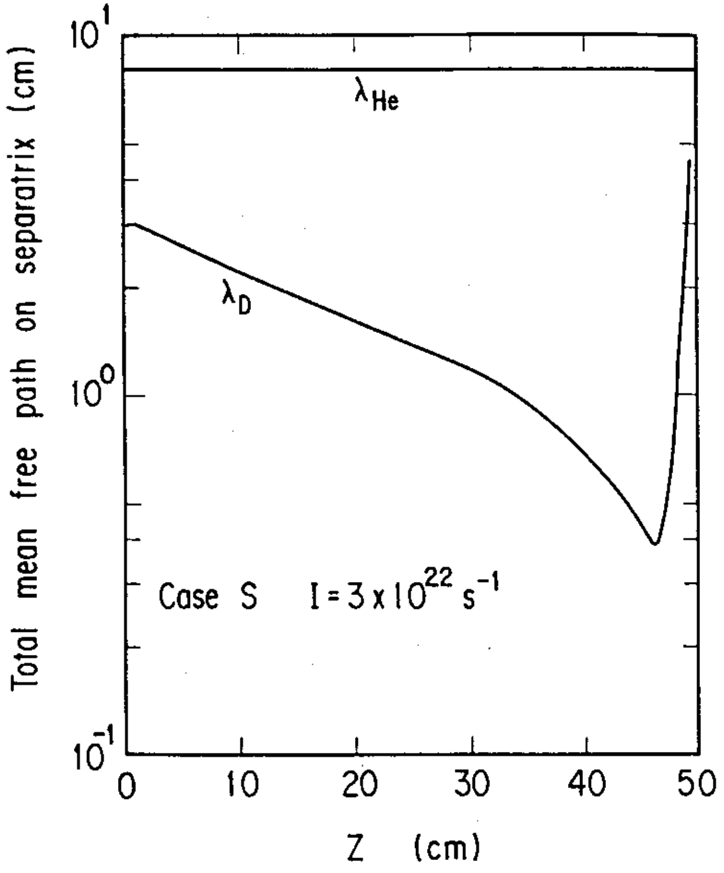
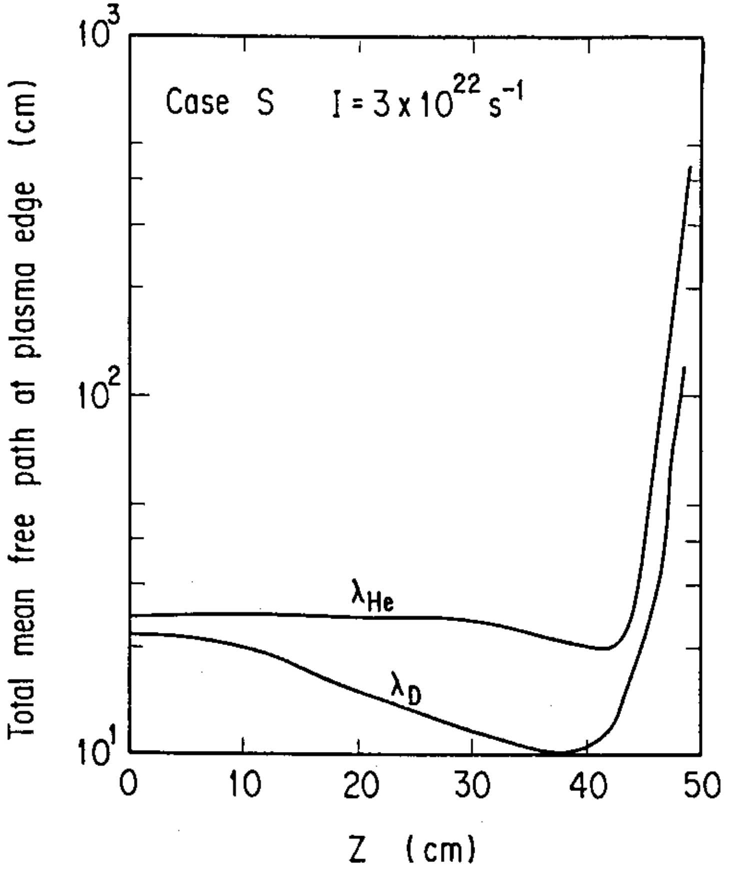


Fig. 4(a): Total mean free pathes of He and D neutrals on the separatrix line are shown as a function of Z.



