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EFFECTS OF LOW Z IMPURITIES DURING THE STARTUP PHASE OF A LARGE TOKAMAK

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ABSTRACT

The requirements placed on a tokamak ohmic heating system (i.e. loop voltage) to initiate the plasma become more severe as the size increases because of the current density decrease. During the startup phase even small concentrations of low Z impurities can affect the plasma energy balance very substantially and have very important effects on the evolution of the discharge. The startup phase has been studied using a simple zero dimensional computer code. Because the dominant energy loss mechanisms during startup, radiation, and ionization are a volume effect, the zero dimensional code was adequate to treat this phase. The results of this study which have been applied to TFTR indicate that the plasma evolution is a sensitive function of the applied loop voltage, impurity concentration, initial filling pressure and the manner in which gas is fed into the discharge.

I. INTRODUCTION

The initiation of a discharge in a large tokamak, for instance the proposed TFTR, T-20, JET or JT-60 devices, poses some new and important problems which have not been previously encountered in smaller presently operating devices. In the quasi-steady state, the energy input per unit volume from the ohmic heating scales roughly as R^{-2}. Yet, the energy loss due to ionization and line radiation by both the constituent gas as well as impurities does not scale favorably with increasing size. The significance of this limitation on the scaling of the ohmic heating power has been recognized for a long time especially with respect to high Z impurities which might limit the ultimate electron temperature in a discharge and the performance of an eventual reactor [1]. What has not been stressed previously is that the presence of low Z impurities are also very important in the early stages of the discharge and can determine the success or failure of initiating a discharge.

Before discussing the time dependent zero dimensional model used to simulate the startup phase of a tokamak discharge, an illustration of this problem will be presented. The safety factor, q, imposes a limitation on the maximum average current density, $\langle j \rangle = \frac{1}{2q}\frac{B_T}{\mu_o R}$. Hence, the average ohmic heating power, $P_{OH} \simeq \eta \langle j \rangle^2 < \eta \left[\frac{1}{2q}\frac{B_T}{\mu_o R}\right]^2$. Another limitation imposed on the plasma by the ohmic heating system is the value of the one turn loop voltage, V. Thus,

$$P_{OH} \leq (V/2\pi R)^2/\eta.$$

The maximum corresponds to having no additional inductive voltage to increase the plasma current. In Fig. 1, the two limitations are indicated for the startup phase of the proposed TFTR experiment for $q=3$, $V=150$ V, $R=350$ cm, and $B_T=3.67$ T. In addition for comparison, the energy loss from line radiation is indicated for a plasma with an electron density of $3 \times 10^{13} \mathrm{cm}^{-3}$ and an oxygen impurity density of $9 \times 10^{11} \mathrm{cm}^{-3}$. This calculation taken from Cox and Tucker [2] assumes coronal equilibrium. The choice of $q=3$ may be somewhat conservative because generally $q \simeq 1$ on the axis. Thus, near the axis, the temperature might be expected to be somewhat higher than the average temperature and correspondingly the energy loss from oxygen line radiation and the power input less. Nonetheless, the volume averaged energy balance might be fairly close to what is indicated by assuming $q=3$. Several implications can be inferred from Fig. 1 with respect to the effect of low Z impurities and the design of the ohmic heating system. To minimize the deleterious effects of the low Z impurities it is beneficial to decrease the electron density during the startup phase since $P_{rad}=n_e n_I F(T_e)$. While increasing the loop voltage above 150 V may be somewhat beneficial, increasing the voltage to an arbitrarily high value is not justified because of the MHD limitations indicated by the safety factor q.

These very simple observations have several implications with respect to designing the ohmic heating system of a large device. In general, engineering considerations usually favor a low breakdown voltage. As shown, the maximum energy input for a given loop voltage as well as MHD considerations put further limits on the desired loop voltage. This qualitative picture very quickly indicates the range over which a suitable choice of loop voltage can be made.

In the succeeding discussion, the time dependent model will be used to present a more quantitative picture as well as present clearly the effects of ionizing the hydrogen gas in a pure discharge. In Sec. II, the model will be discussed and in Sec. III the results of the model will be applied to TFTR. Section IV is a very brief summary of the main results.

