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TWO-CHAMBER MODEL FOR DIVERTORS WITH PLASMA RECYCLING

By

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TWO-CHAMBER MODEL FOR DIVERTORS WITH PLASMA RECYCLING

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ABSTRACT

To model particle and heat loss terms at the edge of a tokamak with a divertor or pumped limiter, a simple two-chamber formulation of the scrapeoff has been constructed by integrating the fluid equations, including sources, along open field lines. The model is then solved for a wide range of density and temperature conditions in the scrapeoff, using geometrical parameters typical of the PDX poloidal divertor. The solutions characterize four divertor operating conditions for beam-heated plasmas: plugged, unplugged, blowthrough, and blowback.

I. INTRODUCTION

Plasma transport models of radial flow in tokamaks with a divertor or pumped limiter must include particle and heat loss terms due to flow along magnetic field lines in the scrapeoff. The plasma entering the scrapeoff flows along open field lines until it reaches the neutralizer plate. The resulting neutral gas interacts with the incoming plasma and modifies its properties and flow. The greatest effect occurs when there is a large recycling of the neutral gas. This happens when the neutrals are ionized by the plasma near the neutralizer and are swept back to the neutralizer with the cycle repeated a number of times. This enhancement of the plasma flow near the neutralizing surface serves to amplify the particle flux, and reduce the temperature, thereby minimizing erosion. The amplification of particle flux due to recycling also reduces the upstream plasma flow velocity along the field lines in the scrapeoff, thus changing the edge density of the main plasma region.

The plasma flow in divertors has been modeled as a fluid with one- and two-dimensional codes [1] incorporating numerical models of the neutral transport, such as Monte Carlo treatments [2]. These treatments require significant amounts of computer time and are useful only for studying specific examples of divertors and/or the scrape-off regime. They are impractical as models for edge loss in the scrapeoff for the large codes used to model the radial flow in plasma transport. Instead simpler models of the scrapeoff must be used that do not require excessive amounts of computer time. We have developed a simple two-chamber model to explore the effects of recycling on both the characteristics of the high recycling regions and the main plasma radial transport in the scrapeoff. In this paper, we describe the model and provide solutions for the scrape-off region as a stand-alone calculation. The radial transport modeling using the BALDUR code is described in another paper [3]. Related two-chamber models have been developed by other authors [4], but generally employ more complicated treatments of the neutral transport. These models also use too much computer time to be practical for the radial transport models.

II. THE TWO-CHAMBER MODEL

To solve for the flow of material entering the scrapeoff into a high-recycling region, we ignore all radial flows in the scrapeoff and consider only parallel flow along the field lines. The fluid equations, including sources, have been derived in arbitrary coordinates by Singer and Langer [5], who also evaluated the most important transport terms in a collision dominated plasma. The radial and poloidal transport can be neglected in calculating the flow to the divertor when cross-field transport near the midplane gives broad profiles of density and temperature. Assuming a constant ratio of poloidal to total magnetic field, B_θ/B, the fluid equations for the flows of ions, total momentum, and total energy can be written:

$$\frac{d}{ds}\,(nu) = S \,, \tag{1}$$

$$\frac{d}{ds}\left(mnu^2 + p\right) = 0 \,, \tag{2}$$

$$\frac{d}{ds}\left[q^e + \left(5\ nT + \frac{1}{2}\,mu^2\right)\,u\right] = W \,, \tag{3}$$

where

u = fluid velocity ,

m = ion mass ,

$T = \frac{1}{2}\left(T_e + T_i\right)$,

S = ion source due to ionization of neutrals ,

W = energy source,

and s is the distance along a magnetic field line. Neglected are viscosity terms, electron momentum, and neutral friction on the ions. Integrating these equations from the entrance of the scrapeoff to the recycling channel (see Fig. 1), subscript 1, to the material boundary, subscript 2, yields

$$\Gamma_2 - \Gamma_1 = \int_1^2 S ds \ , \tag{4}$$

$$\left(mu_2^2 + 2\ T_2\right) n_2 = \left(mu_1^2 + 2\ T_1\right) n_1 \ , \tag{5}$$

$$Q_2 - \left(5\ T_1 \Gamma_1 + q_1^e\right) = \int W ds = \Delta E \int S ds \ , \tag{6}$$

where $\Gamma = nu$ is the particle flux, $Q_2 = 2\ (\gamma_i + \gamma_e)\ \Gamma_2 T_2$ is the energy flux assumed to flow through the plasma sheath, with $\gamma_i = 1$ and $\gamma_e = 2.9$ in the absence of secondary electron emission, and ΔE is a constant energy loss per ionization.

