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# Heat Flow of a Two-Electron-Temperature Plasma Through the Sheath in the Presence of Electron Emission

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## ABSTRACT

The electrostatic sheath and the heat flow of a two-electron-temperature plasma in the presence of electron emission is investigated analytically. It is shown that the energy flux is remarkably enhanced up to a value near the electron free-flow energy flux as a result of considerable reduction of the sheath potential due to electron emission if the fraction of hot electrons at the sheath edge is much smaller than one. If the hot- to cold-electron temperature is of the order of ten and the hot electron density is comparable with the cold electron density, the action of the sheath as a thermal insulator is improved as a result of suppression of electron emission due to the space-charge effect of hot electrons.

**Keywords** ; secondary electron emission, plasma sheath, heat flow, two-electron-temperature plasma, space-charge limitation

Energetic electrons have been generated in a number of experimental devices during radio-frequency heating. In tokamak experiments using ion cyclotron frequency heating, lower-hybrid wave heating, and rf current-drive, non-thermal energetic electrons appear in scrape-off layer due to strong rf fields[1,2)]. In the tandem mirror, during strong electron cyclotron resonance heating, the electron distribution composed of two Maxwellians at different temperatures is observed in the open end region in front of end plates[3)]. The appearance of energetic electrons is expected to have remarkable effects on the formation of the plasma sheath. Production of energetic electrons makes the sheath voltage large[4)], so that the ion sputtering is increased owing to the higher impact energy resulting from the large potential drop at the sheath[5)]. On the other hand, energetic electrons induce significant emission of secondary electrons, which can lead to remarkable reduction of the sheath potential and enhance the heat flow to walls[6,7)]. Thus, effects of the secondary electron emission in a plasma with energetic electrons are of interest for studying the heat flow and impurity generation. The purpose of this paper is to demonstrate effects of electrons emitted from the wall in the two-electron-temperature plasma by calculating the sheath potential and the heat flow in the presence of electron emission and by comparing results with those in the absence of electron emission.

For the purpose of this paper it is adequate to adopt a model idealized by Hobbs and Wesson[6)]. A plasma filling the half-space $x > 0$ is in contact with an infinite plane wall located at $x = 0$. The electrostatic sheath potential $\phi$, which is defined to be zero at $x = \infty$, builds up satisfying Poisson's equation. For simplicity the ions are assumed to have a monoenergetic distribution function and to arrive at the sheath edge with a particle density $n_i(\infty)$ and an incident velocity $v(\infty)$ accelerated by a presheath potential. Impact of electrons, ions, photons, metastable atoms etc. causes the emission of secondary electrons. The secondary electrons are emitted from the wall with negligible energies and then they move toward the plasma with a velocity corresponding to acceleration by a potential difference $\phi - \phi_0$, where $\phi_0 = \phi(0)$. From the fact that the total current must be zero, the emission flux can be expressed by

$$n_{e2}v_{e2} = \frac{\gamma}{1-\gamma} Z n_i(\infty) v(\infty) \ , \tag{1}$$

where

$$\gamma \equiv \frac{\gamma_e + \gamma_i/Z + J/[Zn_i(\infty)v(\infty)]}{1 + \gamma_i/Z + J/[Zn_i(\infty)v(\infty)]}$$

is an effective coefficient of secondary emission, $Z$ is the charge number of ions, $\gamma_e$ and $\gamma_i$ are emission coefficients for electron and ion impact, and $J$ is the emission flux due to photons, metastable atoms, etc. For primary electrons the distribution function composed of two Maxwellians at different temperatures is adopted to give

$$n_{e1} = Zn_i(\infty)\left[1 - \frac{\gamma}{1-\gamma}\left(\frac{mv^2(\infty)}{-2e\phi_0}\right)^{1/2}\right]$$
$$\times \left[\frac{n_{ec}(\infty)}{n_{ec}(\infty)+n_{eh}(\infty)} \exp\left(\frac{e\phi}{kT_c}\right) + \frac{n_{eh}(\infty)}{n_{ec}(\infty)+n_{eh}(\infty)} \exp\left(\frac{e\phi}{kT_h}\right)\right] \ , \tag{2}$$

where charge neutrality at $x \to \infty$ has been assumed.

