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EFFECT OF ENERGY DEGRADATION ON THE CRITICAL CURRENT IN AN OGRA-TYPE DEVICE

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Abstract

The relation between the trapped ion density achieved in a machine like OGRA and the molecular ion injection current required, the "S-curve" calculated by Simon, has been extended to include the effect of energy transfer from trapped ions to the continuous flux of cold electrons released in the ionization of the neutral background. Because the cross section for charge exchange, the process by which ions are lost before "burnout," increases sharply with decrease in energy, even a little degradation greatly increases the ion loss rate and thereby increases the injection current required to sustain a given density. Our revised result for the critical current for burnout determined from the S-curve, is about twice that calculated neglecting ion energy degradation for the case of injecting 600 Kev H_2^+. In the report, we present new S-curves, and the critical current for a range of H_2^+ injection energies from 500 Kev to 800 Kev.

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1. Introduction

In an OGRA-type fusion device (i. e., a device based on trapping ions by dissociation of energetic molecular ions on collision with either background gas or trapped ions), the critical injection current for neutral "burnout," calculated by Simon,[1] is a sensitive function of the average energy of trapped ions through the energy dependence of the charge exchange process by which ions are lost before burnout. For injection of H_2^+ at energies as high as 600 Kev, of interest to the Oak Ridge Thermonuclear Group, a reduction in energy by, say, ten percent doubles the charge exchange cross section.

In this paper we include in a calculation of the critical current the effect, neglected by Simon, of the degradation of trapped ion energy due to energy transfer to the continuous flux of cold electrons released in the ionization of the neutral background. In summary, our calculation provides the charge exchange cross section, averaged over the ion energy distribution, to be used in Simon's calculation of the critical current, I_{crit}. As an example result, for injection of 600 Kev H_2^+, the corrected I_{crit} turns out to be more than twice that calculated without energy degradation. At higher energies, corresponding to longer ion lifetimes and hence greater degradation, the correction is greater, and thus the expected reduction in current requirements accompanying an increase in injection energy is diminished. We have compared I_{crit} for various injection energies, including the effects of energy degradation. The result is plotted in Fig. 4.

In the next section, Simon's work is reviewed in an approximation due to Mackin.[2] Section 3 treats energy considerations, and Section 4 combines our results with Simon's.

2. Approximate Critical Current Formula

Simon[1] has shown that the relation between the steady state trapped ion density n_+ and the injected molecular ion current I plots an S-shape curve, such as Fig. 1. We are only interested in the solid-line portion, whose upper boundary defines I_{crit}. Simon pointed out that for this portion, where burnout of neutrals is incomplete, loss of ions by charge exchange greatly dominates loss by scattering out the mirrors. Thus, with Mackin,[2] we neglect scattering losses.

The S-curve is a simultaneous solution of the following equations of conservation of ions and neutrals, respectively:

$$\frac{I}{V} B = n_+ n_0 \overline{\sigma_x} v \tag{1}$$

$$\Gamma \frac{I}{V} = \sigma n_+ n_0 \sigma_i v \tag{2}$$

Here n_0 is the neutral density <u>inside</u> the plasma. V is the plasma volume, v the ion velocity, $\overline{\sigma_x}$ the charge exchange cross section averaged over the ion energy distribution. B, to be discussed, is the fraction of the molecular ion beam which is dissociated.

In Eq. (2) governing neutrals, again following Mackin, we have made two assumptions. First, it is assumed that the only important sources of neutral gas are the undissociated molecular ion beam striking the injector, the neutral atoms released in dissociation, and the fast neutrals from charge-exchange striking the walls. The assumed proportionality between neutral input and I is Γ, which according to Simon might be as much as 2. The second assumption is that the only important pumping of neutrals is due to the plasma, whereby neutrals ionized by the plasma are buried in "getters" or are otherwise prevented from returning to the system as neutrals. σ is the efficiency for this process, that is, the fraction of ionized neutrals which are disposed of. σ_i is the ionization cross section. With application to the injection of several hundred Kev ions in mind,

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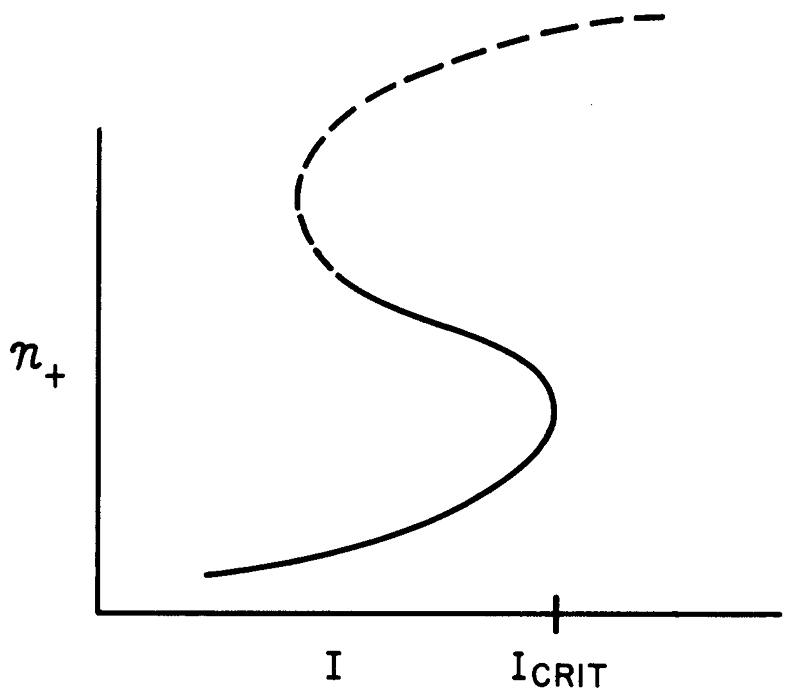

FIG. 1 PROTOTYPE S-CURVE RELATING TRAPPED ION DENSITY n_+ TO INJECTED MOLECULAR ION CURRENT I.

destruction of neutrals by charge exchange has been neglected in comparison with simple ionization.