To solve these equations, we divide the region with open field lines into two chambers: the scrape-off regime and the divertor or high recycling regime. This geometry is sketched in Fig. 1, where the length of the scrapeoff is given by the distance along the field line from the separatrix, $L_1 = \pi qR$, where q is the safety factor and R is the major radius of the tokamak torus.

To close this set of equations, we need a model for the neutral transport. Adopting the approach of Post, Langer, and Petravic [6], we write

$$\frac{d(n_o u_o)}{ds} = -S = -nv_o \langle \sigma v \rangle_{ion} ,$$

and, providing that v_o is a constant, find

$$\int S ds = \Gamma_2 (1 - f_{pump}) [1 - \exp(-\lambda_2/L_2)] . \tag{7}$$

Here it is assumed that a fraction $(1 - f_{pump})$ of the ions striking the material boundary are returned to the recycling channel, and the rest are pumped away. The effective length of the recycling channel is L_2, the mean-free path for ionization by electrons, $\lambda_2 = |v_o|/(n_2 \langle \sigma v \rangle_{ion})$, and $v_o = (2E_o/m_o)^{1/2}$ is the velocity of the neutrals. In this model, a fraction $\exp(-\lambda_2/L_2)$ of the neutrals penetrate through the recycling channel to the main plasma chamber (scrapeoff), and the remaining fraction $[1 - \exp(-\lambda_2/L_2)]$ are ionized in the recycling channel.

Finally, the heat flux q_1^e can be approximated by the flux limited parallel conduction formula,

$$q_1^e = \min[\alpha_L n_e v_{th,e} (T_1 - T_2), \ \kappa_\parallel^e \ (T_1 - T_2)/L_1] ,$$

where $v_{th,e} = (2 \ T_e/m_e)^{1/2}$ is the electron thermal velocity and $\kappa_\parallel^e \ (Z_{eff}, T_b)$ is the parallel thermal conduction coefficient [7] evaluated at the boundarycentered temperature $T_b = (T_1 + T_2)/2$. Here $v_{th,e} = (2\ T_1/m_e)^{1/2}$ for the usual flux-limited theories [8,9] and $v_{th,e} = (2\ T_2/m_e)^{1/2}$ with a thermal barrier [10].

In the model calculations described below, we adopt $\alpha_L = 0.1$ [6], $\langle\sigma v\rangle_{ion}$ is taken from Freeman and Jones [11], and $E_o = 3$ eV is characteristic of the energies for atomic hydrogen produced from the dissociation of H_2. If H^o is produced by charge exchange, then 10 eV would be a more realistic energy (higher energies may be present if the hydrogen is produced by wall reflection [12]).

III. RESULTS

To explore the predictions of the two-chamber model, the approximate fluid equations were solved for physical parameters representative of PDX diverted plasmas: $L_1 = 940$ cm and $L_2 = 25$ cm. The flow at the plate is assumed to be sonic (Mach number, $M = 1$) and the energy loss $\Delta E = 40$ eV. While this model is necessarily simple, it contains the basic contributions of importance for parallel flow in the scrape-off divertor region and should reproduce their qualitative features. The input parameters are the density and temperature in the scrapeoff (n_1, T_1) and the pumping fraction in the divertor (f_{pump}). The density and temperature in the divertor (n_2, T_2) and fluid velocity in the scrapeoff (u_1) are determined from Eqs. (4) to (7). From these the fluxes Γ_1 and Γ_2, Mach number M_1, and recycling, $R = \Gamma_2/\Gamma_1$, can be calculated.