II. MODEL

During the startup phase of a tokamak discharge, the principal energy loss mechanisms are ionization and charge exchange of the constituent gas and also ionization and line radiation of the low Z impurities. This is in contrast with the latter part of the discharge where particle and energy transport as well as high Z impurity radiation are likely to be more important. Because particle and energy transport is not the dominant loss mechanism, it is appropriate to treat the problem zero dimensionally. The constituent gas is assumed to be hydrogen with a small admixture of oxygen impurities. Carbon, another common low Z impurity, can be treated similarly. The following set of differential equations describe the proton density, electron thermal energy, ion energy, neutral density and plasma current evolution:

$$\frac{dn_p}{dt} = n_e \, n_o \, S_{ion} - \frac{n_p}{\tau_p} \qquad (1)$$

$$\frac{3}{2}\,\frac{d}{dt}\,(n_e\,k\,T_e) = \eta j^2 - W_{ion}\,n_e\,n_o\,S_{ion} - Q_{ie} - \frac{3}{2}\,\frac{n_e\,k\,T_e}{\tau_e} - P_{rad} - P^{o}_{ion} \qquad (2)$$

$$\frac{3}{2}\,\frac{d}{dt}\,(n_i\,k\,T_i) = Q_{ie} - n_p\,n_o\,S_{cx} - \frac{3}{2}\,\frac{n_i\,k\,T_i}{\tau_i} \qquad (3)$$

$$L_p\,\frac{di_p}{dt} + i_p\,R_p = V \qquad (4)$$

$$V_v\,\frac{d}{dt}\,n_o = -V_p\,\frac{d}{dt}\,n_p + \Gamma \qquad (5)$$

In Eq. 1, S_{ion} is the ionization rate coefficient and τ_p is the proton particle confinement time. In Eq. 2, W_{ion} is the energy lost per ionizing a hydrogen atom; Q_{ie} is the electron-ion energy transfer, τ_e is the electron energy confinement time; P_{rad} is the power lost by oxygen line radiation and P^{o}_{ion} is the power lost in ionizing the oxygen impurities. In Eq. 3, S_{cx} is the charge exchange rate and τ_i is the ion energy confinement time. In Eq. 4, L_p and R_p are the plasma inductance and resistance while V is the externally applied loop voltage. In Eq. 5, V_v and V_p are the volume of the vacuum vessel and the plasma respectively and Γ is the flow of cold hydrogen gas into the vacuum chamber. All of the other symbols correspond to their customary meaning.

W_{ion} includes the energy lost by ionization, dissociation and radiation of the hydrogen gas. It is set equal to 20 eV. The ionizatior rate coefficient, S_{ion}, is represented by an analytic fit to Lotz's data [3]. The resistivity, η, is simply the Spitzer resistivity with a small correction at low electron densities to account for electron-atom collisions. During startup, the neoclassical enhancement of the resistivity is unimportant. The electron-ion energy transfer, Q_{ie}, is the classical value. It is implicity assumed that the impurities constitute only a small fraction of the plasma ion density. Hence, in Eq. 3, the charge exchange loss of the impurity ions is neglected. During the startup phase, the first few msec of the discharge, the major and minor radii are assumed to be constant, and thus, the plasma inductance is a constant. In Eq. 5, the volume factors take into account that the neutrals are uniformly distributed within the vacuum volume while the plasma occupies a smaller volume limited by a limiter.

Equations 1-5 are sufficient to describe a discharge without impurities. The oxygen impurities are treated in a manner very similar to that used by Düchs and Griem [4] and also recently by Düchs [3]. Eqs. 6-8 describe the time evolution of the oxygen ionization states.

$$V_v \frac{d}{dt}(O_1) = V_p \left[-n_e O_1 S_1 + n_e O_2 (\alpha_1 + \gamma_1 n_e) + \sum_{k=2}^{9} \frac{O_k}{\tau_p^k} \right] \qquad (6)$$

$$\frac{d}{dt} O_k = n_e O_{k-1} S_{k-1} - n_e O_k \left[S_k + \alpha_{k-1} + \gamma_{k-1} n_e \right] + n_e O_{k+1} (\alpha_k + \gamma_k n_e) - \frac{O_k}{\tau_p^k} \qquad (7)$$

$$\frac{d}{dt} O_9 = n_e O_8 S_8 - n_e O_9 (\alpha_8 + \gamma_8 n_e) - \frac{O_9}{\tau_p^9} \qquad (8)$$

O_k is the oxygen density of the k'th ionization state; S_k is the ionization rate of the k'th state; α and γ are the radiative and three body recombination rates. The ionization, radiation and three-body recombination rates are calculated using the results of Düchs [3] and Düchs and Griem [4]. Finite partilce confinement time is included as well as impurity recycling. Z_{eff} is calculated from the proton and oxygen concentration. According to Düchs [3], the power lost by ionization and recombination can be expressed by:

$$P_{ion}^{O} = \sum_{j=1}^{8} \chi_j \, n_e \, (S_j \, O_j - \gamma_j \, n_e \, O_{j+1}) + \frac{3}{2} kT_e \, \alpha_j \, n_e \, O_{j+1}$$

where χ_j is the ionization potential.