Because it turns out that electrons reach an energy ~ 100 ev, ionization by electrons should be included on the right side of (2). The products $\sigma_i v$ for ions and electrons are comparable. The trapped ion and electron densities are also comparable, since, for neutrality, n_- equals n_+ plus the secondary ion density resulting from ionization of neutrals, and, as will be pointed out, the latter is much less than n_+ when either is important. Thus, for simplicity, we may include ionization by electrons merely by doubling σ_i in (2).

Note that for the most part we shall neglect the slight energy dependence of quantities such as $\sigma_i v$ in comparison with the very strong energy dependence of σ_x.

Dividing (1) by (2) gives

$$B = \frac{\Gamma}{\sigma} \frac{\overline{\sigma_x}}{\sigma_i} \quad . \tag{3}$$

Thus, having neglected scattering, we find that the dissociation fraction, B, is constant over the portion of the S-curve under consideration, except for the variation of $\overline{\sigma_x}$ with n_+ and I to be derived later. Further, inserting values, B is quite small. Thus we may neglect attenuation of the molecular ion beam along its path, L, through the plasma, so that B is adequately given by

$$B = \sigma_B L(n_+ + n_0) \quad . \tag{4}$$

σ_B is the dissociation cross section, assumed to be the same for all kinds of dissociation centers including trapped ions and neutrals. Dissociation by secondary ions has been neglected since, as Mackin points out and as was mentioned earlier, for values of n_+ large enough so that an appreciable fraction of the neutrals are ionized, n_+ is much greater than either the neutral or secondary ion densities. Dissociation by electrons, neglected by Simon, is also omitted here.

Combining (2), (3), and (4) gives:

$$n_+^2 - n_+\left(\frac{\Gamma}{\sigma}\ \frac{\overline{\sigma_x}}{\sigma_i\sigma_B L}\right) + \frac{\Gamma}{\sigma}\frac{I}{V}\frac{1}{\sigma_i v} = 0 \quad . \tag{5}$$

Given $\overline{\sigma_x}$, this equation, quadratic in n_+, defines the portion of the S-curve under discussion, the solid-line portion in Fig. 1. The turning point defining I_{crit} can be found by taking the derivative of (5) with respect to n_+, setting $dI/dn_+ = 0$, and solving the result simultaneously with (5). For the case without energy degradation, $\overline{\sigma_x}$ being then a known constant, the turning point is more easily found as the point where the two solutions of (5), the quadratic equation in n_+, coincide. That is, we set the discriminant equal to zero and solve for I, which yields Mackin's approximation

$$I_{crit} = \frac{V}{4}\ \frac{\Gamma}{\sigma}\ \frac{\overline{\sigma_x}^2\ v}{\sigma_i\sigma_B^2\ L^2} \quad . \tag{6}$$

Mackin has found that this formula agrees well with Simon's exact results for numerous cases tested. Also, this solution for constant σ_x has an interesting corollary. n_+ is then just half the coefficient of the first power of n_+ in (5). Substituting this quantity into (4) gives

$$(n_0)_{crit} = (n_+)_{crit} = \frac{1}{2}\ \frac{\Gamma}{\sigma}\ \frac{\overline{\sigma_x}}{\sigma_i\sigma_B L} \quad . \tag{7}$$

Thus the ratio n_+/n_0 at the critical current is always unity. In the next section it is shown that $\overline{\sigma_x}$ depends only on this ratio.

Because $\overline{\sigma_x}$ depends on n_+ and I, formula (6) for the critical current is not correct. However, as we shall see in Section 4, it is approximately valid and will be used to estimate the critical current at various injection energies relative to that for 600 Kev H_2^+.

3. Calculation of $\overline{\sigma_x}$

Assuming plasma radiation to be negligible, the energy deposited in the system by degrading hot ions, $\triangle$ per ion, leaves the system via escaping secondary ions and electrons resulting from ionization. Each electron removes energy $\overline{E_-} - \phi$, $\overline{E_-}$ being the average electron energy weighted by their escape rate and ϕ being the potential energy difference from the plasma interior to the walls due to the electric field which establishes in order to restrict electron escape. Since an examination of rates shows that secondary ions are not heated appreciably, they each remove just energy ϕ, assuming them to be singly charged (hydrogen background). Thus, since secondary ions and electrons are produced in equal numbers, neglecting a slight excess of ions due to charge exchange, secondary ions gain from the electric field just the kinetic energy electrons lose to it. Or, each electron-ion pair removes from the system energy $\overline{E_-}$.

Thus, energy conservation in steady state requires that

$$\left(\frac{n_+}{\tau}\right)\triangle = (n_+ n_0 \sigma_i v)\ \overline{E_-} \quad . \tag{8}$$

On the left, τ is the ion lifetime, and $n_+/\tau = IB/V$ is the ion trapping rate per unit volume. On the right, the quantity in parenthesis is the rate per unit volume for forming secondary ion-electron pairs, that is, the ionization rate. Again, σ_i is doubled to take into account ionization by electrons. We have neglected cold electrons from sources other than ionization of neutrals which might drift through the system and be trapped long enough to gain some energy. Even if their numbers were great, such electrons would each remove only an energy $\overline{E_-} - \phi$ to be compared with $\overline{E_-}$ removed by ion-electron pairs produced by ionization. Even for considerable electron flow, it has been shown that $\phi \sim \overline{E_-}$, so that $\overline{E_-} - \phi \ll \overline{E_-}$ (ref. 3).