The midplane Mach number in Fig. 2 is shown as a function of midplane scrape-off density for a range of pumping fractions. The temperature in the scrapeoff is fixed at 95 eV. The decrease in M_1 with increasing density is a consequence of the increased recycling in the divertor. The recycling is large if the ionization opacity for the neutrals in the divertor is much greater than one. The effect of increasing the pumping is to make it more difficult to sustain high recycling because the source of returning neutrals in the divertor is decreased.

The temperature behavior in the divertor is important for understanding divertor operation and for comparison with experiments. Correspondingly, the midplane Mach number is important for determining the loss of plasma in the scrapeoff. The divertor temperature, T_2, and midplane Mach number, M_1, are plotted in Figs. 3 and 4, respectively, as a function of midplane density for a range of midplane temperatures. (There is no pumping included in these calculations; letting f_{pump} be greater than zero would shift the inflection points to higher densities to compensate for the reduced fraction of neutrals available for recycling.)

As seen in Fig. 3, the divertor temperature decreases with increasing density n_1. The decrease is small until the opacity to neutrals, τ, is the order of one, by $\tau = 3$ a plateau is approached, and then little additional change occurs. (The lines of constant opacity are indicated by a dashed line.) For $\tau \gtrsim 3$, less than 5% of the returning neutrals reaches the upstream scrapeoff, the source function is constant, and the flow stagnates. This behavior in the flow is seen in Fig. 4. At sufficiently low scrape-off temperature ($T_1 \lesssim 30$ eV), however, the divertor temperature is too low to attain such large opacities and the flow never stagnates (though it can be small).

At sufficiently high density n_1 (depending on temperature in the scrapeoff) the divertor temperature drops, and sometimes sharply, to a very low value, ~ 3-4 eV. Further decrease is inhibited by the exponential sensitivity of $\langle\sigma v\rangle$ to temperature when T is much smaller than the ionization threshold of hydrogen. This change in temperature is associated with a change in electron thermal conductivity as the plasma goes from collisionless to collisional. The thermal conductivity of the collisional plasma is, of course, very sensitive to temperature. A corresponding change in Mach number is also observed at this boundary. The collisional and collisionless regimes are delineated in Figs. 3 and 4.

Various operating regimes for a tokamak divertor can be tentatively identified with different regions of the temperature density and Mach number density plots as indicated in Figs. 3 and 4. These are: plugged, unplugged, blowthrough, and a possible fourth regime which we call blowback.

In the unplugged regime, the temperature is nearly constant along the magnetic field. In the plugged regime, there is a significant drop in temperature going into the divertor.

The blowthrough regime is an unplugged divertor with very low upstream scrape-off temperature due to the large thermal conductivity. The divertor is transparent to neutrals and the M_1 is large, ≈ 0.5, in the scrapeoff. The term blowthrough is used because as the density is raised in a plugged scrapeoff, the temperature drops rapidly, the divertor becomes transparent to neutrals, and unplugs. The previously plugged flow goes from nearly stagnant to nearly sonic ($M \sim 0.5$), thus allowing significant flow into the divertor from the scrapeoff.

In the blowback state, the plasma neutralizes outside the divertor because the scrape-off width becomes very large. This condition is restricted to high densities and low temperature where the collisionality is large [5]. The plasma may then be blown back into the main chamber by recycling in the scrapeoff. The temperature for this operating regime cannot be too low as the divertor must remain plugged enough to prevent significant loss of plasma in the divertor.

The first three regimes correspond qualitatively with those observed on ASDEX by Shimomura et al. [13]. The blowback regime would only be distinguished using two-dimensional measurements.

IV. SUMMARY

We have presented a simplified one-dimensional model of the tokamak scrapeoff containing most of the basic physical processes important for determining particle and energy flow. The model can be used to represent edge losses into a divertor in large transport codes which model the radial profiles of tokamaks. The results of such modeling with the BALDUR transport code are discussed elsewhere [1,14].