Multiplying by $d\Psi/d\xi$ and integrating Poisson's equation from $\infty$ to $\xi$, we obtain

$$\frac{1}{2}\left(\frac{d\Psi}{d\xi}\right)^2 = \frac{2W}{Z}\left[\left(1+\frac{Z\Psi}{W}\right)^{1/2} - 1\right] - \frac{2\gamma}{1-\gamma}\left(\frac{m}{M}\frac{W}{\Psi_0}\right)^{1/2}\left[\Psi_0 - (\Psi_0 - \Psi)^{1/2}\right]$$
$$+ \left[1 - \frac{\gamma}{1-\gamma}\left(\frac{m}{M}\frac{W}{\Psi_0}\right)^{1/2}\right]\{(1-\alpha)\left[\exp(-\Psi) - 1\right] + \alpha\tau\left[\exp(-\Psi/\tau) - 1\right]\} \ , \tag{3}$$

where

$$\xi = \frac{x}{\lambda_D}\,, \quad \alpha = \frac{n_{eh}(\infty)}{n_{ec}(\infty) + n_{eh}(\infty)}\,, \quad \tau = \frac{T_h}{T_c}\,, \quad \Psi(\xi) = -e\phi(x)/kT_c\,,$$

$$W = Mv^2(\infty)/2kT_c\,,$$

and the Debye length is defined by $\lambda_D^2 = \varepsilon_0 kT_c/Zn_i(\infty)e^2$.

From the fact that the total current is zero, we obtain the equation to determine the wall potential $\Psi_0$ as

$$\left[1 - \frac{\gamma}{1-\gamma}\left(\frac{m}{M}\frac{W}{\Psi_0}\right)^{1/2}\right]\left[(1-\alpha)\exp(-\Psi_0) + \alpha\sqrt{\tau}\exp(-\Psi_0/\tau)\right]$$

$$= \frac{2}{1-\gamma}\left(\frac{\pi m}{M}W\right)^{1/2}\,. \qquad (4)$$

It has been shown that the generalized Bohm criterion is fulfilled with the equality sign at the plasma-sheath boundary[8]. This fact gives

$$W\left[(1-\alpha) + \frac{\alpha}{\tau}\right]$$

$$= \frac{1}{2} + \frac{\gamma}{1-\gamma}\left(\frac{m}{M}\right)^{1/2}\left(\frac{W}{\Psi_0}\right)^{3/2}\left\{\frac{1}{2} + \Psi_0\left[(1-\alpha) + \frac{\alpha}{\tau}\right]\right\}\,, \qquad (5)$$

which is a modified Bohm criterion[9]. The incident ion energy $W$ necessary to maintain stability of the sheath is almost independent of the emission coefficient because of the smallness of $(m/M)^{1/2}$. It is seen from Eq. (4) that the emission of secondary electrons causes the sheath potential to fall. The value $\Psi_0$ is of the order of one in the range $\alpha \leq (1-\gamma)^{-1}(2\pi m/\tau M)^{1/2}$ and is of the order of $\tau$ in the range $\alpha > (1-\gamma)^{-1}(2\pi m/\tau M)^{1/2}$ if $\tau \gg 1$.

The electron emission is limited due to the space-charge effect in the sheath. The equation to determine the limiting value $\gamma_c$ is obtained by equating the right hand side of Eq. (3) to zero at the wall, i.e. $d\Psi/d\xi = 0$ at $\Psi = \Psi_0$. For $\gamma > \gamma_c$ a very shallow potential well is formed just in front of the wall so as to reflect a fraction of the emitted electrons to the wall, satisfying $d\Psi/d\xi = 0$ at the bottom of the potential well. As a result of the space-charge effect, the effective $\gamma$ is maintained to be equal to $\gamma_c$. It should be noted that the space charge of hot electrons has an effect to suppress the electron emission when $\Psi_0$ is of the order of $\tau$. The limiting values $\Psi_{0c}$, $W_c$, and $\gamma_c$ are determined by solving Eqs. (4), (5), and $d\Psi/d\xi = 0$ simultaneously.