Another relation between Δ and $\overline{E_-}$ is obtained from the ion energy distribution. The ion lifetime, τ, being limited by charge exchange, is much less than the scattering time, or thermalization time, and hence energy dispersion is negligible. Furthermore, it turns out that the electron energy is low enough so that energy transfer from fast ions to ions already degraded and to secondary ions is negligible compared with transfer to electrons. Therefore, barring collective transfer mechanisms, which we neglect here, the trapped ion energy is altered only by dynamical friction due to collisions with electrons. In consequence, the Fokker-Planck equation governing the ion energy distribution in steady state is solvable, being linear and first order, with exponential solutions, an example being given in Fig. 2. However, simple as the exact result is, the complication of taking appropriate averages of it to get Δ as a function of $\overline{E_-}$ makes it profitable to employ the following simpler approximation.

We take for the ion energy distribution a step function of width Δ, as shown in Fig. 2. Then the ion lifetime can be thought of as <u>either</u> the time to slow down from the initial trapped ion energy, E_0, to $E_0 - \Delta$, just $\Delta/(dE/dt)$ if dE/dt is the energy transfer rate, <u>or</u>, equivalently, the average charge exchange time over the interval E_0 to $E_0 - \Delta$. Equating these two expressions gives

$$\tau = \frac{\Delta}{\frac{dE}{dt}} = \frac{1}{n_0 \sigma_x v} \left(\frac{\sigma_x}{\overline{\sigma_x}} \right) . \qquad (9)$$

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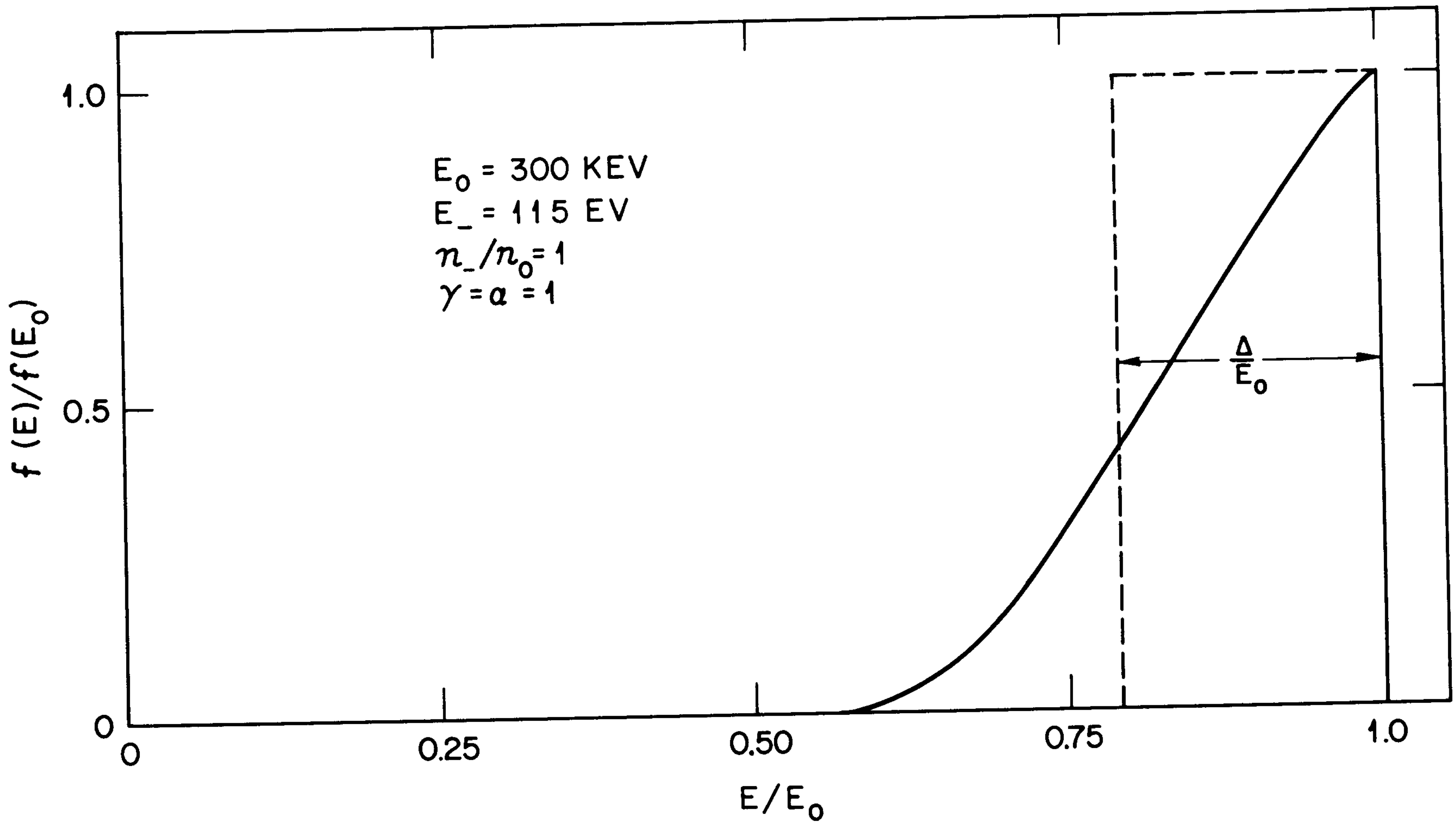

