PHYSICAL REVIEW LETTERS

VOLUME 13 | 10 AUGUST 1964 | NUMBER 6

OBSERVATION OF BURNOUT IN A STEADY-STATE PLASMA*

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(Received 2 July 1964)

Experimental observations have been made which support our theoretical model[1] that predicts the conditions for burnout in a steady-state plasma. The model assumes that in the normal plasma, the electron temperature is limited by excitation processes in the un-ionized gas; in other words, by radiation cooling. As the gas input is reduced, or the applied power increased, the excitation processes finally can no longer dissipate the applied power. Beyond the critical point, the electron temperature suddenly rises, the gas becomes almost completely ionized, the plasma potential becomes quite positive, and energetic positive ions are ejected from the plasma. The ejection of high-energy ions from various plasmas has been noted before,[2] and various mechanisms have been proposed for the phenomena.[3]

The apparatus used in this study is the pressure-gradient arc, shown schematically in Fig. 1. In this apparatus, electrons from a hot tantalum cathode flow along lines of magnetic force into a hollow, copper anode. Gas is fed into the hollow anode, forming a local high-pressure region, and a localized plasma is formed in the hole. At modest power inputs, a quiescent stream of plasma flows from the opening opposite the cathode. At higher power inputs, a "bursting" effect is observed, and high-energy ions are ejected, as shown in Fig. 2.

In our theoretical analysis of the phenomena, we make several crude assumptions to get a first approximation to reality. First, we assume that the incident electron beam transfers its energy to the plasma electrons with 100% efficiency. Such an assumption is reasonable in the light of the various experiments showing strong plasma-beam interactions.[4]

Second, we assume that in the non-burned-out case, the major loss of electron energy is by excitation processes in the un-ionized gas. Thus, the power balance equation, to a first approxi-

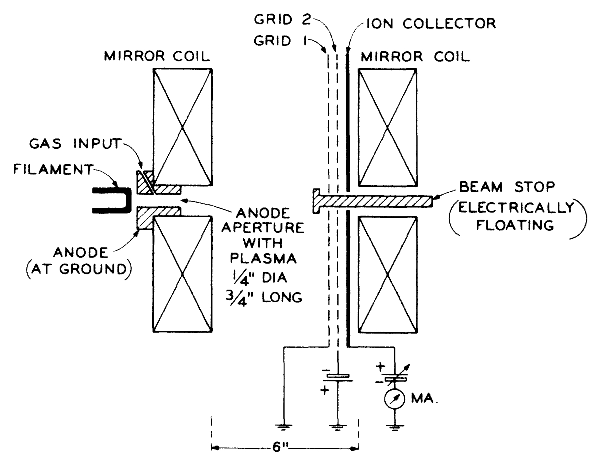

FIG. 1. Schematic of apparatus showing gridded probe used to measure positive ion flux. Grid 2 repels electrons. Grid 1 prevents electric field lines from grid 2 from leaking into the main volume. Operating conditions: Pressure in the main volume is about 10^{-5} Torr; the magnetic field is about 4500 G in the mirrors and 1500 G in the midplane. The mirror configuration is not needed for the "bursting" phenomena to occur, but was used merely for convenience in this case. The gas used was argon. The cathode voltage was about minus 200.

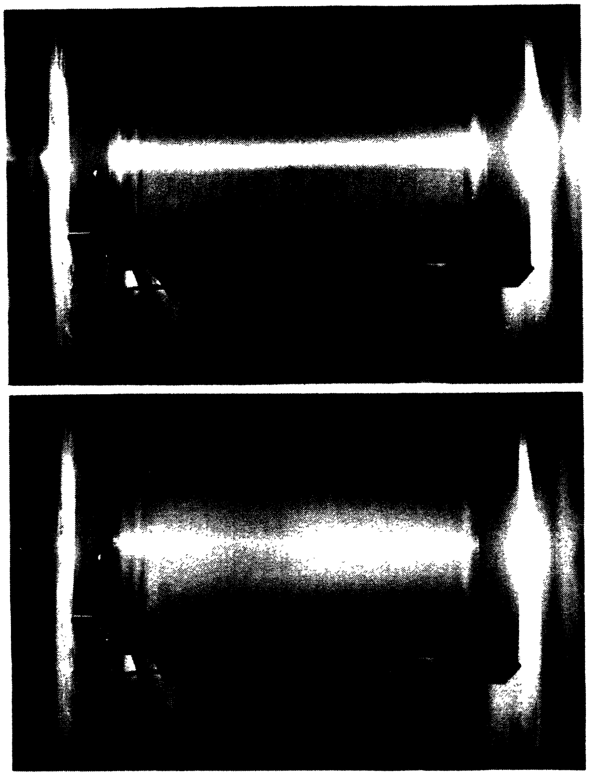

FIG. 2. Top: normal, quiescent plasma; bottom: ion-emitting plasma. Note the broad band of light which is due to energetic ions ejected across the magnetic field. The axial magnetic field runs left to right. In these pictures, there is a plasma source at both ends of the plasma column.