For simplicity, the oxygen impurities are all assumed to be in the ground state at the start of the calculation, and no time dependent flux of oxygen is included in the model. Recently Griem [5] has suggested a modification of the original equation proposed by Düchs and Griem [4] for the power loss due to line radiation. This modification has been included in the model to calculate the power loss due to line radiation.

The above system of differential equations, Eqs. 1-8, were solved numerically assuming a set of initial conditions corresponding to a plasma preionization of $n_e = 1.0 \times 10^{11}$ cm^{-3}, $T_e = 1$ eV, $T_i = 1$ eV and a filling pressure consistent with the final desired electron density. Fortunately, the results are relatively insensitive to the initial temperature and density.

At this point, it is worthwhile to discuss some of the inherent limitations in the model. Clearly, no one dimensional effects are treated for instance skin currents and plasma transport [6]. The effects of plasma transport are taken into account phenemologically through τ_p, τ_e and τ_i. τ_p is set equal to 10 msec and τ_e and $\tau_i = \tau_p/2$. At these early times, the particle and energy transport is not well known. The results of the ST experiment indicates that the particle confinement time was ~2 msec at early times [7]. Thus, the choice of 10 msec may be somewhat optimistic though in a larger device particle confinement might be expected to increase somewhat. Fortunately, the results are not sensitive to this choice.

The inclusion of a finite particle confinement time (τ_p^k = 10 msec) for the impurity ions must also be taken with caution because classically the impurities diffuse inward and would be expected to have very long confinement times. The inclusion of a finite confinement time was motivated by the results of the TFR group [8] which observed significant oxygen recycling. Once again, the results are not sensitive to this choice.

Another assumption inherent in Eq. 1 and 4 is that the plasma does not screen out the neutrals. This assumption is consistent with the concept of growing a small plasma (a ≃ 20 cm) off a limiter. In this case, as in present experiments, the neutrals do appear to be able to penetrate into the discharge at least during early times. Nonetheless, the treatment of neutral penetration must be viewed as quite approximate. This limitation is not as significant as it might appear at first glance, because for a desired final electron density the gross energy balance should be essentially correct. As will be shown later, the temporal evolution of the discharge is essentially determined by the overall energy balance.

Perhaps the greatest uncertainty (as great as a factor of 3) is in calculating the oxygen line radiation for as discussed by Düchs and Griem [4] there are significant possible errors in the ionization and recombination rates and only the resonant lines are accounted for. This uncertainty is further complicated by not knowing a priori the oxygen concentration or the time dependent flux of oxygen entering the discharge. These difficulties with calculating the oxygen line radiation are also encountered in a one-dimensional treatment of the startup phase. In spite of the various uncertainties in the model, it appears that several conclusions can be obtained about the startup phase of a large tokamak discharge.

III. RESULTS

All of the calculations were performed for the proposed startup of the TFTR experiment. As noted above, the discharge is assumed to begin near the outer vacuum wall with a minor radius of $a = 20$ cm and a major radius of $R = 350$ cm, the ratio of the vacuum volume to the plasma volume was 30.

In all of the calculations, in order to obtain some general results, the applied loop voltage is assumed constant in time. Another zero dimensional code is used in the design and engineering of the TFTR device which includes all of the actual circuit parameters. Figures 2-4 are for a $Z_{eff} = 1$ discharge without any oxygen impurities. Figure 2 is a plot illustrating the current and electron temperature evolution as a function of time for different applied one turn voltages. The initial neutral density if fully ionized corresponds to a final average electron density of 3×10^{13} cm^{-3}. As can be seen if the voltage decreases to below ~55 V, the current and temperature fail to evolve properly. This corresponds to failing to fully ionize the gas because of insufficient ohmic heating power. The remaining neutrals act as an energy loss mechanism by ionization and charge exchange loss. In practice even in this case, the discharge may actually succeed in evolving because the plasma would tend to screen out the neutrals. Also some of the neutrals might stick to the wall and not recycle in resulting in a lower electron density. Even if the discharge does succeed in evolving, it is desirable to avoid operating in a regime where the current and temperature fail to evolve properly because the voltage on the surface of the plasma is quite high for a long time and this can result in a runaway discharge.

Because the model assumes a thermal electron distribution function, it is not possible to evaluate the evolution of the distribution function beyond calculating E/E_{CRIT} [9] to determine when the plasma would be susceptible to runaway electrons. In general in the early part of the discharge ($t < 1$ msec), even when the discharge succeeds in evolving it appears that a considerable fraction of the distribution function could runaway. In practice, the acutual production of runaways appears to be fairly sensitive to the plasma equilibrium and stray fields, both of which could be altered somewhat to minimize the runaway production. The entire question of producing a runaway discharge in an actual device is beyond the scope of this model and should be carefully studied. Nonetheless, it appears that a potentially more serious situation occurs when the discharge fails to evolve normally and the voltage remains high for a long period of time during which runaways are more likely to be produced.

