12

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Dependence of the Ion Current on Voltage in a Reflex Triode

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Results are reported on the dependence of the current of a pulsed ion beam produced in a reflex triode upon the applied resistive voltage in the range 0.6 to 1.3 MV. The measured peak ion current at the maximum voltage tested is 20 kA, corresponding to a current density of 200 A/~~cm^2~~ SQ.CM.

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DEPENDENCE OF THE ION CURRENT ON VOLTAGE IN A REFLEX TRIODE

During the last few years there has been increased interest on the production of intense ion beams[1-11] using the existing pulsed power technology initially developed for the generation of relativistic electron pulses. Recent intensive studies of such ion beams have furnished valuable information on their properties and propagation characteristics. However, presently very little is known about the scaling of their current with the applied voltage. In this paper we report experimental results on the variation of the ion current (I_i) with applied resistive voltage (V_o) in the range 0.6 to 1.3 MV.

A schematic of the experiment is shown in Fig. 1. Electrons emitted from the 23.0 - cm O.D., 1.5 - cm thick annular carbon cathode are accelerated by the 60 nsec duration positive voltage pulse that is applied on the anode from the VEBA generator[12], pass through it and form a virtual cathode. The anode is constructed from 12 μm thick solid polyethylene film interwoven between 0.7 mm diameter metal wires spaced 2.8 cm apart as shown in Fig. 1. The metal wires serve the dual function of holding the plastic film in place and uniformly "turning-on" the cathode. The ions are extracted out of the plasma formed from the plastic by the oscillating electrons. The protons that are accelerated toward the virtual cathode pass through it and form a drifting beam. Both the triode and the drift region are immersed in a uniform magnetic field B_O, which can be varied from 0 to 10 kG.

The anode voltage is measured using a capacitive voltage divider, which is located behind the insulator of the diode. The anode current is measured by integrating the output (dI/dt) of a small pick-up loop that is situated in the

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vacuum side of the diode. Typical voltage (a), current (b) and dI/dt(c) waveforms are shown in Fig. 2. The origin of the first peak in the current waveform appearing about 10 nsec from the beginning of the pulse is not presently well understood.

The number of protons in the beam is measured by the nuclear activation technique[2-6,13] Briefly, this technique consists of measuring the radioactivity induced on a 3 - mm thick carbon target by the drifting protons. The numbers of protons is inferred from the measured number of γ-rays associated with the annihilation of positrons (β^+), which are produced from the decay of ^{13}N. The nitrogen is generated by the resonant reaction $^{12}C(p,\gamma)$ ^{13}N that has a threshold of about 400 keV. At the higher energies, the number of counts is corrected[13] for the activity of the $^{12}C(d,n)^{13}N$ reaction induced by the natural isotopic abundance of deuterium in polyethylene.

The peak ion current is inferred from the measured number of protons by the activation technique and the ion pulse shape determined with a scintillator-photodiode system. A micron thick layer of aluminum on the face of the scintillator renders the detector light-tight. A typical oscilloscope trace of the scintillator-photodiode system is shown in Fig. 2d. It has been determined from time of flight measurements that the first peak is due to electrons and the second peak to protons. It is apparent from this trace that the proton pulse is triangular with a baseline of about 40 nsec. In addition, the time of flight measurements indicate that the energy of protons is approximately equal to the voltage applied to the anode. From the attenuation of the signal as a function of the plastic thickness placed in front of the scintillator, it has been determined that the energy of electrons is less than or equal to 85 keV. The presence of electrons while a positive pulse is applied on the anode, indicates that due to inductive effects, there is a potential difference between the cathode and the end wall. The emission of these electrons has been further verified by Faraday cups, which also indicate that the proton beam is space charge neutralized.

It is found that at the corrected (resistive) voltage V_O [V_O = applied voltage - inductive voltage] of 1.3 MV, the peak ion current is approximately 20 kA and the corresponding ion current density is about 200 A/cm^2. At V_O = 1.3 MV and d = 5.3 cm, the bipolar flow predicts (neglecting edge effects) proton current density of only 8A/cm^2. The 20 kA current appears to be the limit of the 20 Ω impedance generator. This is consistent with the fact that the ion current density increased to 1 kA/cm^2, when the area of the cathode was reduced to 5 cm^2.

From the measured V_O and number of protons per pulse, the total energy of the ion pulse is computed. The computed energy is in agreement with calorimetry measurements.