mation, is

$$W = n_e n_g \sigma_{ex} v_e \Delta E V. \qquad (1)$$

Here, W is the power input to the plasma (erg sec^{-1}), n_e is the electron density (cm^{-3}), n_g is the gas density (cm^{-3}), σ_{ex} is the excitation cross section (cm^2), v_e is the mean electron velocity (cm sec^{-1}), ΔE is the energy lost per excitation (erg), and V is the plasma volume (cm^3).

Since the plasma is assumed to be dense, we replace the electron density n_e with the ion density n_i. (Single ionization is assumed.) Now, we assume that in this apparatus,

$$n_i + n_g = n_{g0}, \qquad (2)$$

where n_{g0} is the gas density in the plasma region before any power is applied. We can substitute Eq. (2) into Eq. (1) to obtain a formula for the gas density in the plasma as a function of power input:

$$n_g = \tfrac{1}{2} n_{g0}(1 + \{1 - 4W/n_{g0}^2 \sigma_{ex} v_e \Delta E V\}^{1/2}). \qquad (3)$$

The equation predicts that as the power input is increased, n_g gradually decreases until the quantity in the radical becomes zero. Increasing the power input beyond this point causes the radical to become imaginary. Further analysis shows that what actually occurs is that n_g discontinuously drops to zero. At the transition, we find the following relationship:

$$n_{g0} = 2\{W/\sigma_{ex} v_e \Delta E V\}^{1/2}. \qquad (4)$$

Physically, what occurs at the transition is that at the critical point, an increase of input power causes n_e to grow, but n_g shrinks faster, so that the product $n_e n_g$ decreases. Thus an increase of input power causes a decrease of excitation loss, n_e further grows, n_g further shrinks, and a runaway condition occurs which ends with $n_g = 0$, or burnout. In multi-electron atoms such as argon, a similar burnout phenomenon should occur, except that a multi-electron atom would probably end up in a multiply ionized, difficult-to-excite state, but not necessarily be stripped of electrons.

Experimental verification of the above theory has been obtained both from old data (predating the theory), and from recent experiments. The old data show that the theory approximately predicts the gas pressure at which the plasma transition occurs. The new data show that (1) the gas density at which the observed "burnout" transition occurs has the correct functional dependence on power input; (2) in the burnout condition many, if not all, gas atoms are ionized; (3) in the burnout condition, the emission of spectral lines in deuterium and helium plasmas virtually ceases.

The dependence of gas input to the anode vs power input required for the transition is shown in Fig. 3. Gas density in the anode, n_{g0}, is assumed to be proportional to gas flow rate. As predicted by Eq. (4), n_{g0} should be proportional to $W^{1/2}$, since σ_{ex}, v_e, ΔE, and V in this case are constants. The plotted curve is for argon, since the blowup phenomenon, shown in Fig. 2, was easy to observe in this gas. The experimental curve shows the correct functional form, supporting the model.

Verification that many of the gas atoms in the plasma were indeed ionized in the burnout case was accomplished by means of particle accountability. Most of the ions escaping from the anode aperture, as shown in Fig. 2, were collected on a large gridded probe, as shown in Fig. 1, and the steady-state current was measured. Assuming that an equal number of ions stream from the