The voltage, V_c, at which the model predicts that the current and temperature will fail to evolve properly is a sensitive function of the filling pressure, as illustrated in Fig. 3. This indicates that it is desirable to startup the plasma in as low a filling pressure as possible. (The lower limit is usually determined by obtaining a runaway discharge.) This is qualitatively consistent with the results of a number of recent tokamak experiments where regimes of high electron density were attained by starting at lower densities and then pulsing gas in. Figure 4 is a result of a calculation in which the initial filling pressure corresponds to an electron density of $1. \times 10^{13}$ cm^{-3} and the gas is injected to give a final electron density of 3×10^{13}. In the pulsed gas case, the current evolves to a higher value and fewer resistive-volt seconds were consumed. During the startup phase of the TFTR device when the plasma minor radius is small compared with the minor radius of the vacuum vessel, the influx of cold gas and also low Z impurities from the walls can in principle be quite substantial. Hence, experimentally the flow of gas during the startup phase may not be a very controllable parameter since the gas flow will be determined in part by the prior history of the device and also the surface conditions.

Figure 5 dramatically illustrates the effects of low Z impurities. In this case, the oxygen ion density constitutes 2% of the plasma ion density of $3 \times 10^{13} \mathrm{cm}^{-3}$ and a 150 V loop voltage is supplied. The pure hydrogen case is presented for comparison. As can be seen even with this modest amount of oxygen impurities, there is a very significant deleterious effect on the current and temperature evolution. Because of engineering consideration, a high loop voltage is usually applied only to get through the startup phase and then the applied loop voltage is decreased. If the voltage is decreased before 10 msec to less than ~90 V, the current would decrease because iR>V. To overcome the problems imposed by low Z impurities, the discharge must be initiated at lower filling pressures and the gas pulsed in at a later time. Nonetheless, the presence of low Z impurities can quite significantly alter the energy balance and the evolution of the discharge.

One other solution to some of these problems is auxiliary heating during the startup phase. While this solution will work if there is a suitable auxiliary heating method and may have to be used in the generation of devices after TFTR, T-20, JET and JT-60, it is quite expensive. In Fig. 5 where the oxygen impurities are significantly affecting the energy balance, the maximum power input from the ohmic heating system is ~4 MW. Thus for auxiliary heating to be a significant energy input, it will have to supply power on the order of the ohmic heating power. Though compared with the 40 MW of neutral beam heating being planned for TFTR, this is not a great requirement, it is far from insignificant. Hence, it is advantageous to attempt to startup the discharge if possible with the ohmic heating system alone.

IV. CONCLUSION

The model indicates several important aspects about the startup phase of a large tokamak. First, the presence of even quite small concentrations of low Z impurities can have quite substantial effects on the current and temperature evolution. Second, the loop-voltage requirements imposed by the plasma can be calculated. Third, the control of the flow of gas and the initial neutral density appears to be quite important.