(b): Total mean free pathes of He and D neutrals at the plasma edge are shown as a function of Z.

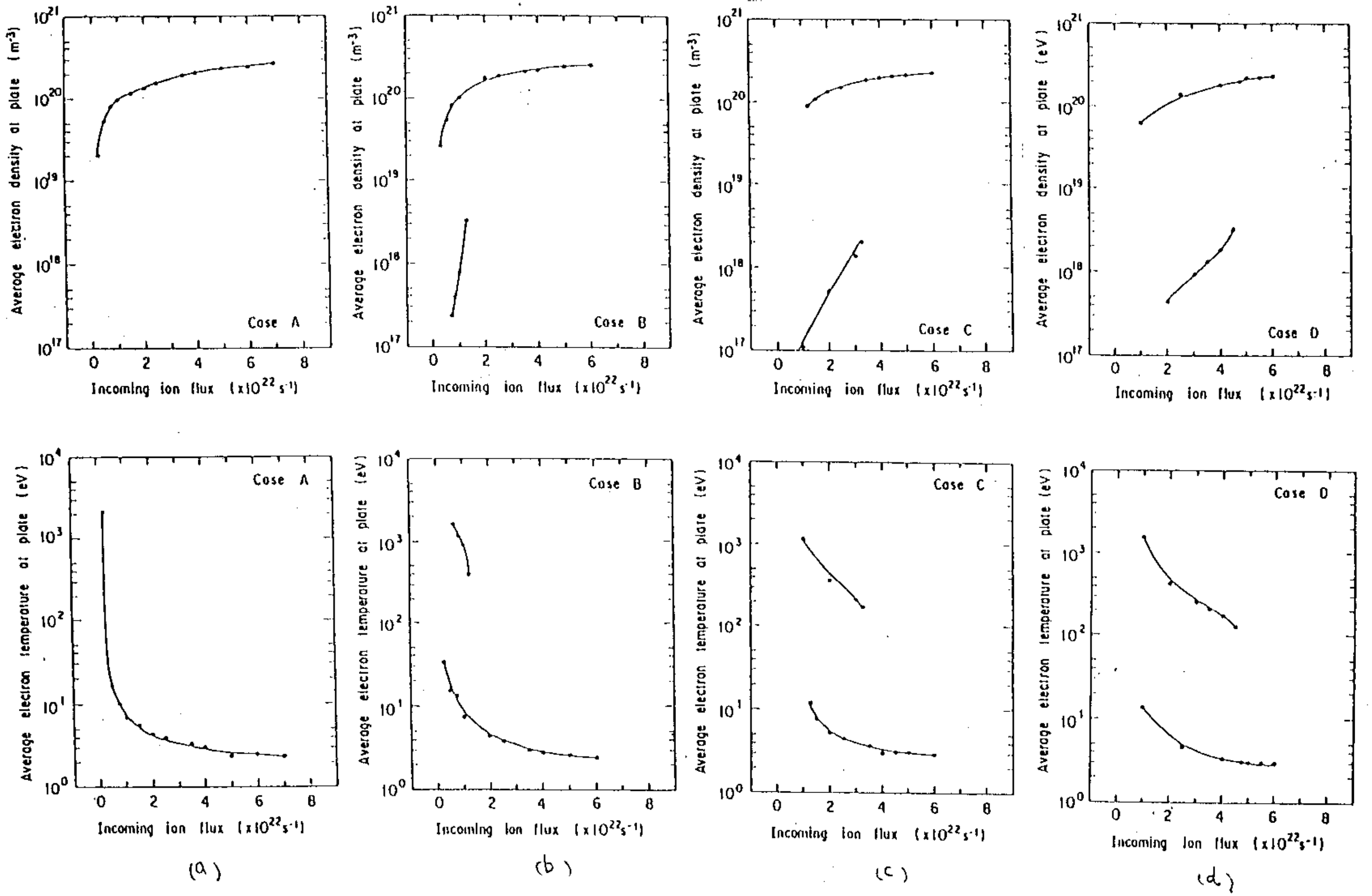


Fig. 5 : Average electron density and temperature at plate are shown as a function of incoming ion flux for the cases (A), (B), (C) and (D). Heat flux is 24 MW.

