Theory of a stable ion source discharge

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Abstract

An ion source discharge is modelled under the assumption that beam plasma instabilities are stable and classical Coulomb collisions are sufficiently frequent to provide bulk electron thermalization.

Key words : Ion source, plasma, discharge.

The advances being made today in thermonuclear experiments are due in large measure to the advent of intense ion (neutral) beam sources. Conversely, these promising results serve to spur on the development of still more efficient sources having improved characteristics[1].

Despite a considerable effort, worldwide, there is still no theoretical basis for predicting the impedance characteristics of such ion source devices. In the high pressure, collisional, regime the discharge theory of Schottky[2] can be used to model the axial distribution of potential within the positive column, but not in terms of the overall potential applied at the external electrodes. In the low pressure, collisionless, regime the "free-fall" discharge theory of Tonks and Langmuir[3] is useful but the proportion of primary to secondary (*i.e.*, thermalized plasma electrons) ionizing electrons is not known theoretically.

The presence of both primary (beam) and plasma electron components substantially complicates the theoretical problem. Besides influencing the gas ionization rate the coupling of beam energy to the plasma is manifested in the well-known Langmuir Paradox[4]. The detailed resolution of this "Paradox" depends upon understanding the electron beam-plasma instability[5] and is extremely complex[6], involving effects due to parametric coupling[7,8], plasma inhomogeneity[9], and quasilinear development[10]. A comprehensive theory incorporating all of these important effects remains to be developed.

In the present work we do not propound a general theory, rather we develop a classical theory for predicting the ion source discharge impedance in the complete absence of instabilities. This development is important for two reasons: first, the classical energy equilibration rate constitutes an irreducible minimum, and hence gives information useful for any ion source, and second, the model may be experimentally realisable over a limited parameter range since the beam-plasma instability can have a finite threshold[6] or be stabilized by various effects[11].

Some initial understanding of the ionization process can be obtained by investigating the simplest form of the discharge particle balance equation. Specifically, the volume electron-gas ionization rate is set equal to the plasma loss rate:

$$\langle \sigma v_e \rangle n_n n = \frac{n_i}{\tau} \tag{1}$$

where it is assumed that surface recombination dominates, $\langle \sigma v_e \rangle$ is the averaged electron-gas ionization rate coefficient[12], n is the density of ionizing electrons, n_n is the neutral gas density, n_i is the ion plasma density and τ is the plasma loss (replacement) time. In the free-fall regime:

$$\tau \alpha \frac{V}{Ac_s} \tag{2}$$

where V is the discharge volume, A is the loss (electrode, wall) area, and c_s is the ion acoustic speed:

$$c_s \alpha \, (T_e/m_i)^{\frac{1}{2}} \tag{3}$$

where T_e is the electron plasma temperature and m_i is the ion mass. We justify the use of equation (2) in that we wish to evaluate 1 in the limit where ionization is due solely to plasma electrons. In that limit primary electrons are nonexistent and no anomalously strong tail of fast electrons exists to enhance the ambipolar plasma loss rate[5]. Combining 1–3 and setting $n = n_e = n_i$ we obtain:

$$\langle \sigma v_e \rangle n_n \cong \frac{A}{V}(T_e/m_i)^{\frac{1}{2}} \tag{4}$$

$\langle \sigma v_e \rangle$ is given in various references[12–14] for a Maxwellian distribution of ionizing electrons. The strong dependance of $\langle \sigma v_e \rangle$ on T_e dominates equation (4), the characteristic form of which is identical for all gases and is shown, schematically, in Fig. 1.

The principal result to be obtained from this simple parameter study is that for some minimum fill gas pressure plasma electron ionization is unable to sustain a discharge. Such low pressure discharges can only be sustained by primary ionization.

Typically, ion source discharges having $Vp/A \lesssim 10^{-2}$ cm-Torr will be dominated by primary electron ionization.