We find that the divertor opacity to neutrals and electron collisionality determine the different operating regimes. The first condition establishes the particle recycling, while the second determines the energy transport along the open field lines. The model shows qualitatively how these physical processes determine the scrape-off conditions. It also makes it possible to model readily the dependence of the edge plasma flow and recycling on various geometrical factors, such as the fraction of gas pumped in the divertor, the length of the scrapeoff, and the length of the divertor.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

FIG. 1. Schematic representation of the two-chamber model for divertors with recycling.

FIG. 2. Midplane Mach number is plotted as a function of density for three pumping fractions.

FIG. 3. The divertor temperature is plotted as a function of density for a range of midplane temperatures with no pumping, $f_{pump} = 0.0$. Various operating regimes and plasma conditions are indicated qualitatively. The opacity of the divertor for $\tau = 1$ and 3 is indicated by the small dashed line. The boundary between a collisional and collisionless plasma is indicated by the long-shot dashed line.

FIG. 4. The midplane Mach number is plotted for the model calculations discussed in Fig. 3.

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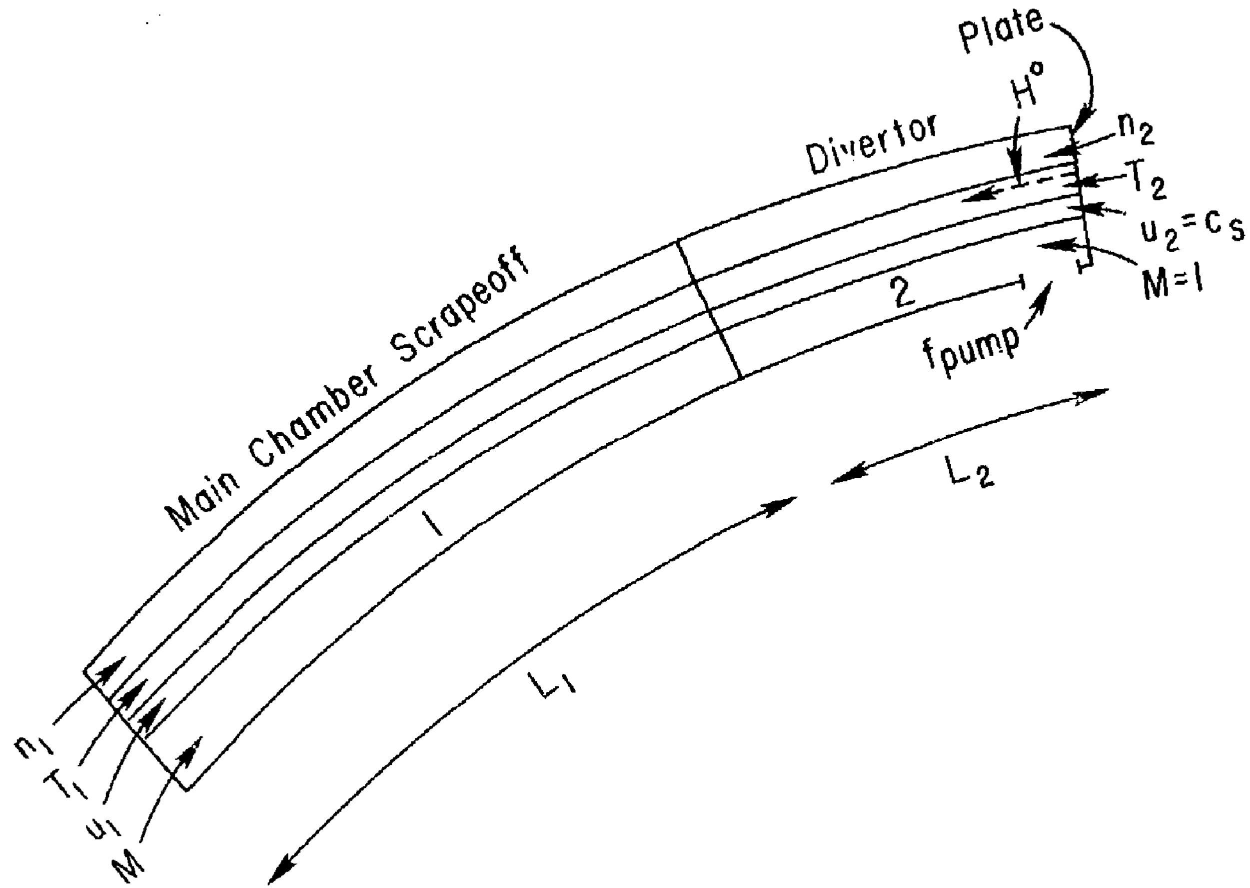