We now evaluate the energy flux $Q$ to the wall. Each primary electron striking the wall carries on average an energy of $2kT_c(1+\tau\Gamma_{eh}/\Gamma_{ec})/(1+\Gamma_{eh}/\Gamma_{ec})$, and the ratio of particle flux of hot electrons to that of cold electrons is expressed by $\Gamma_{eh}/\Gamma_{ec} = \alpha/(1-\alpha)\tau^{1/2}\exp[\Psi_0(1-1/\tau)]$. Each ion has the energy $kT_c(W+\Psi_0)$ at $x=0$. The secondary electrons make a negligible contribution to $Q$ at $x=0$ because of their low initial energy. The thermal insulation effect of the sheath can be evaluated by comparing the energy flux with the electron free-flow energy flux expressed by

$$Q_{ef} = Zn_i(\infty)\left(\frac{2kT_c}{\pi m}\right)^{1/2} kT_c\left[(1-\alpha)+\alpha\tau^{3/2}\right] \quad . \tag{6}$$

The energy flux ratio, $F(\gamma) \equiv Q/Q_{ef}$, is given by

$$F(\gamma) = \left(\pi\frac{m}{M}W\right)^{1/2}\left[(1-\alpha)+\alpha\tau^{3/2}\right]^{-1} \times\left\{\frac{2}{1-\gamma}\frac{1-\alpha+\alpha\tau^{3/2}\exp[\Psi_0(1-1/\tau)]}{1-\alpha+\alpha\tau^{1/2}\exp[\Psi_0(1-1/\tau)]}+\frac{W}{Z}+\Psi_0\right\} \quad . \tag{7}$$

The smallest value of $F$ is obtained when $\gamma = 0$, and the maximum value occurs when $\gamma = \gamma_c$.

Figure 1 shows the normalized sheath potential and the normalized incident energy of ions as a function of the the fraction of the hot electron at the sheath edge, $\alpha \equiv n_{eh}(\infty)/[n_{ec}(\infty) + n_{eh}(\infty)]$, and Figure 2 shows the energy flux ratio as a function of $\alpha$ in the absence of electron emission, taking the temperature ratio $\tau \equiv T_h/T_c$ as a parameter. The electron emission coefficient under conditions of space-charge limitation is shown in Fig. 3, the normalized sheath potential and the normalized incident energy of ions are in Fig. 4, and the energy flux ratio is in Fig. 5. In order to show effects of secondary electron emission, we compare the results shown in Figs. 4 and 5 with those in Figs. 1 and 2. The normalized sheath potential imposed by space-charge saturation is a small value of the order of one if the fraction of the hot electron is smaller than $(1-\gamma)^{-1}(2\pi m/\tau M)^{1/2}$. The electron emission leads to a considerable reduction of the sheath potential in this range, so that the energy flux is enhanced up to a value near of the electron free-flow energy flux. The energy flux ratio $F_c$ has the maximum value at a particle density ratio around $(1-\gamma)^{-1}(2\pi m/\tau M)^{1/2}$. It is seen from Fig. 3 that the electron emission is suppressed due to the space-charge effect of hot electrons in the range $\alpha > (1-\gamma)^{-1}(2\pi m/\tau M)^{1/2}$ if the temperature ratio is of the order of ten. The sheath potential of the order of $\tau$ is set up and the action of the sheath as a thermal insulator is improved as a results of suppression of electron emission as shown in Figs. 4 and 5. The formation of the large sheath potential due to existence of hot electrons has beneficial and detrimental effects with regard to plasma-wall interactions. In the presence of the large sheath potential the ion sputtering is increased owing to the higher ion impact energy resulting from the sheath potential drop, but the total energy flux is decreased owing to the thermal insulation effect of the sheath.