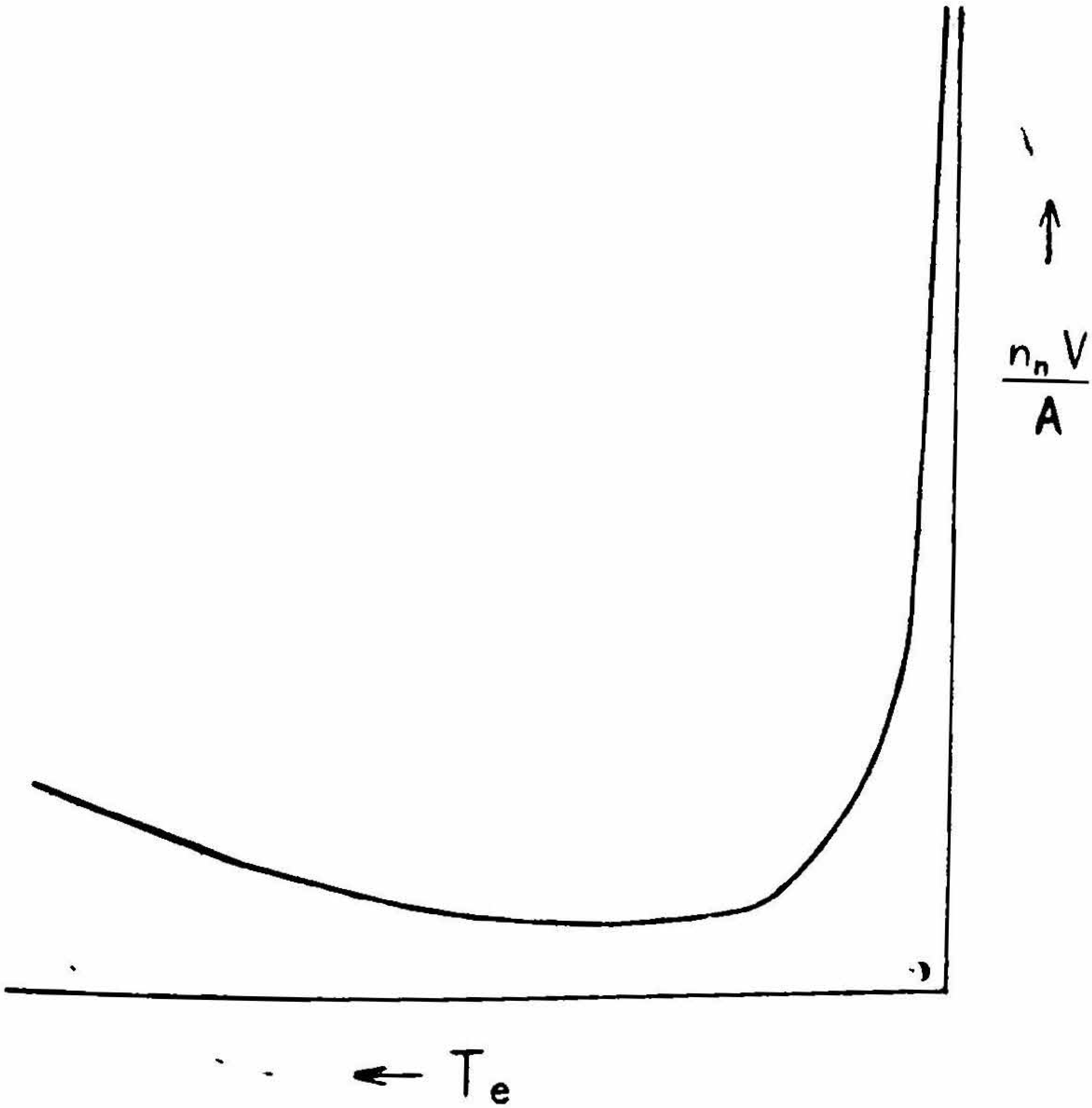

FIG. 1. General dependance of discharge electron temperature on fill gas pressure assuming secondary ionization only.