FIG. 1

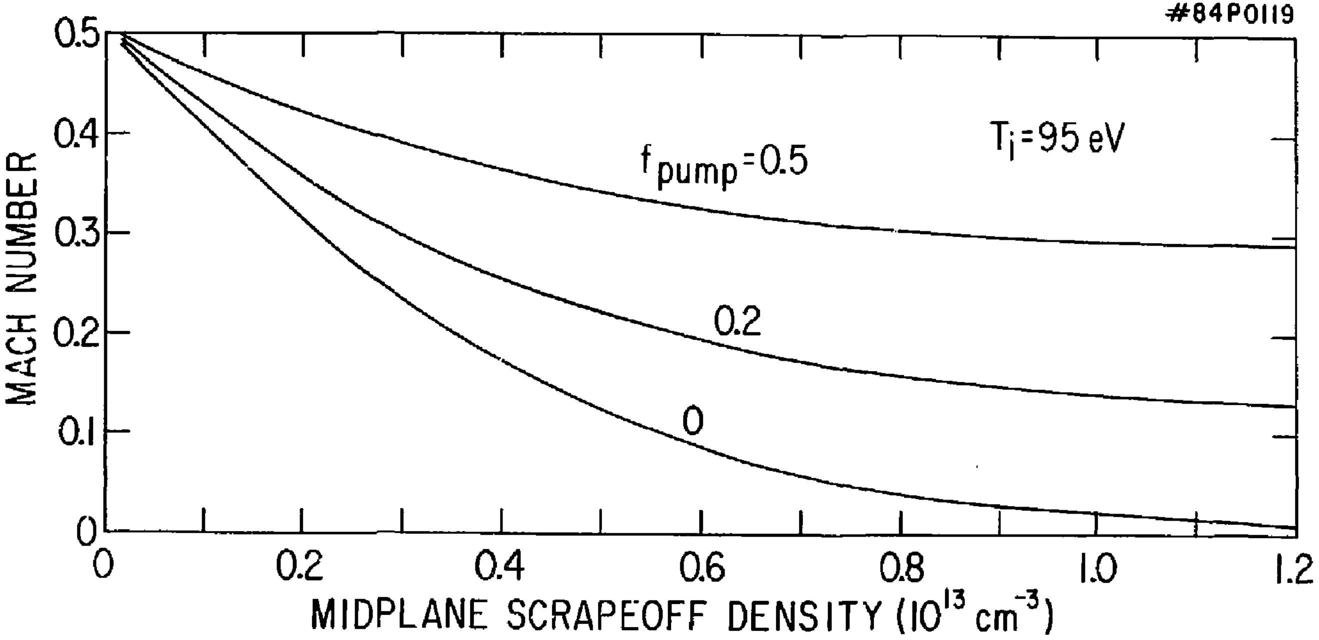
#84P0119
MACH NUMBER
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1.0
1.2
MIDPLANE SCRAPEOFF DENSITY (10^{13} cm^{-3})
T_i=95 eV
f_{pump}=0.5
0.2
0