In summary, effects of secondary electron emission on the electrostatic sheath and the heat flow of a two-electron-temperature plasma is studied theoretically. If the particle density of hot electrons at the sheath edge is much smaller than that of cold electrons, electron emission induces considerable reduction of the sheath potential and remarkable enhancement of the heat flow. Suppression of the secondary electron emission due to the space-charge effect of hot electrons can be expected if the hot- to cold-electron temperature is of the order of ten and the hot electron density is comparable with the cold electron density.

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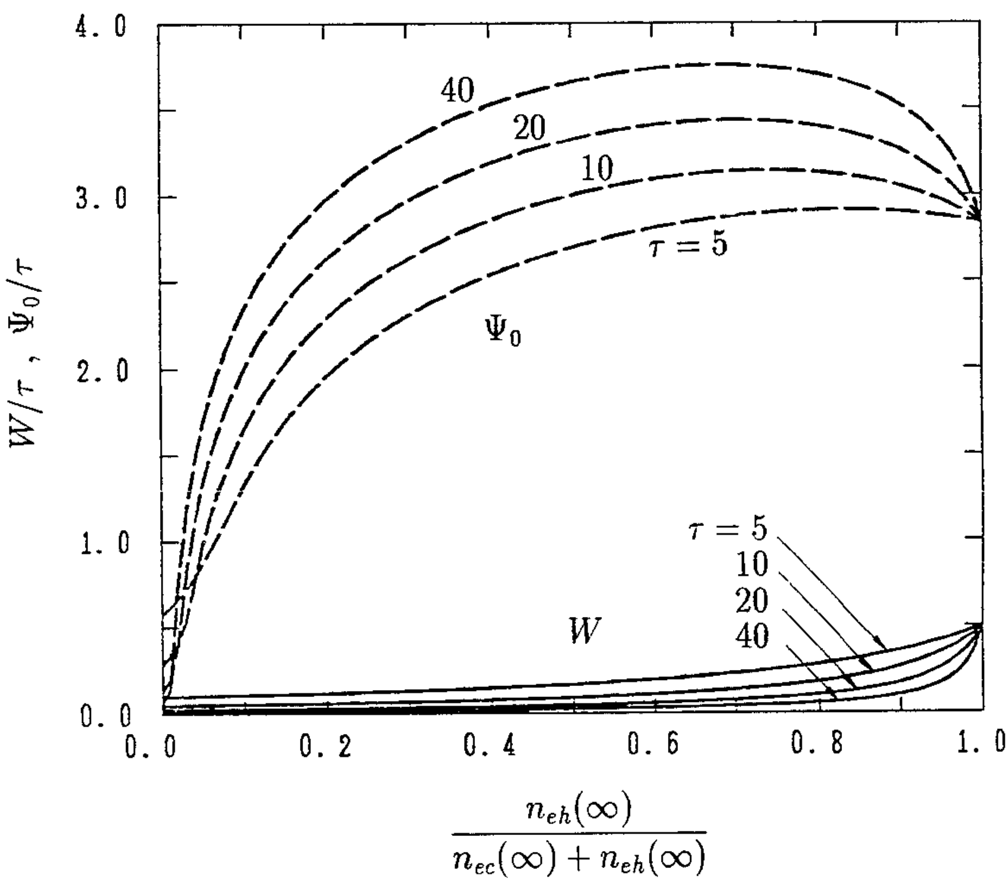


**Fig. 1** Normalized sheath potential $\Psi_0$ (broken lines) and initial kinetic energy of monoenergetic incident ions, $W$, (solid lines) in the absence of electron emission as a function of the density ratio $\alpha \equiv n_{eh}(\infty)/[n_{ec}(\infty) + n_{eh}(\infty)]$ for various values of the temperature ratio $\tau \equiv T_h/T_c$.