FIG. 2 TYPICAL ION ENERGY DISTRIBUTION

σ_x without the bar denotes the charge exchange cross section at E_0. Approximating the variation of this cross section with energy as $\propto E^{-q}$ (q being ~ 5 for 300 Kev H^+ trapped ions and hydrogen background), we find

$$\frac{\overline{\sigma_x}}{\sigma_x} = \frac{1}{\Delta} \int_{E_0-\Delta}^{E_0} dE \left(\frac{E_0}{E}\right)^q = \frac{1}{q-1} \frac{E_0}{\Delta} \left[\left(\frac{E_0}{E_0 - \Delta} \right)^{q-1} - 1 \right] . \tag{10}$$

Since electrons escape only by scattering, we assume they approximately thermalize and employ for dE/dt Chandrasekhar's results quoted by Spitzer,[4] or rather an approximation good to 5% due to Rose,[5]

$$\frac{dE}{dt} = \gamma n_- \frac{2\sigma_c E_0^2}{mv} g(E_-) , \tag{11}$$

where

$$g(E_-) = \frac{1}{1 + \sqrt{\frac{6}{\pi}} \left(\frac{M}{m} \alpha \frac{E_-}{E_0} \right)^{3/2}} . \tag{12}$$

n_- is the electron density, m their mass. We have not averaged quantities over the ion energy distribution here, but simply take the ion energy to be E_0. Thus σ_c is the 90°-Coulomb scattering cross section at E_0, being 3×10^{-23} cm^2 at 300 kev and varying as E_0^{-2}. The electron energy on which g depends is the mean energy of electrons in the system, which we write as $\alpha \overline{E_-}$ to distinguish it from $\overline{E_-}$, which may be thought of as the mean energy of electrons in process of escape. We expect α to be of order unity. Exactly what α is depends somewhat sensitively on the true electron energy distribution as modified by the plasma potential.

With $\gamma = 1$, Eq. (11) is the energy transfer rate to a Maxwellian electron distribution. Recent results of numerical integration of the Fokker-Planck equation by the Livermore group[6] indicate that in non-equilibrium situations the low-energy portion of the electron distribution, the only portion to which ions transfer energy, tends not to have time to fill out completely, with the consequence that dE/dt is less than that for a Maxwellian distribution by as much as a factor of 2. Thus, in addition to treating Maxwellian electron distributions, we shall also report an S-curve with $\gamma = 0.5$.

Simultaneous solution of Eqs. (8) to (12) with (5) from the previous section completely defines the S-curve. It is enlightening first to rewrite these equations as follows. Combining Eq. (11) and the expression for τ in terms of dE/dt from Eq. (9) with Eq. (8) gives

$$\frac{\overline{E_-}}{E_0} = \left(\frac{n_-}{n_0}\, g\right) \frac{\gamma\sigma_c}{\sigma_i}\, \frac{M}{m} \quad . \tag{13}$$

Multiplying Eq. (12) by n_-/n_0 and combining with Eq. (13) gives

$$\left(\frac{\overline{E_-}}{E_0}\right)^{5/2} \sqrt{\frac{6}{\pi}\frac{M}{m}}\; \frac{\sigma_i}{\gamma\sigma_c}\, \alpha^{3/2} + \frac{m}{M}\, \frac{\sigma_i}{\gamma\sigma_c}\, \frac{\overline{E_-}}{E_0} = \frac{n_-}{n_0} \quad . \tag{14}$$

Further, combining Eqs. (9), (11), and (13) gives

$$\frac{\overline{\sigma_x}}{\sigma_x} = \frac{\overline{E_-}}{E_0}\, \frac{\sigma_i}{\sigma_x}\, \frac{E_0}{\Delta} \quad . \tag{15}$$

In order that Eq. (5) reduces to an equation in n_+ and I only, we would like to know $\overline{\sigma_x}/\sigma_x$ as a function of these variables. Indeed, eliminating Δ/E_0 from Eq. (10) and Eq. (15) to give $\overline{\sigma_x}/\sigma_x$ in terms of $\overline{E_-}/E_0$, and combining with Eq. (14), we obtain $\overline{\sigma_x}/\sigma_x$ as a function of n_-/n_0. In turn, using Eq. (2) and noting that in the region of interest $n_- \cong n_+$, as has been discussed earlier, we find

$$\frac{n_-}{n_0} \cong \frac{n_+}{n_0} = \frac{n_+^2 \sigma_i v}{(I/V)(\Gamma/\sigma)} \quad . \tag{16}$$

The ratio $\overline{\sigma_x}/\sigma_x$ for the 600 Kev H_2^+ case, obtained graphically, is given in Fig. 3 with $\alpha = 1$ and $\gamma = 1$ (Maxwellian electrons), and also for $\gamma = 0.5$. At $n_-/n_0 = 1$, the critical current condition according to Eq. (16) and results from the previous section, $\overline{\sigma_x}/\sigma_x$ is 2. This is 20% lower than the exact value, 2.4, obtained by averaging σ_x over the true ion energy distribution for this case, which is the example distribution in Fig. 2.