FIG. 2

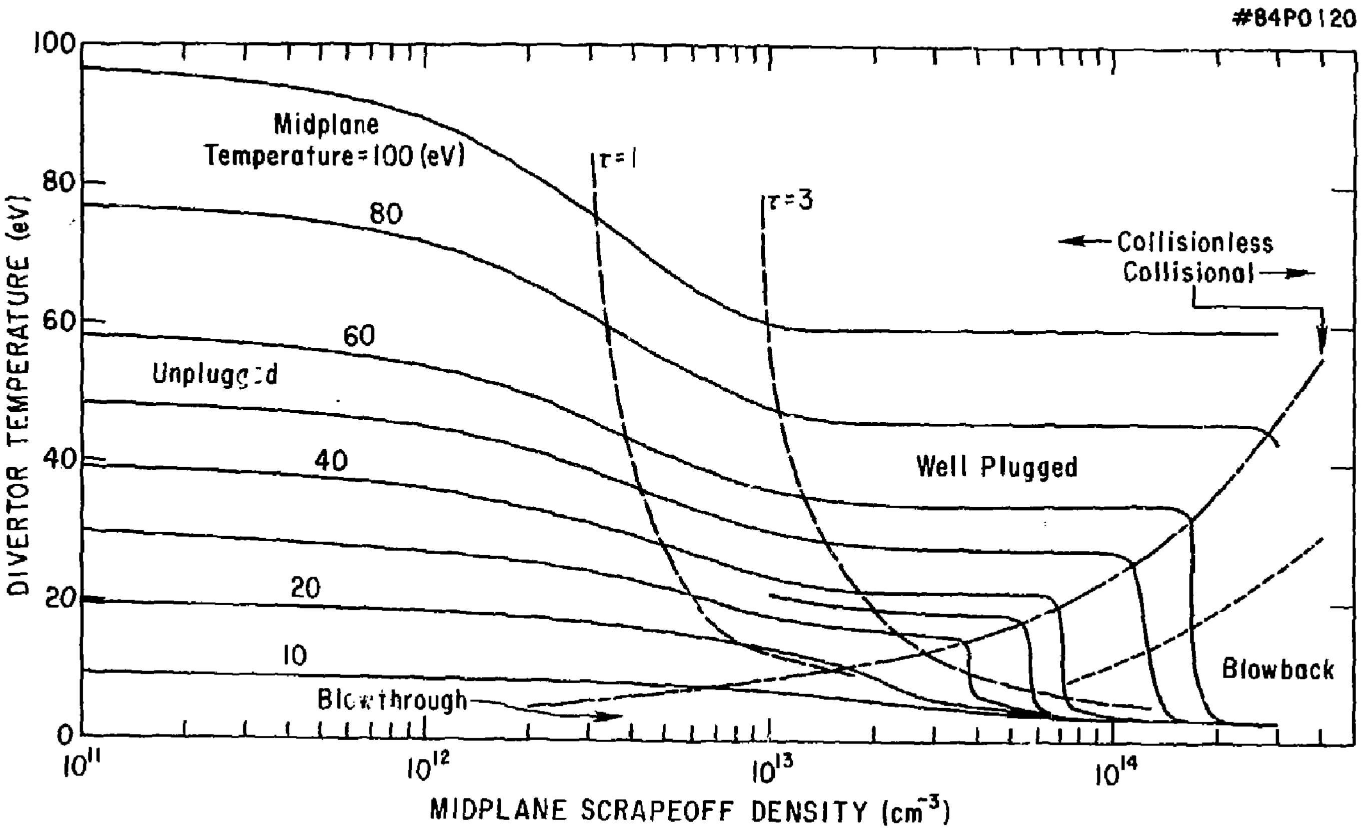
#84P0120
Midplane
Temperature = 100 (eV)
80
60
40
20
10
Unplugged
$\tau=1$
$\tau=3$
Collisionless
Collisional
Well Plugged
Blowback
Blowthrough
DIVERTOR TEMPERATURE (eV)
100
80
60
40
20
0
10^{11}
10^{12}
10^{13}
10^{14}
MIDPLANE SCRAPEOFF DENSITY (cm^{-3})