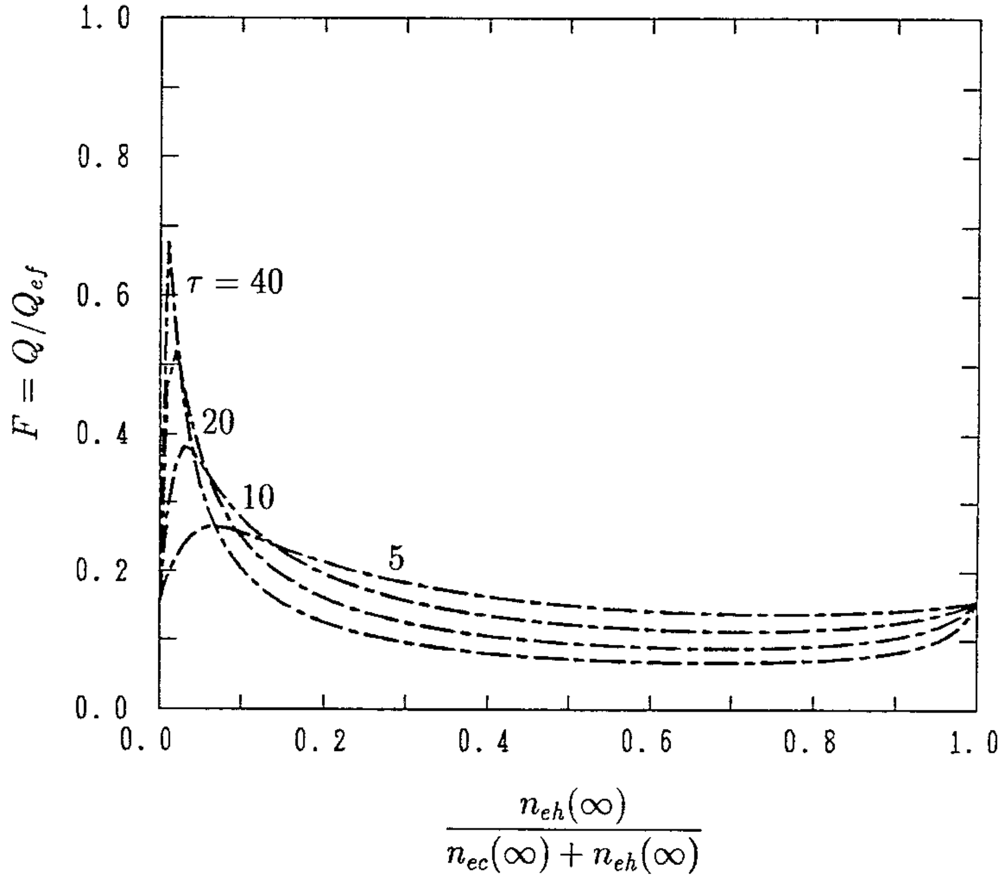


**Fig. 2** Ratio of the energy flux to the electron free-flow energy flux, $F \equiv Q/Q_{ef}$, in the absence of electron emission as a function of the density ratio for various values of the temperature ratio $\tau$.