A good approximation to $\overline{\sigma_x}/\sigma_x$ versus n_-/n_0, also plotted in Fig. 3 for comparison, was arrived at as follows. First, note that for sufficiently large $\overline{E_-}$, Eq. (14) simplifies to

$$\frac{\overline{E_-}}{E_0} \rightarrow \left(\frac{n_-}{n_0}\right)^{2/5} \left(\sqrt{\frac{\pi}{6}}\,\frac{m}{M}\,\frac{\gamma\sigma_c}{\sigma_i}\,\frac{1}{\alpha^{3/2}}\right)^{2/5} \quad . \tag{17}$$

Also, for large enough Δ, compatible with large $\overline{E_-}$, the term unity in parentheses on the right side of Eq. (10) may be dropped, whereupon, combining with Eq. (15), we obtain

$$\frac{\overline{\sigma_x}}{\sigma_x} \rightarrow \frac{\dfrac{\sigma_i}{\sigma_x}\,\dfrac{\overline{E_-}}{E_0}}{1 - \left(\dfrac{1}{(q-1)\,\dfrac{\overline{E_-}}{E_0}\,\dfrac{\sigma_i}{\sigma_x}}\right)^{1/(q-1)}} \quad . \tag{18}$$

In comparison with the numerator, the denominator of Eq. (18) is slowly varying and may be regarded as a constant. Then, employing Eq. (17), we see that $\overline{\sigma_x}/\sigma_x$

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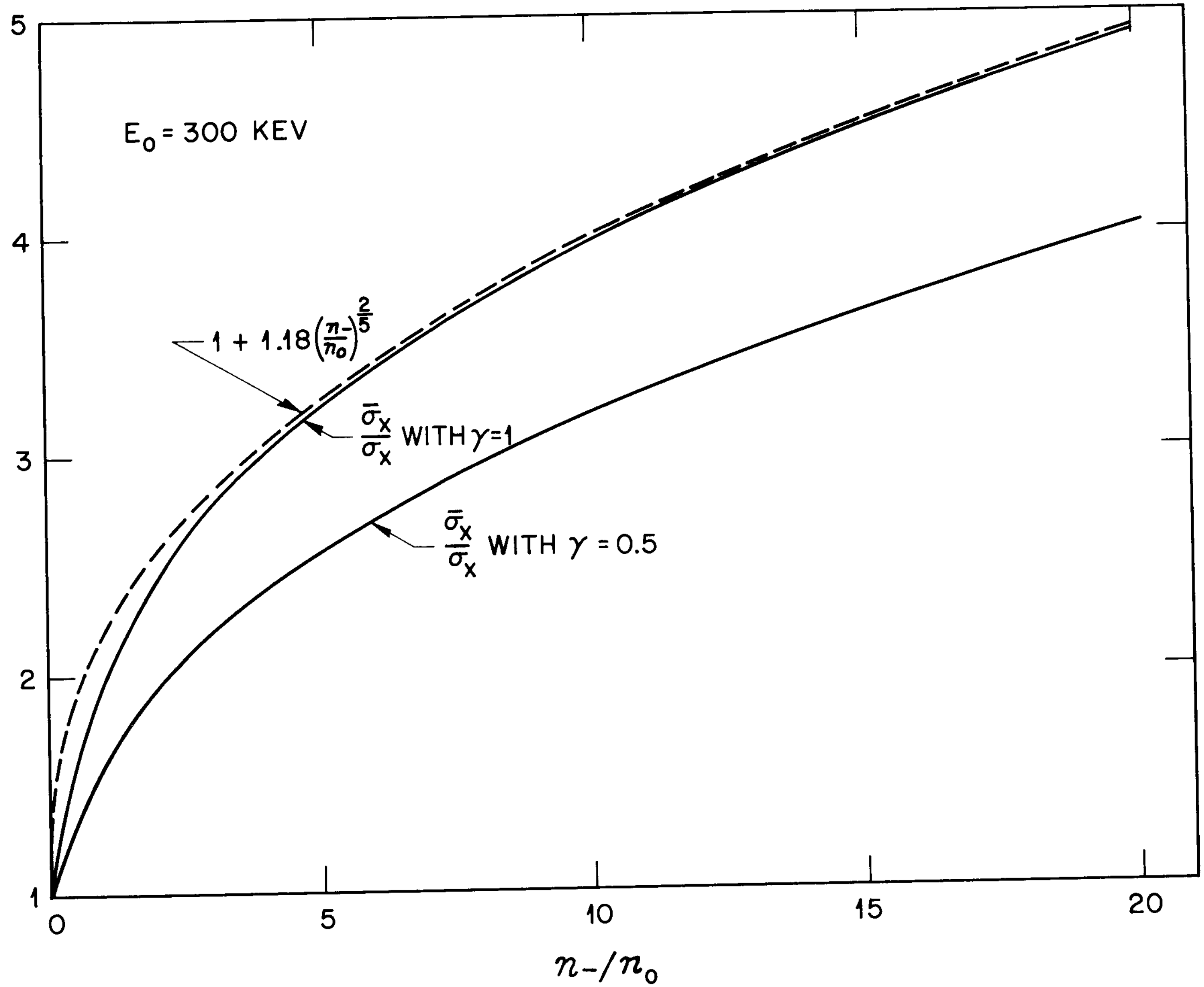

FIG. 3 $\bar{\sigma}_x / \sigma_x$ VERSUS n_- / n_0

is proportional to $(n_-/n_0)^{2/5}$. Adding unity to such a term in order that the limit at $n_-/n_0 = 0$ be correct, we take as an approximation to $\overline{\sigma_x^-}/\sigma_x^-$ for the case of 600 Kev H_2^+ injection

$$\overline{\sigma_x^-}/\sigma_x^- \cong 1 + 1.18\left(\frac{n_-}{n_0}\right)^{2/5} , \tag{19}$$

where the coefficient was chosen to give the good agreement with exact results exhibited in Fig. 3, for $\gamma = 1$. At other injection energies, or for smaller γ, the coefficient is, of course, different. For 600 Kev H_2^+ injection but $\gamma = 0.5$, the coefficient is .875.

For too large results, our calculation of $\overline{\sigma_x^-}/\sigma_x^-$ is untrustworthy. An important source of error is the fact that our assumed energy dependence of σ_x^- begins to be an overestimate below about 100 Kev. Thus, our result is too large if $E_0 - \Delta < 100$ Kev. For $E_0 = 300$ Kev (600 Kev H_2^+), this limit is unimportant. From (10), with $q = 5$, we see that in that case this criterion is satisfied for $\overline{\sigma_x^-}/\sigma_x^- < 30$, which permits us to calculate the portion of the S-curve of interest.