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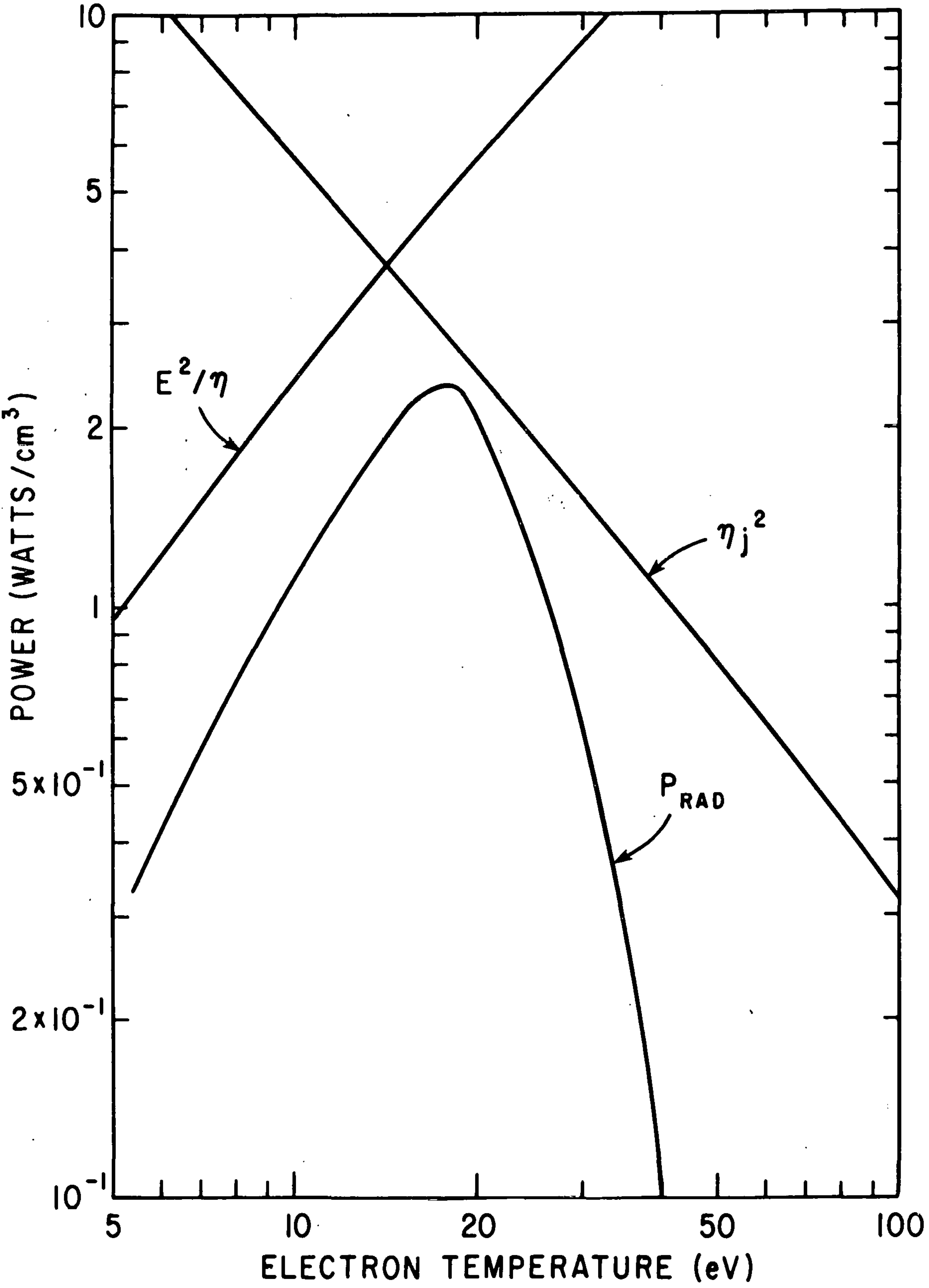

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Fig. 1. The power radiated by oxygen line radiation is compared with the maximum power input.