The model we will now construct will assume we are in this low pressure regime where plasma electron-gas ionization can be neglected. We could use the work of Demirkhanov *et al.*[15] to correct the loss rate of equation (2) and thereby incorporate the effect of non-Maxwellian fast primary electrons. However, the experimentally[16] observed ratio of primary to plasma electron densities is so low as to correct the free-fall model by less than 10% and we will neglect it here. The stability of the beam-plasma interaction[5] also requires this limit. We will, however, replace the proportionality in equations (2) and (3) by the constants obtained numerically by Caruso[17] and Self[18] so that the ion loss rate becomes :

$$\oint n_i \vec{v} \cdot \vec{dA} = 1/3\, n_i (2T_e/m_i)^{\frac{1}{2}} A. \qquad (5)$$

It is appropriate to employ the low n_n assumption for common ion sources[15] having well ionized plasmas and n_e in the range of $10^{13}\,cm^{-3}$. At these plasma densities and typical electron plasma temperatures of ~ 5 eV the classical Coulomb collisional mean free path length is of the order of a millimeter, the collision frequency being given by:

$$\nu = 5\cdot8 \times 10^{-6}\, n_e \Lambda / T_e^{3/2} \tag{6}$$

where the Coulomb logarithm is :

$$\begin{aligned} \Lambda &= 23 - \ln (n_e^{1/2} T_e^{-3/2}), \quad T_e \lesssim 10\,\text{eV} \\ &= 24 - \ln (n_e^{1/2} T_e^{-1}), \quad T_e \gtrsim 10\,\text{eV} \end{aligned} \tag{7}$$

For the parameters of greatest interest, then, Coulomb collisions are adequate to thermalize the plasma electrons, consistent with our desire to ignore the effects of electron plasma oscillations. Equating (5) with the creation rate by primary electrons

$$1/3\, n_i (2T_e/m_i)^{1/2} A = \frac{I}{q}\left[\frac{1 - e^{-(V/A)\,(1/\lambda_i + 1/\lambda_x)}}{1 + \lambda_i \lambda_x}\right] \tag{8}$$

where λ_i and λ_x are the mean free paths for ionization and atomic excitation processes (by primaries) and I is the (primary) current flowing in the source.

In the free-fall model[4] the average power required for gas ionization is:

$$P = T_e \ln [0\cdot8\, (m_i/m_e)^{1/2}]\, \frac{I}{q}\left[\frac{1 - e^{-(V/A)\,(1/\lambda_i + 1/\lambda_x)}}{1 + \lambda_i \lambda_x}\right]. \tag{9}$$

This can be equated to the power supplied through electron Coulomb collisions[19]:

$$P = I\, \frac{3 \ln \Lambda}{4\pi}\, \frac{m_e}{v_p^2}\, \frac{\omega_{pe}^4}{n_e}\, \frac{V}{A} \tag{10}$$

where v_p is the primary velocity, and ω_{pe} is the electron plasma frequency.

For space charge limited thermionic cathodes (typical of many sources) we must further require that :

$$I = qan_e\, (T_e/2\pi m_e)^{1/2}\, J_0\, (\text{eV}/T_e) \tag{11}$$

where q is the electronic charge, a is the cathode area, and J_0 is the function given by Crawford[20], having a value which typically falls between 1 and 2.

The simultaneous solution of equations (8) through (11) is compared with typical experimental results[16] in Fig. 2, for hydrogen gas. The source impedance characteristics are reproduced to within the accuracy of the experimentally available data. A further comparison with the observed ion saturation current available is made in Fig. 3, again for hydrogen and using the additional equation :