4. Results

Two kinds of results are presented. First, without employing the approximations of Eqs. (17) - (19), we have calculated for several E_0 the ratio $\overline{\sigma_x^-}/\sigma_x^-$ at $n_-/n_0 = 1$, which, as was established in Sec. 2, is the approximate critical condition. Employing these values in formula (6) for I_{crit}, we obtain the critical current at each energy relative to that at $E_0 = 300$ Kev (600 Kev H_2^+). The results are plotted in Fig. 4 along with the result when energy degradation is omitted (i.e., $\overline{\sigma_x^-} = \sigma_x^-$). Only σ_x^- was averaged over the ion energy distribution. σ_B^-, σ_i^-, and v were evaluated at E_0. The factor γ appearing in (11) was taken as unity.

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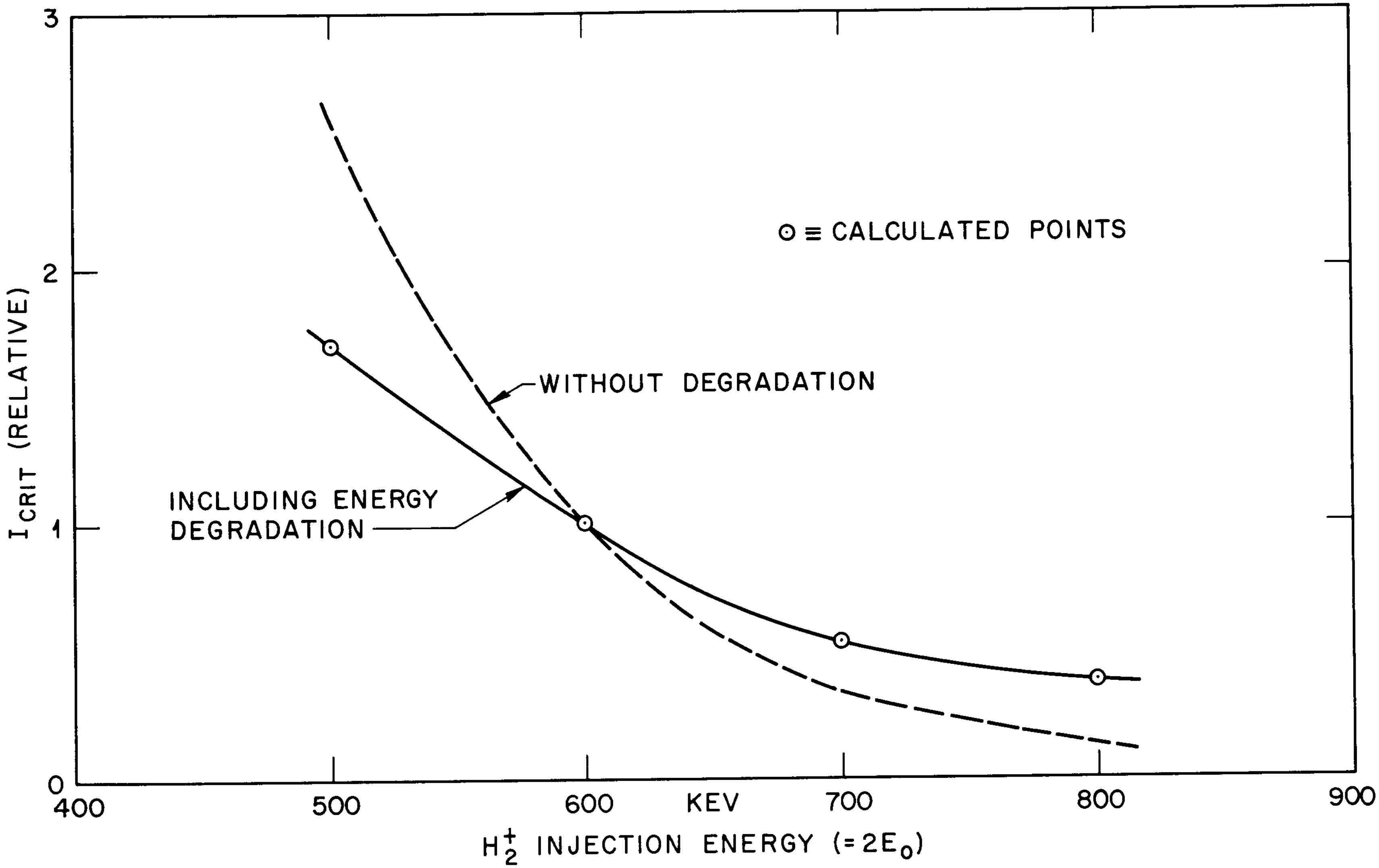

FIG. 4 CRITICAL CURRENT VERSUS INJECTION ENERGY

At each injection energy, the electron energy, $\overline{E_-}$, at the critical current condition turns out to be around 100 ev, ranging from 110 ev to 126 ev as E_0 varies from 250 Kev to 400 Kev. That $\overline{E_-}$ should be approximately independent of E_0 arises as follows: In (13), first multiplying by E_0, $(\sigma_c^-/\sigma_i^-)E_0$ is constant, since $\sigma_c^-/\sigma_i^- \propto E_0^{-1}$, and n_-/n_0 at the critical condition is independent of E_0, being always unity. Thus any dependence of $\overline{E_-}$ on E_0 comes from g. But at the critical condition, $\overline{E_-}/E_0$ is low enough that g, defined in terms of $\overline{E_-}/E_0$ by (12), is almost constant.