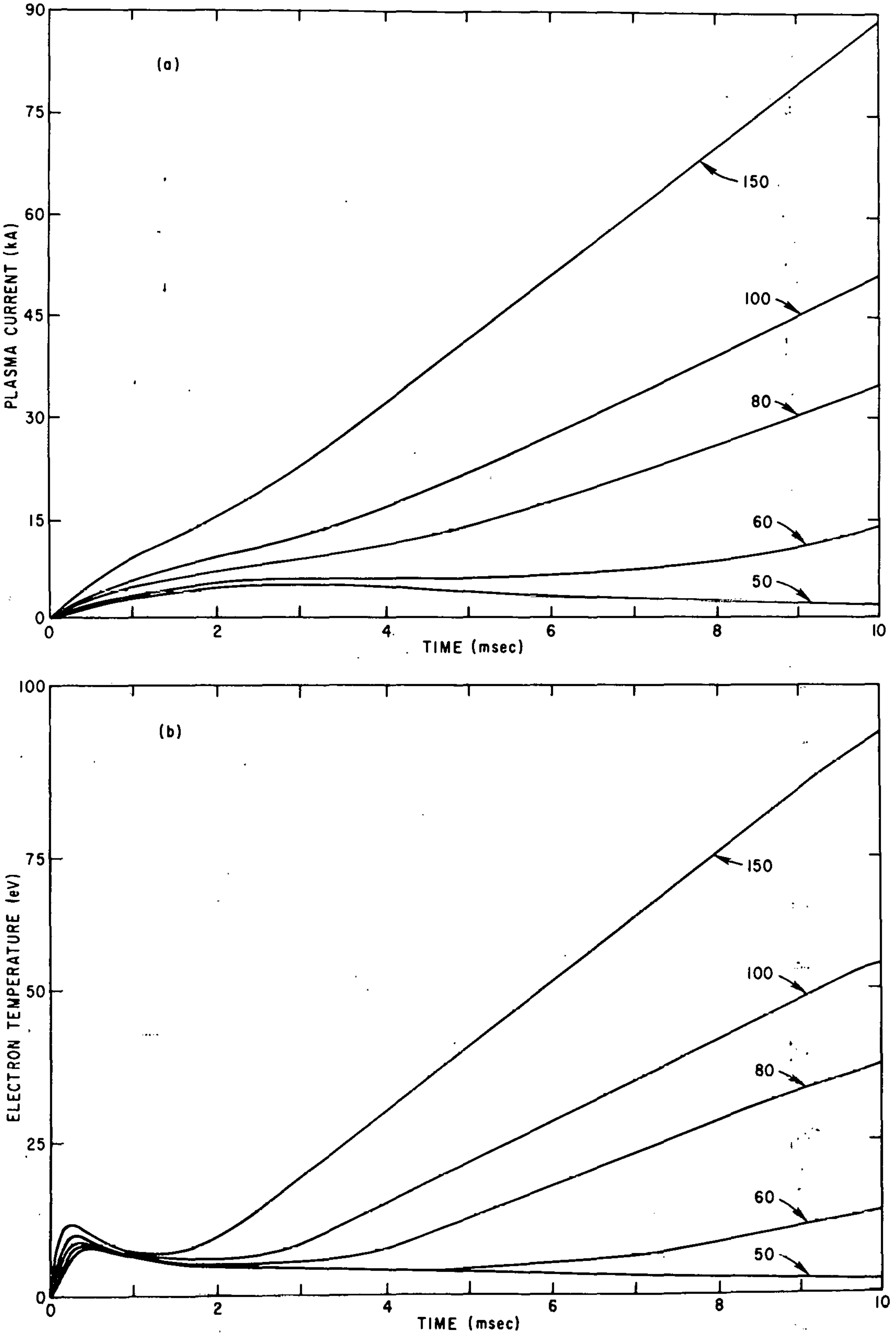

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Fig. 2. a and b illustrate the temporal evolution of the plasma current and electron temperature in a pure hydrogen discharge as a function of applied loop voltage. The filling pressure corresponds to a final electron density of 3.0×10^{13} cm^{-3}.