$$j_{sat} = 1/3\, n_i\, (2T_e/m_i)^{1/2}. \tag{12}$$

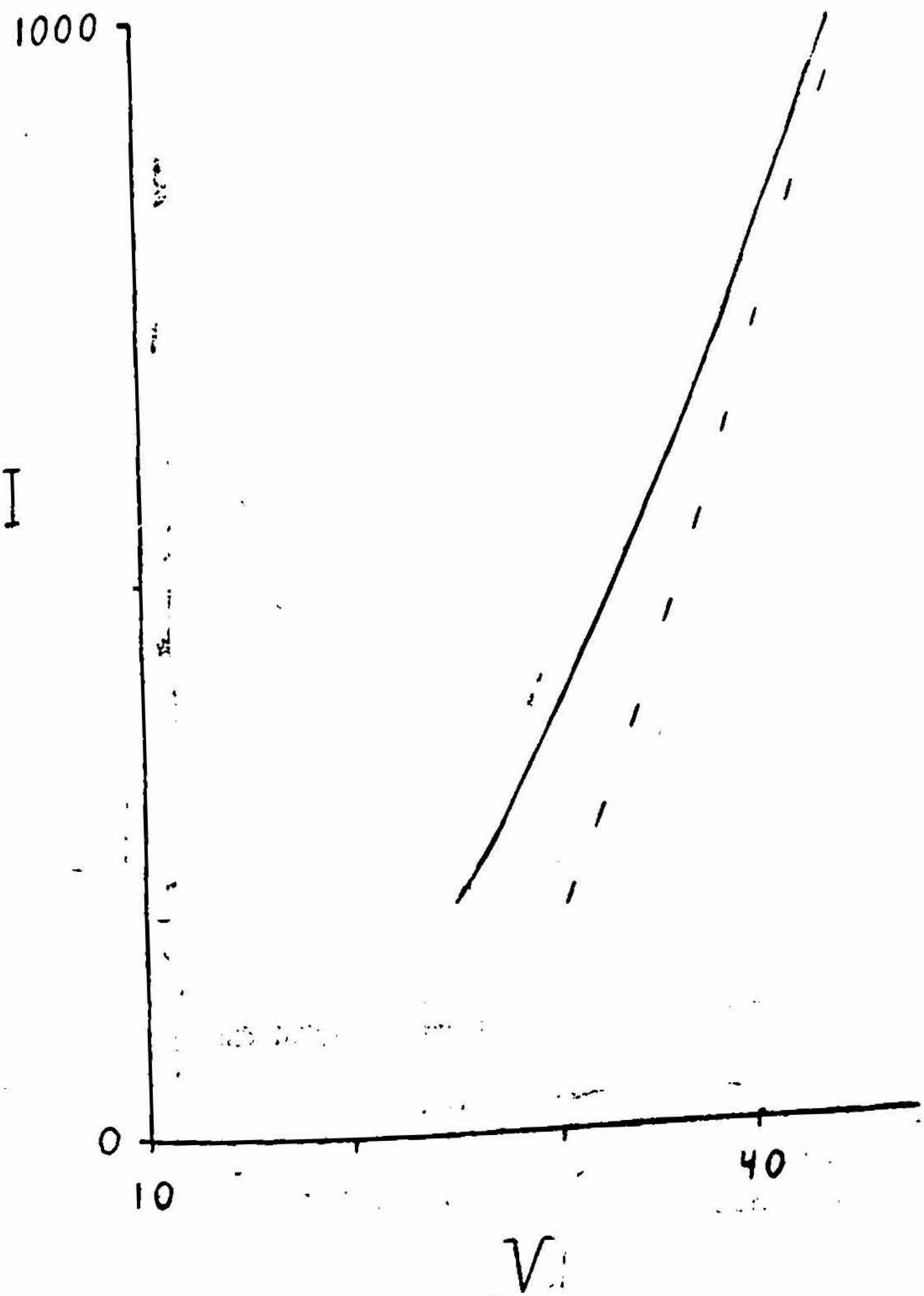

FIG. 2. Discharge current, in amperes, *versus* the applied discharge voltage. Solid line: experiment, Dashed line: theory.