Concerning the sensitivity to assumptions, varying the power of the energy on which σ_x^- depends from q = 5 to q = 6 changes $\overline{\sigma_x^-}/\sigma_x^-$ by $< 20\%$. Varying α, the ratio of the mean energy of electrons to the mean energy of those escaping, from 1 to 2 decreases $\overline{\sigma_x^-}$ around 10%, hence I_{crit} by 20%, but has remarkably little effect on the ratios of critical currents at different E_0 presented in Fig. 4.

Our second class of results consists of revised S-curves, just the portion dominated by charge exchange, for injection of 600 Kev H_2^+. The results for L = 10 meters and L = 20 meters are given in Fig. 5, which is a plot of (5) with $\overline{\sigma_x^-}/\sigma_x^-$ from approximation (19) together with the relation between n_-/n_0 and n_+ and I given by (16). Here $\alpha = 1$, and $\gamma = 1$, corresponding to a Maxwellian electron distribution. Values of other parameters are indicated on the curve. Note that σ_i^- is twice that for ionization by ions only to take into account ionization by electrons, as was discussed in Sec. 2. The critical current given by these curves is $\sim$50% higher than that calculated by the prescription just discussed by which Fig. 4 was obtained; however, the dependence of I_{crit} on L is exactly that predicted by (6), and by approximation (21) which follows.

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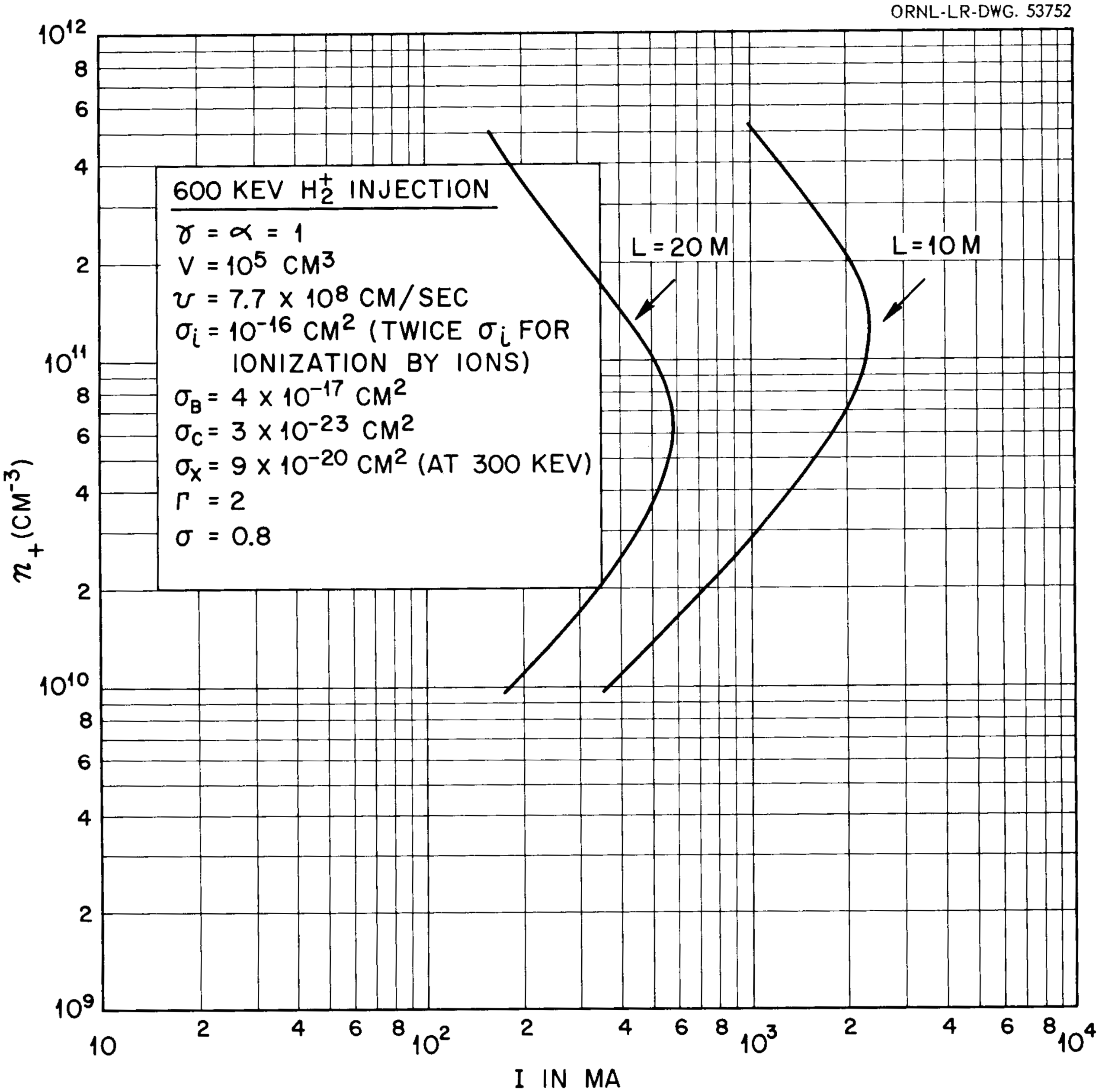

FIG. 5 STEADY STATE ION DENSITY VERSUS MOLECULAR ION INJECTION CURRENT

In Fig. 6, we replot the S-curve with energy degradation for L = 20 meters and $\gamma = 1$ and compare it with that for the same L but $\gamma = 0.5$, corresponding to an energy transfer rate from ions to electrons one-half that for a Maxwellian electron distribution. For comparison, in Fig. 6 there is also shown for L = 20 meters the S-curve for $\gamma = 0$, that is, no energy degradation (hence, also, no ionization by electrons). We give both Simon's exact result and Mackin's approximation employing the simplifying assumptions discussed in Sec. 2.