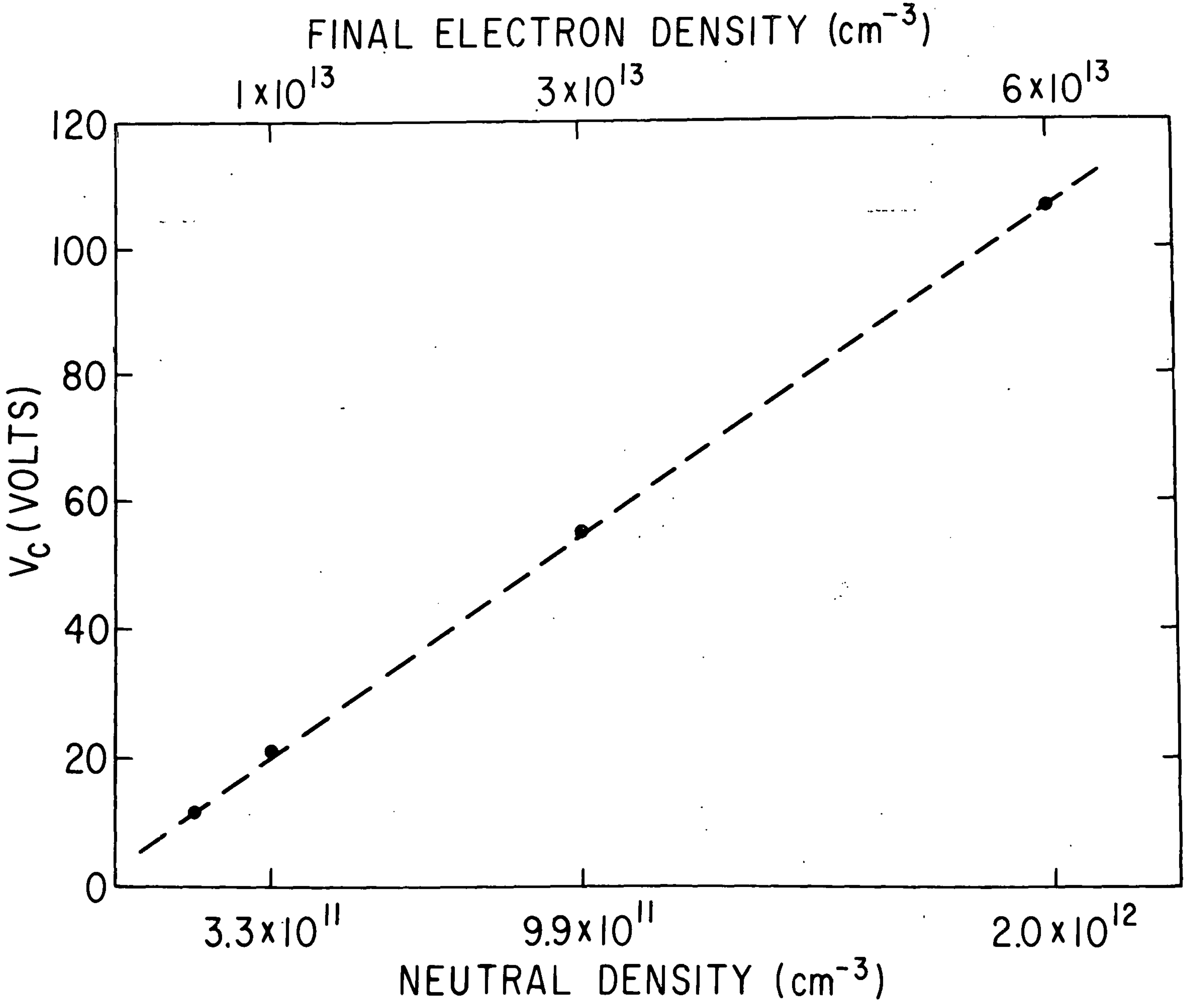

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Fig. 3. This is a plot of the minimum required loop voltage to establish a discharge as a function of initial neutral density. The corresponding final electron density is also indicated.

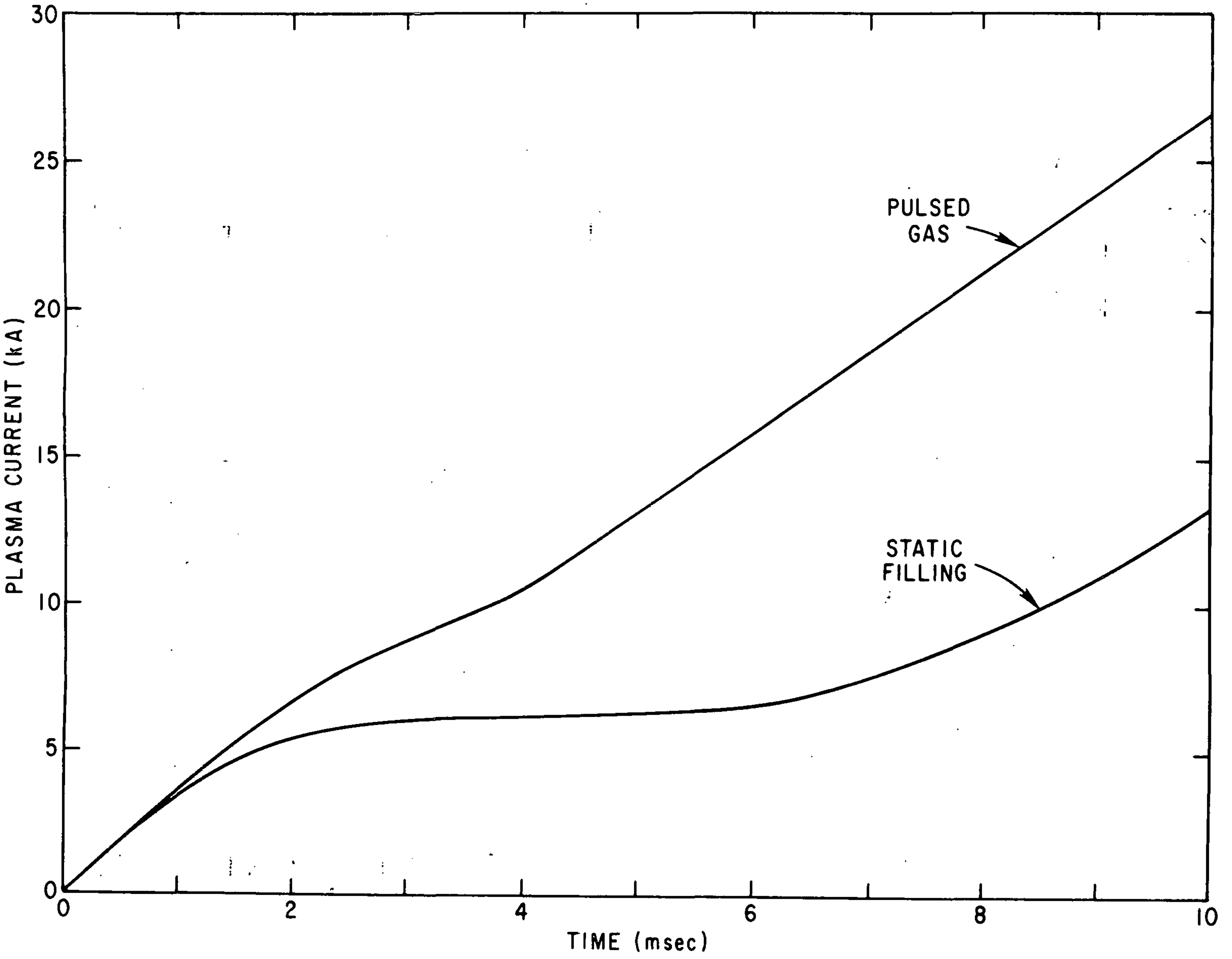

Fig. 4. This shows the effects of pulsing gas versus static initial filling. In both cases, the loop voltage is 60 V and the final electron density is $3. \times 10^{13}$ cm^{-3}.