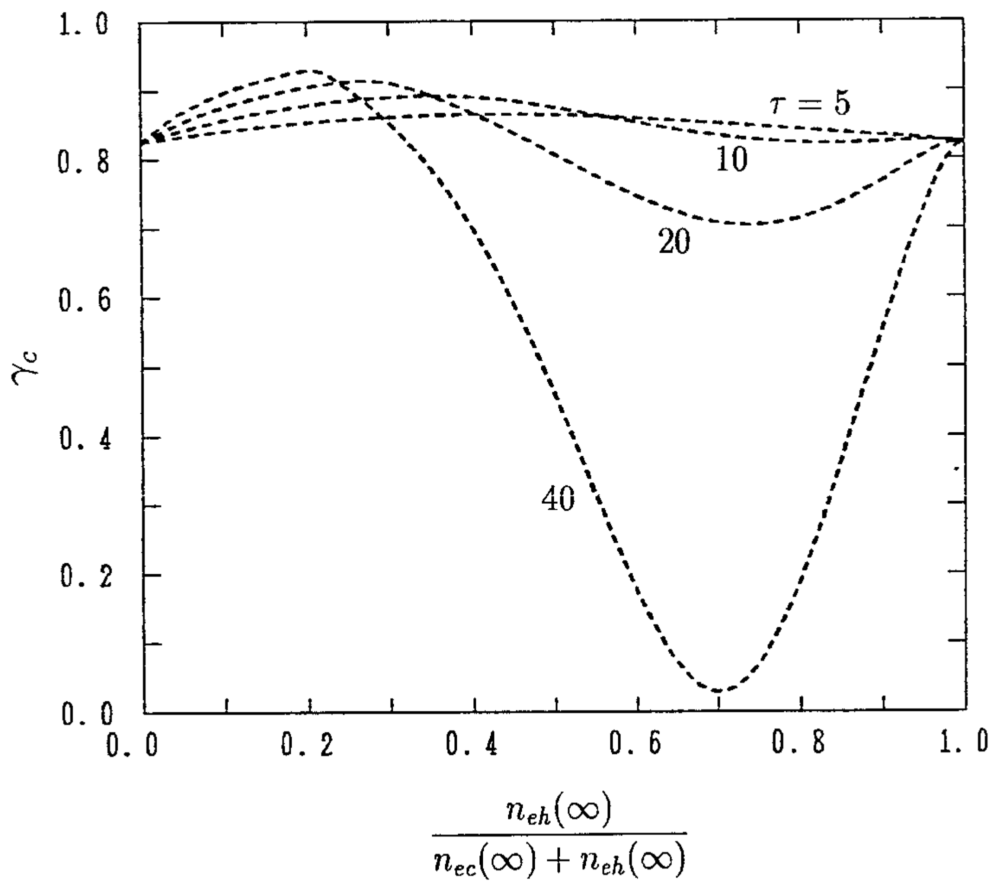


**Fig. 3** Limiting values of the secondary electron emission coefficient $\gamma_c$ as a function of the density ratio for various values of the temperature ratio $\tau$.