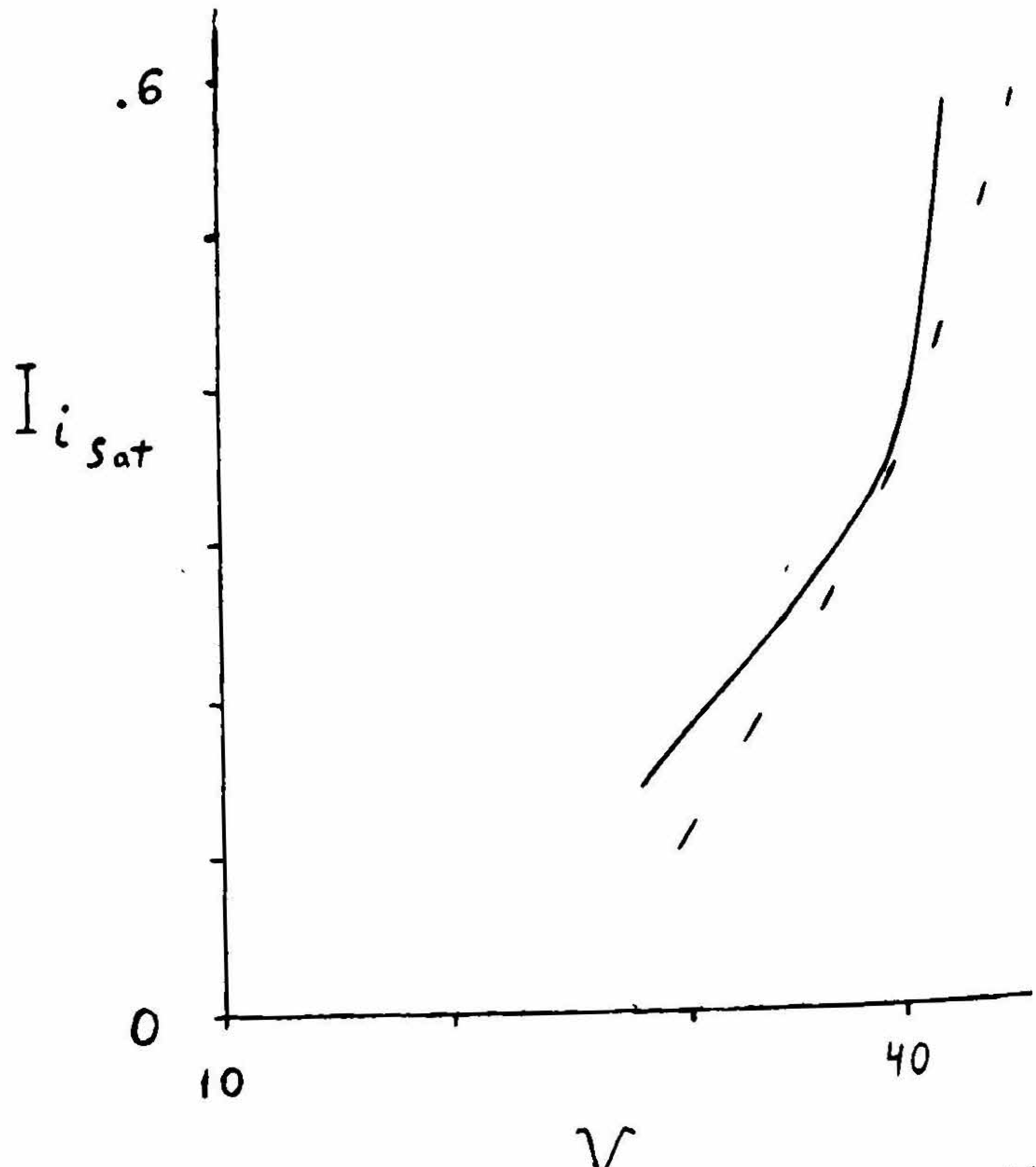

FIG. 3. Ion saturation current, in amperes, *versus* the applied discharge voltage. Solid line: experiment, Dashed line: theory.

Again the comparison is quite good.

The present simple theory may prove useful in designing and optimizing ion sources for fusion experiments.

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