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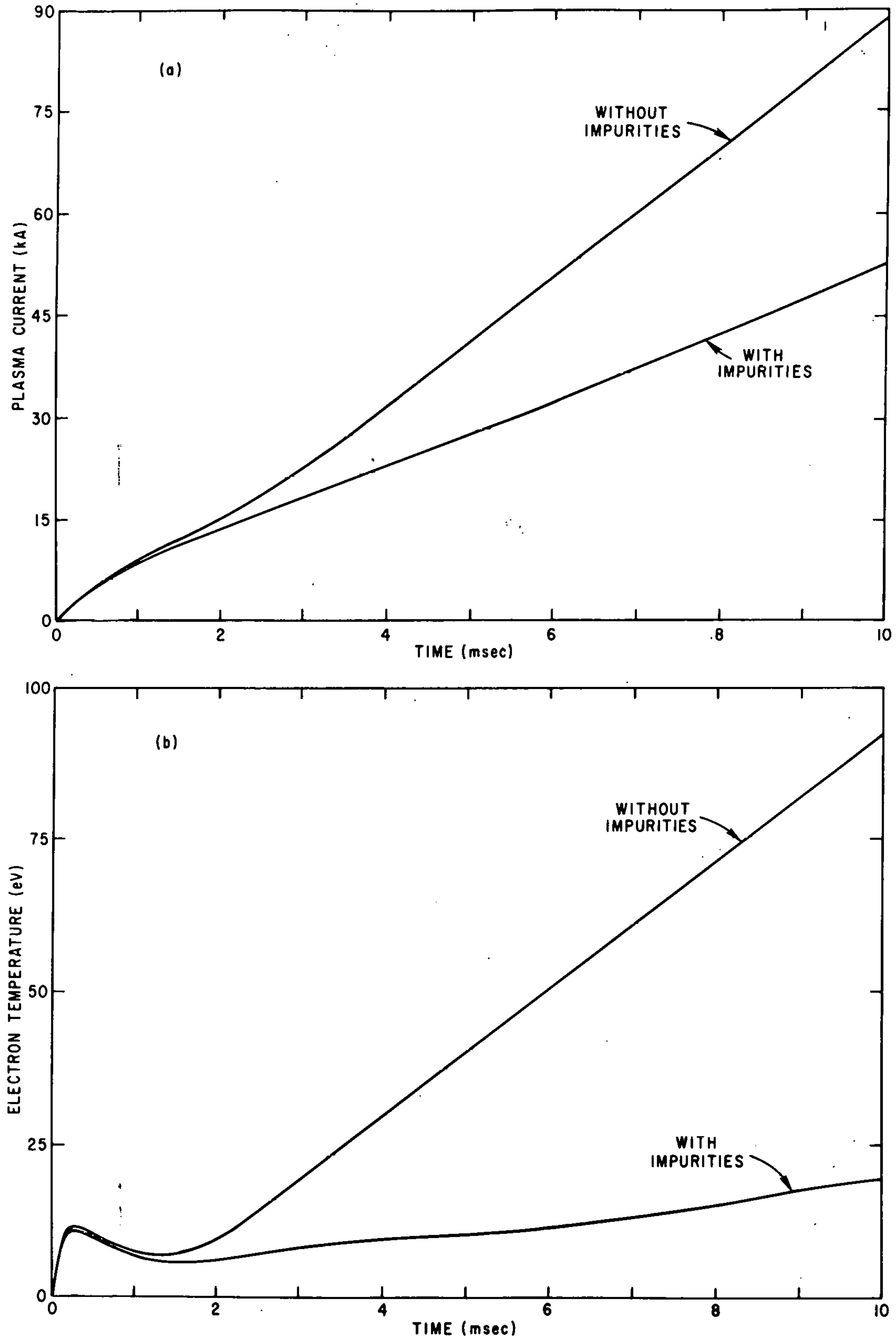

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Fig. 5. a and b illustrate the temporal evolution of the plasma current and electron temperature in a hydrogen discharge with 2% oxygen impurities. The initial neutral density corresponds to a final ion density of 3×10^{13} cm^{-3} and the loop voltage is 150 V.