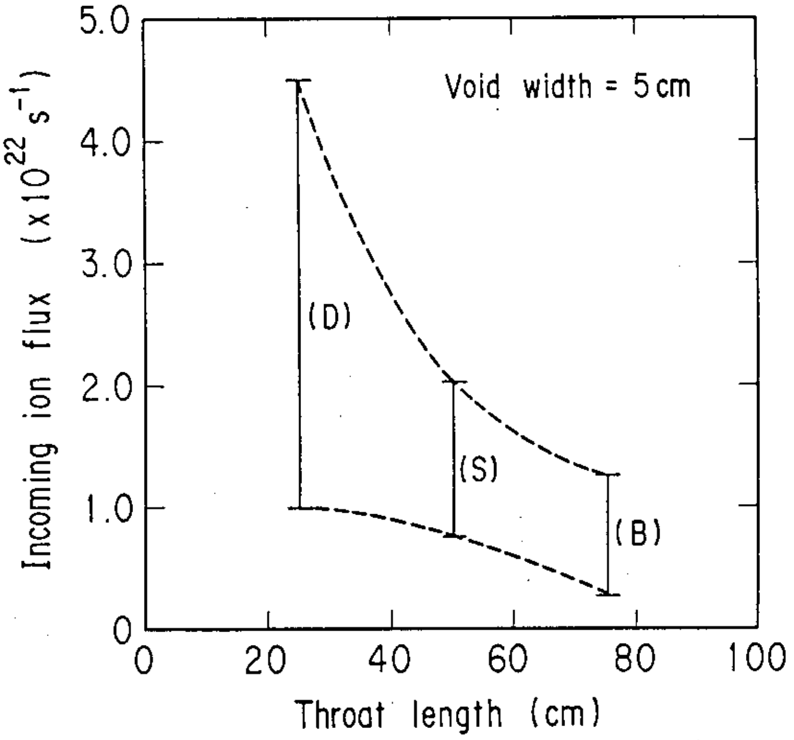
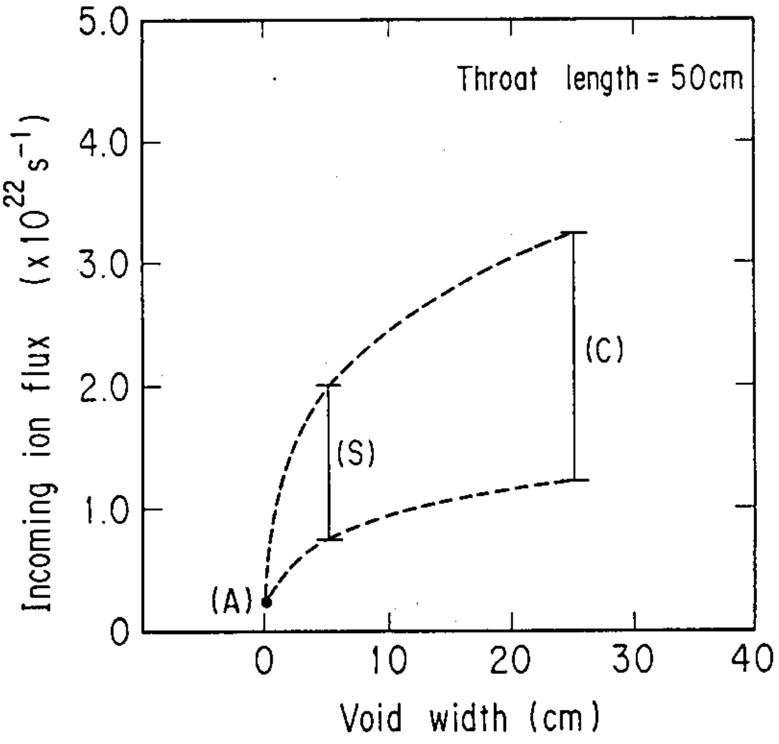


Fig. 6(a): The range of incoming ion flux that the double-volued solution appears is shown as a function of throat length. Heat flux is 24 MW.



(b): The range of incoming ion flux that the double-valued solution appears is shown as a function of void width. Heat flux is 24 MW.