It is of fundamental interest to know the dependence of the ion current I_i upon the resistive voltage V_O applied on the anode of a reflex triode. When the shape of the ion pulse is not very sensitive to the applied voltage, the ion current is proportional to the total number of protons in the beam N_p, that can be measured accurately and ambiguously by the nuclear activation technique. Figure 3 shows the product $N_p d^2$, where d is the opening of the anode-cathode gap, as a function of the anode voltage V_O. Least square fitting of the data in the voltage range between 0.55 to 1.3 MV shows that $N_p d^2$ varies as $V_O^{4.0 \pm 0.7}$. N_p has been determined by the activation technique assuming that the thick target yield of the $C^{12}(p,\gamma)N^{13}$ reaction is 7.5 X 10^{-10} per proton. However, the yield of this reaction drops very rapidly below 0.55 MeV. Since the voltage V_O is not known with an accuracy better than 15%, it is possible that the value of N_p for the six low voltage shots in Fig. 3 has been grossly under estimated. Least square fitting of the data, after omitting the six low voltage shots gives that $N_p d^2$ varies as $V_O^{2.6 \pm 0.8}$. A similar scaling is obtained if the value of N_p for the six low voltage shots increased by a factor of two.

Detailed comparison of the experimental results with theoretical predictions is not presently possible, because the theory of the reflex triode has not been developed as yet[14]. However, some insight in the current versus voltage characteristics of the triode may be gained by solving Poisson s equation near the cathode (crosshatched region in Fig. 4), where only ions of mass M and monoenergetic electrons of mass m that have not as yet crossed the anode are present. Under steady state conditions, the oscillating electrons do not enter the crosshatched region because the potential V is less than ΔV, where $e\Delta V$ is equal to twice the energy loss of a typical electron during its first crossing of the anode. Introducing the dimensionless variables $\Psi = V/V_O$, $\xi^2 = (m/2e)^{1/2} (J_e/\epsilon_O V_O^{3/2}) x^2$, and $\alpha = (J_i/J_e)(M/m)^{1/2}$, Poisson's equation becomes,

$$\frac{d^2\Psi}{d\xi^2} = \frac{1}{\Psi^{1/2}} - \frac{\alpha}{(1-\Psi)^{1/2}} \quad , \qquad (1)$$

where J_e is the electron current density emitted from the cathode, J_i is the ion current density ϵ_O is the permittivity of vacuum and V_O is the potential applied on the anode. Integrating Eq. (1) from $\Psi = 0$ to Ψ, it is obtained

$$\left(\frac{d\Psi}{d\xi}\right)^2 = 4\left[\Psi^{1/2} + \alpha(1-\Psi)^{1/2} - \alpha\right] \quad . \qquad (2)$$

Since $(d\Psi/d\xi)^2 \geq 0$, and for thin anodes $\Delta V/V_O \ll 1$, Eq. (2) at $V = \Delta V$, gives $\alpha \leqq 2(V_O/\Delta V)^{1/2}$, or after using the definition of α

$$J_i/J_e \leq 2\left(\frac{V_O}{\Delta V}\frac{m}{M}\right)^{1/2} \qquad (3)$$

Equation (3) is exact and is valid for relativistic electrons as well. Because $\Delta V \sim V_0^{-0.4}$ in the energy range of interest, Eq. (3) demonstrates that J_i varies with voltage faster than J_e by $V_0^{0.7}$. For $0.4 \leq V_0 \leq 1$ MV, the ratio $V_0/\Delta V$ is with better than 10% equal to the times an oscillating electron crosses the anode.

In addition, Antonsen and Ott[8] have recently computed self-consistently the steady state ion and electron current densities in a double diode, assuming that the electrons are suffering only elastic collisions in the anode foil. In the non-relativistic limit, they predict that $J_i/J_e = (\nu+1)\ (zm/M)^{1/2}$, where ze is the ion charge and ν^{-1} is proportional to the square of the mean scattering angle, i.e., $\nu = 2(1+\ell n4)/3\langle\Delta\theta^2\rangle$. It can be shown from their results that for $10 < \nu < 45$, $J_e \sim V_0^{3/2}$. Since $\langle\Delta\theta^2\rangle \sim V_0^{-2}$, their theoretical model predicts that J_i scales as $V_0^{3.5}$.