FIG. 3

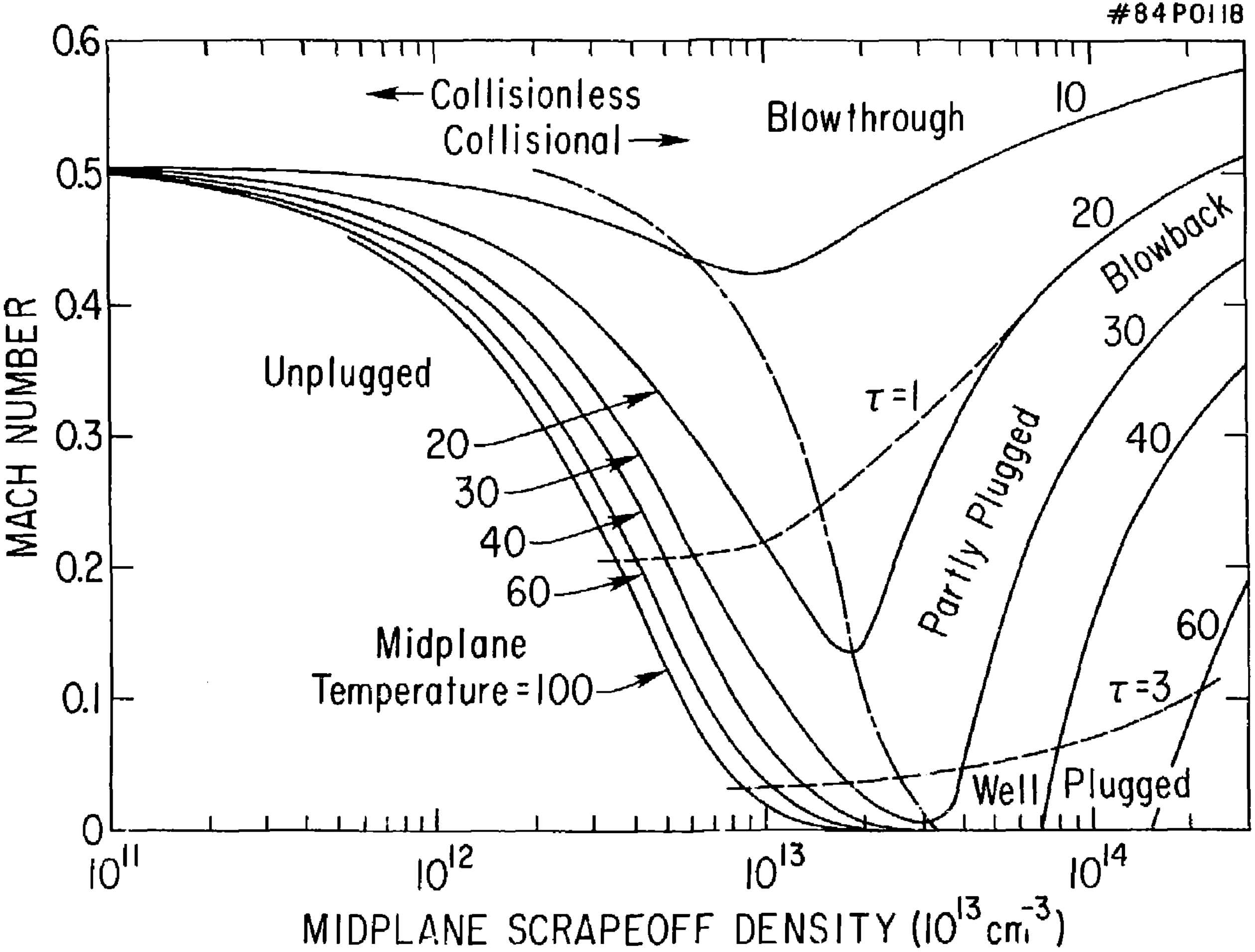
#84P0118
MACH NUMBER
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{11}
10^{12}
10^{13}
10^{14}
MIDPLANE SCRAPEOFF DENSITY (10^{13} cm^{-3})
← Collisionless
Collisional →
Blowthrough
Blowback
Unplugged
Partly Plugged
Well Plugged
τ=1
τ=3
10
20
30
40
60
Midplane
Temperature = 100

FIG. 4

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