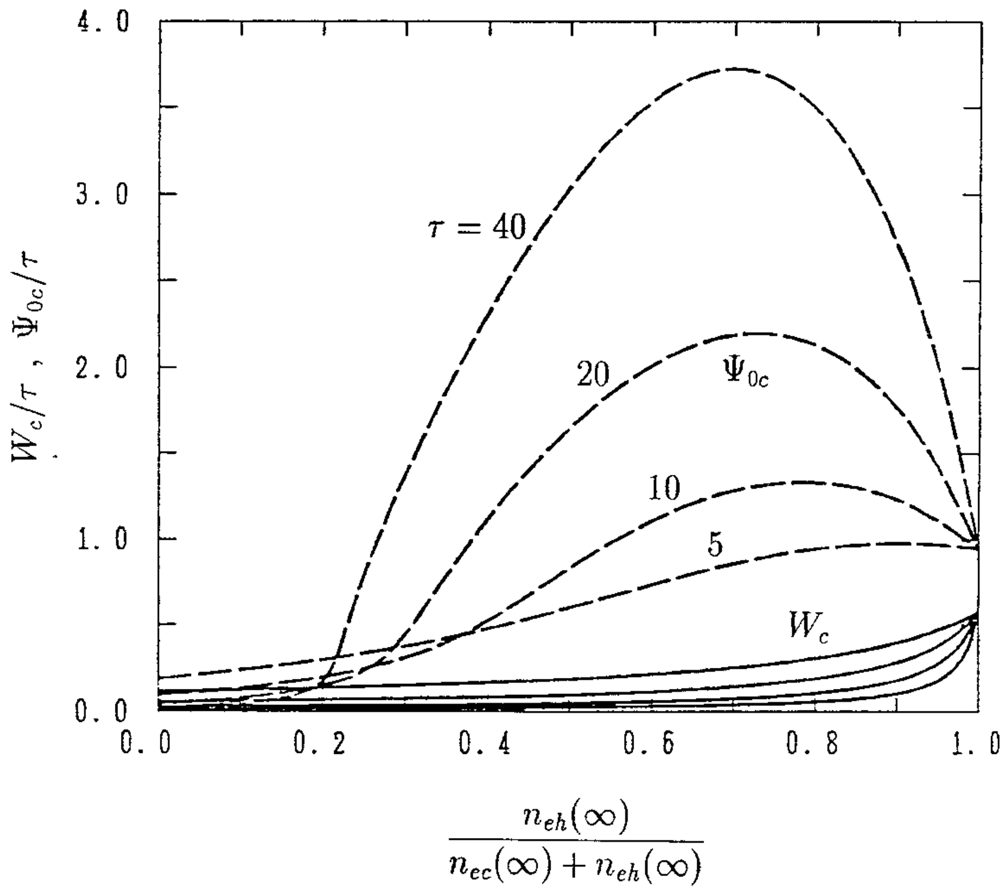


**Fig. 4** Normalized sheath potential and initial incident energy of ions, $\Psi_{0c}$ and $W_c$, under conditions of space-charge limitation as a function of the density ratio for various values of the temperature ratio.

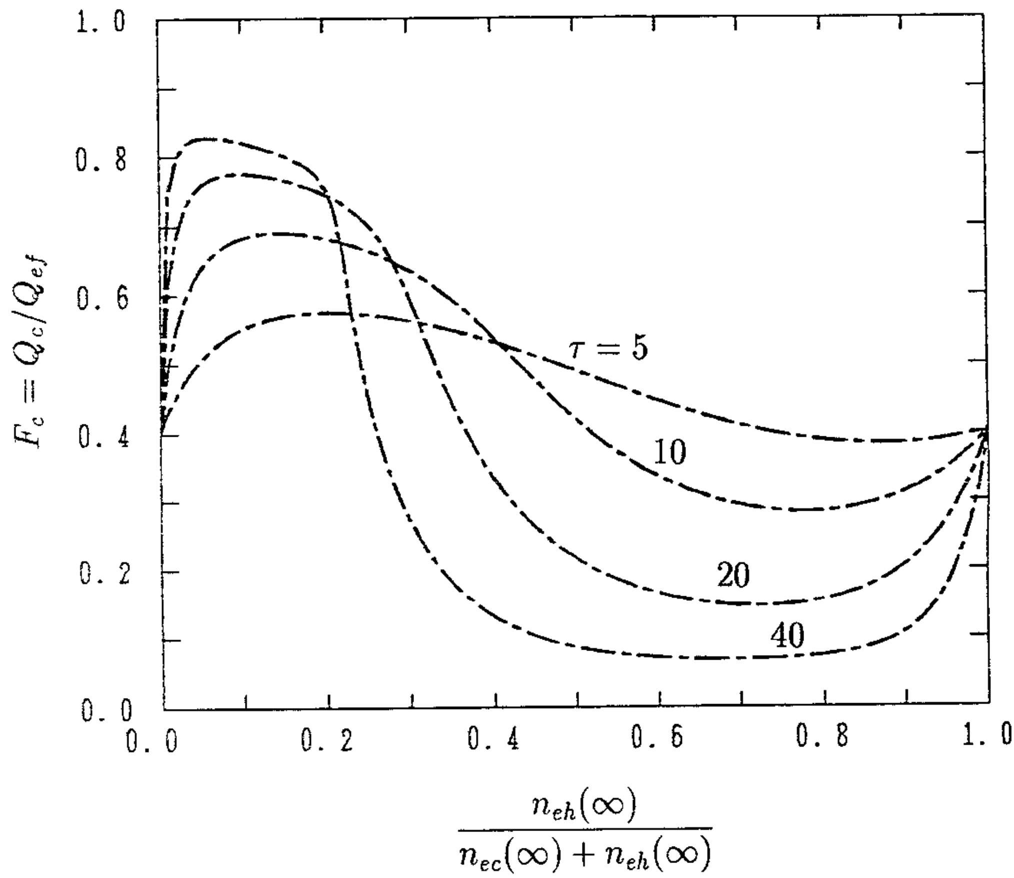


Fig. 5 Ratio of the energy flux to the electron free-flow energy flux, $F_c$, under conditions of space-charge limitation as a function of the density ratio.

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