The above models are based on the assumption that the device operates in a steady state. Preliminary computer simulation results at NRL by Lee and Goldstein shown that a steady state is reached for short pulses only for anodes that are considerably thicker than those used in the experiment. Under conditions pertinent to the experiment, the code predicts a J_i at the end of a 50 nsec pulse that scales as $V_0^{2.5}$.

Although the accuracy of the experimental results is not good enough to establish the exact relationship between J_i and V_0, it is clear from these results that J_i scales considerably faster than $V_0^{3/2}$ predicted by the Child-Langmuir law for bipolar flow. In addition, incomplete theoretical models and preliminary computer simulation experiments predict that J_i in a reflex triode scales faster than $V_0^{3/2}$.

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14. Among the two ion sources based on the electron reflex action, only the steady state double diode has been investigated theoretically, because it is considerably simpler than the reflex triode. Although not appreciated initially, these two devices appear to have several disimilar features.

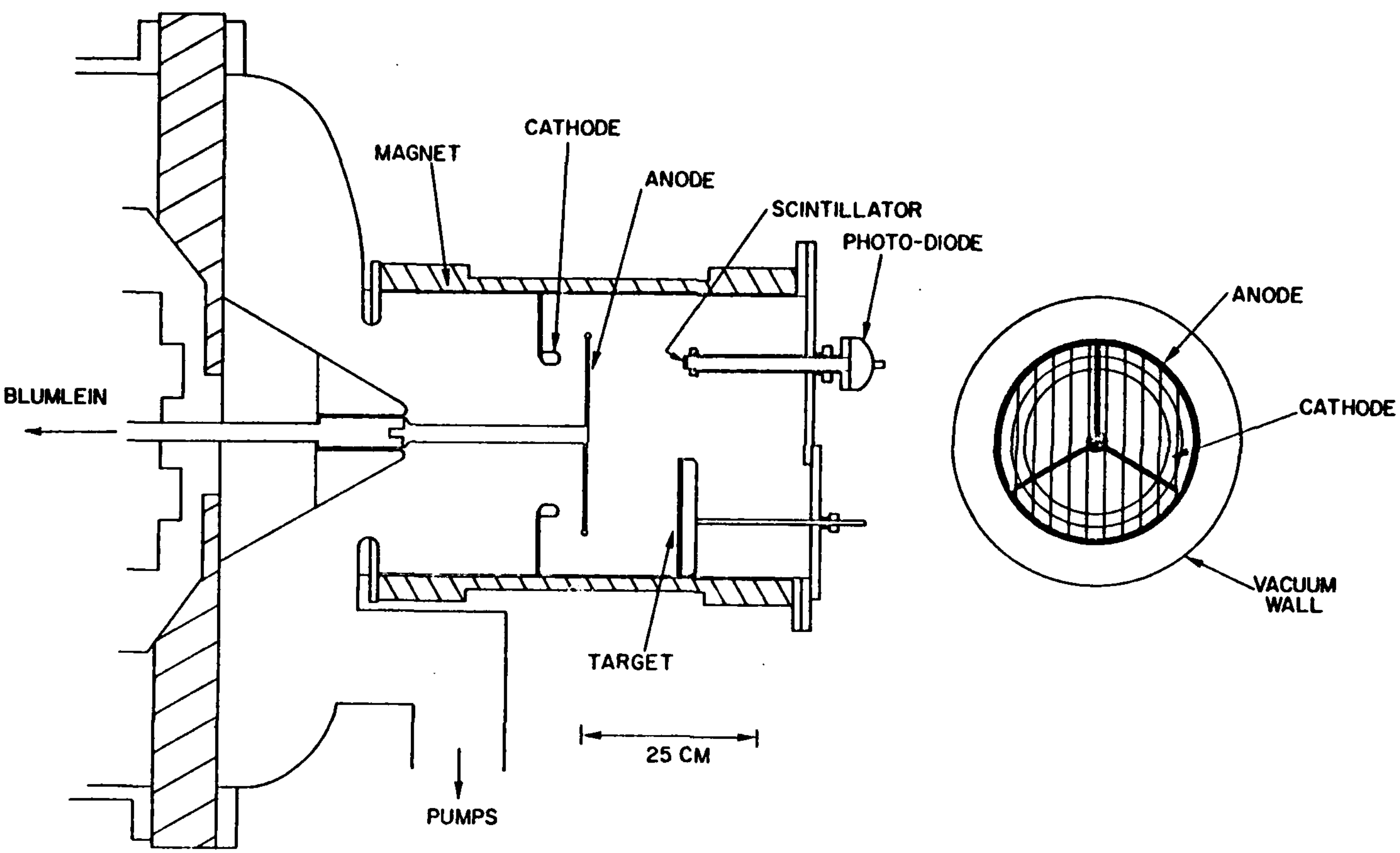

Fig. 1 — Schematic of the experiment

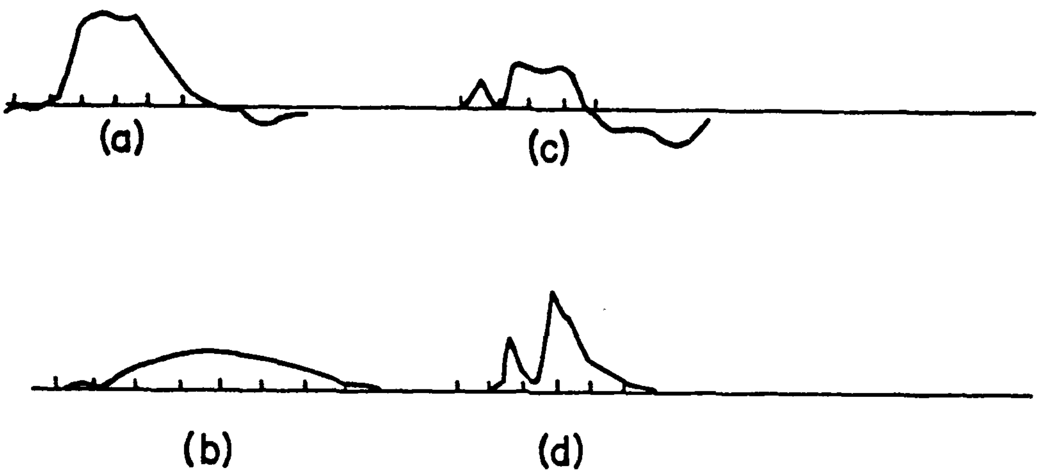

Fig. 2 — Voltage (a), anode current (b), dI/dt (c), and ion current (d) waveforms. For all traces the time scale is 20 nsec/div.