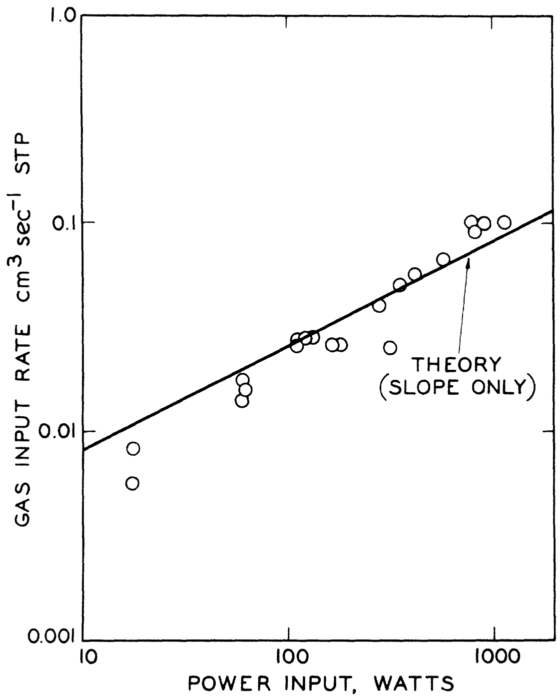

FIG. 3. Dependence of plasma transition from normal to ion-emitting state as a function of gas flow and applied power. Argon gas was used.

hole facing the cathode, and assuming that the argon was singly ionized, we find that 70% of the gas atoms fed into the apparatus reach the collector plate as ions. Thus, at the least, we can say that percentage of ionization is high.

From the fact that the argon atoms are almost completely ionized during their trip through the plasma, we can infer a lower density limit of about 10^{12} electrons cm^{-3} for the plasma. An upper limit for the plasma density is obtained by following Eq. (2) of our model, or by assuming that the ion loss rate after burnout is approximately the same as the gas atom loss rate before burnout. This upper plasma density limit is about 10^{14} cm^{-3}. The true electron density therefore probably lies between these two limits, $10^{12} < n_e < 10^{14}$.

Spectroscopic studies also strongly suggest that burnout has occurred. A modified form of the apparatus was constructed in which, among other modifications, a slit was provided so that we could look directly into the burnout region with a spectroscope. We intended initially to look for neutral atom depletion at burnout by comparing the intensity of spectral lines from He^0 with He^+. To our surprise, at the transition all light emitted as spectral lines essentially disappeared! A similar phenomenon was observed with D_2. The apparatus in all other ways continued to function properly, drawing the full voltage and current from the power supply, keeping the filament incandescent by ion bombardment (filament heating power is turned off once the plasma is established), and emitting enormous quantities of radiation at approximately the ion cyclotron frequency. Power accountability studies showed that most of the electron-beam power was not being dumped into the cathode half of the hollow anode, but was approximately equally shared between the cathode and anticathode halves of the anode. Thus, the apparatus seemed to contain plasma, although no spectral light was emitted.

Further experiments, involving the measuring of the energy of the ions emitted from the hollow anode, also support the burnout model, although lack of space prohibits more involved discussion.

If a burned-out, neutral-free plasma has been achieved, one has possibly an excellent environment for carrying out thermonuclear reactions. The strong radio radiation near the ion cyclotron frequency observed in the modified apparatus suggests that ions are gaining energy, which also is of interest to the thermonuclear program.

The authors wish to express their appreciation to W. F. Peed, who carried out the spectroscopic investigations in this report, and to J. G. Harris, who both constructed the apparatus and kept it in fine running condition.

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*Research sponsored by the U. S. Atomic Energy Commission under contract with the Union Carbide Corporation.

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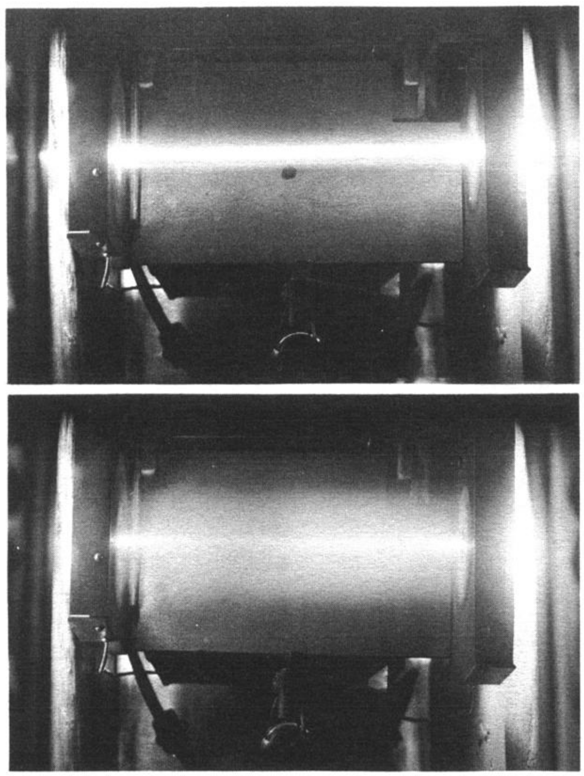

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