For convenience, we have used the ORACLE to plot Figs. 5 and 6. Reasonably good results can be obtained more simply by replacing approximation (19) by a similar form

$$\frac{\overline{\sigma_x}}{\sigma_x} \cong 1 + \beta\sqrt{\frac{n_-}{n_0}} \quad . \tag{20}$$

Then, as in the case with σ_x constant, (5) becomes simply quadratic in n_+ and easy to solve. Again, also, the critical condition is obtained by setting the discriminant of this new quadratic equation equal to zero and solving the resulting equation for I, which yields

$$I_{crit} = I_0 \left(\beta + \sqrt{1 + \beta^2}\right)^2 \quad . \tag{21}$$

Here I_0 is the critical current without energy degradation given by (6) with v and all cross sections, including σ_x, evaluated at E_0, but with σ_i doubled to account for ionization by electrons. Thus the correction factor depends only on β, and in particular it is independent of I, V, and L. Formula (21) agrees to within 2% with the curves of Fig. 5, if we take $\beta = 1$ chosen to give the correct

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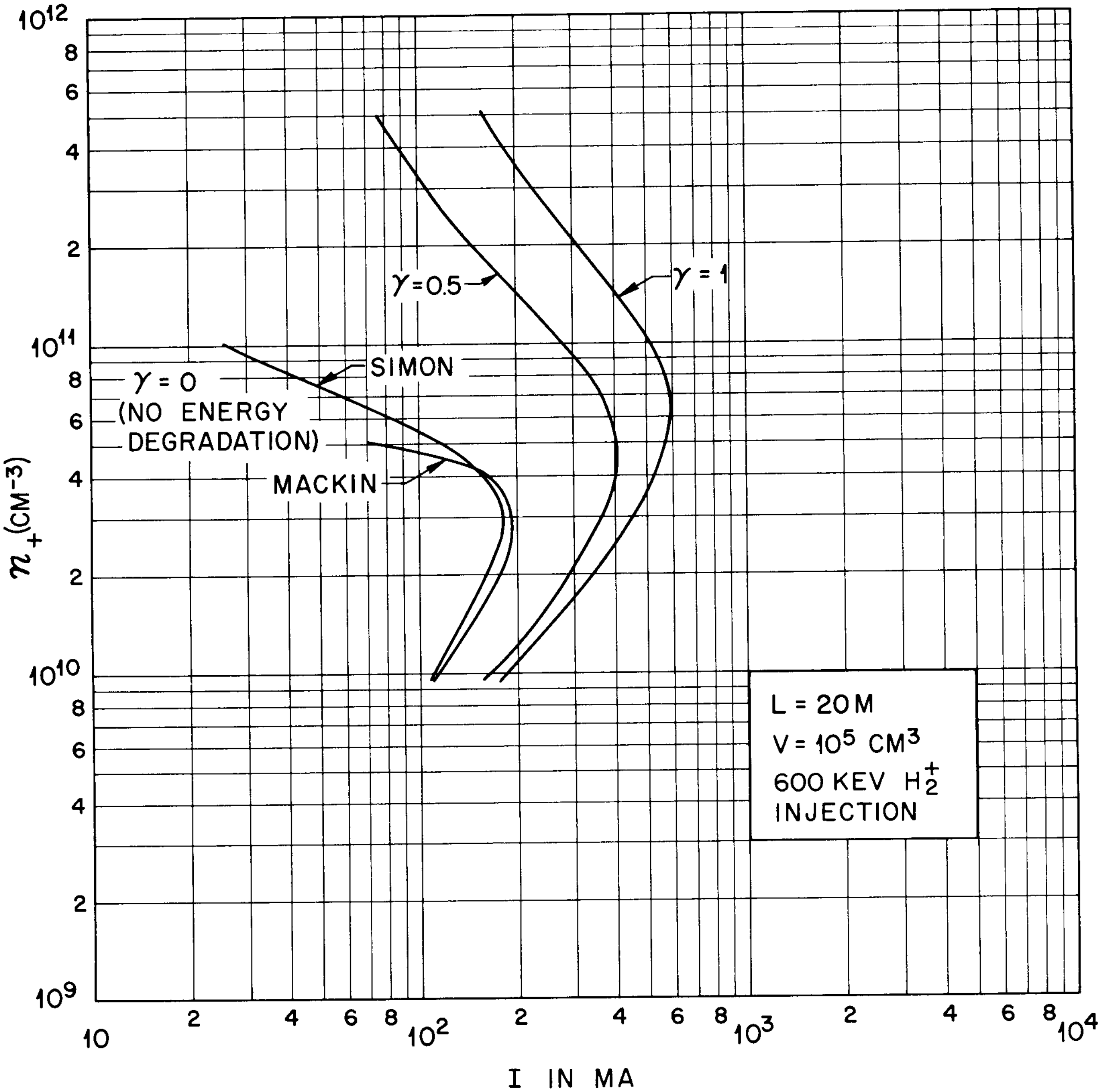

FIG. 6 COMPARISON OF "S-CURVES" FOR SEVERAL VALUES OF γ, THE RATE OF ENERGY TRANSFER FROM IONS TO ELECTRONS RELATIVE TO THE RATE IF THE ELECTRON DISTRIBUTION WERE MAXWELLIAN.

$\overline{\sigma_x}/\sigma_x$ at $n_-/n_0 = 1$. Unfortunately, this approach suffers from the fact that we have not found a reliable, simple formula for β as a function of E_0.

We would like to thank G. R. North for his ORACLE computations.

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