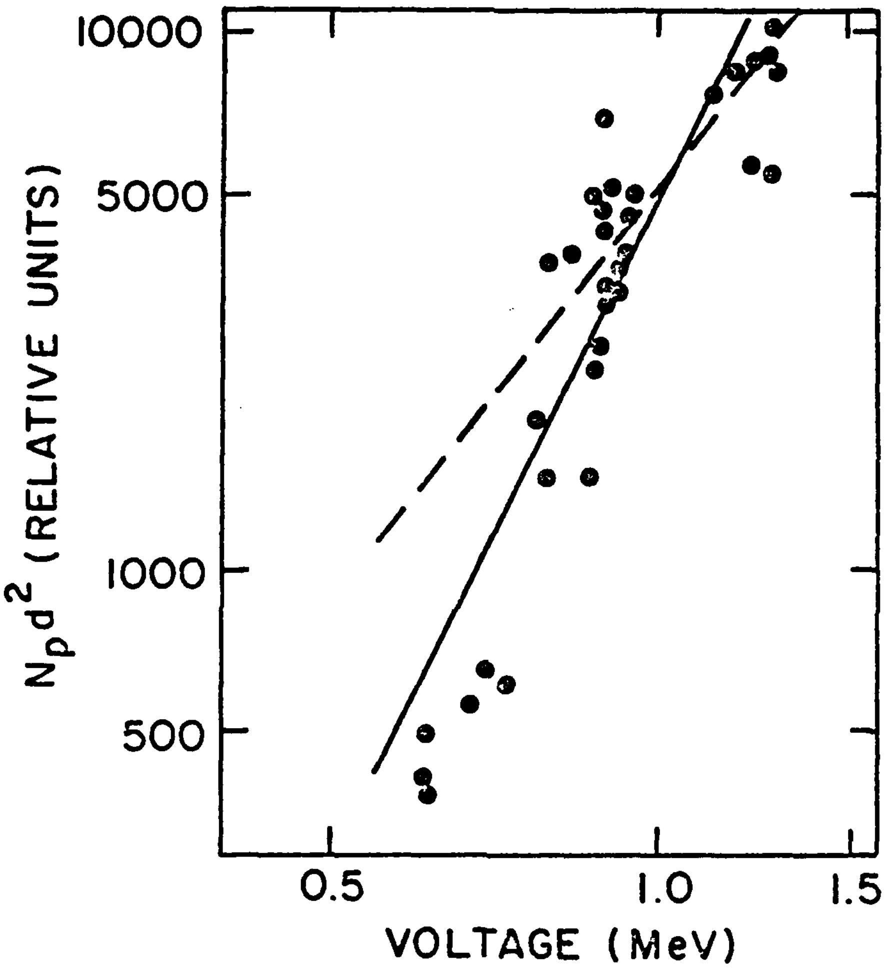

Fig. 3 — Number of protons per pulse (N_p) multiplied by the square of the anode-cathode spacing vs. corrected voltage V_o, at B_o = 1.6 kG. Least square fitting gives for the slope of the solid-line 4.0 ± 0.7. The slope of the dotted-line is 2.6 ± 0.8.

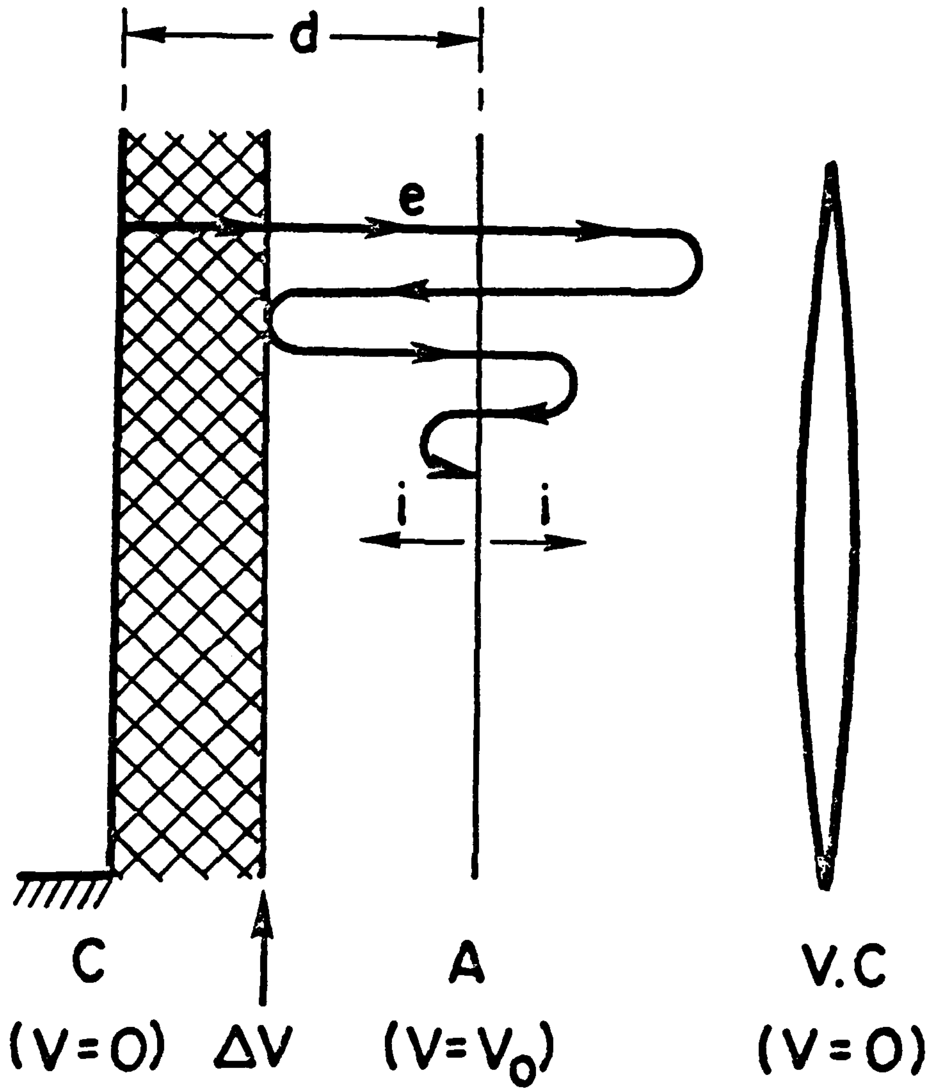

Fig. 4 — Schematic of a reflex triode

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