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ON THE PROPAGATION OF HIGH-CURRENT BEAMS OF RELATIVISTIC ELECTRONS IN GASES*

by

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ABSTRACT

The transit time of high current beams of relativistic electrons (40-50 kA, 350 keV) through an air filled (0.2-2.5 Torr) drift tube has been measured. It is longer than expected, even allowing for the loss of beam front electrons and for orbiting of the electrons in the beam self magnetic field. Also, a pressure dependent non-uniformity in the beam motion was observed which may account for this delay.

Recent technological advances in the production of high-current beams of relativistic electrons and possible applications have stimulated research interest in the behaviour of these beams under various conditions.[1,2] To provide rapid neutralization of the space charge, these beams are usually propagated into a gas or preformed plasma. Alfven[3] and Lawson[4] have shown that fully neutralized beams with a uniform current distribution cannot exist for total currents above a critical limit $I_c = 17{,}000\ \beta\gamma$ amps, where $\beta = \frac{v}{c}$ and $\gamma = (1-\beta^2)^{-\frac{1}{2}}$. Recently Rostoker and Hammer[5] have postulated the existence of non-uniform beam equilibria capable of maintaining considerably higher total beam currents. In these cases, the average propagation velocity along the beam axis drops according to $\langle\beta_z\rangle = 2\beta\ I_1(L)/\left[L\ I_o(L)\right]$. In this equation "L" is given by $I = 8{,}500\ \beta\gamma\ L\ I_1(L)/I_o(L)$ amps, where "I" is the experimentally observed net beam current and $I_{o,1}$, are the modified Bessel functions. To investigate these problems, measurements were made on a 50-kA, 50-nsec beam of 350 keV electrons propagating in air. The electron beam was produced[6] in a vacuum diode driven by a pulsed high voltage Blumlein generator. The electrons entered a lucite drift tube, 13 cm in diameter and 6.4 m long, through a 0.025 mm titanium foil. At injection, the beam diameter was about 10 cm and the angular spread of electrons about 20 deg. To provide a return path for the beam current the drift tube was lined with Al-mesh.

For diagnostic purposes, the average magnetic field at the tube wall was measured at various positions along the tube using sets of integrated magnetic pick-up loops. At the downstream tube end, and at two positions along the tube wall (.55 m and 3 m from the diode end) tantalum foils and shielded scintillator photodiode combinations were placed to detect impinging fast electrons. In a separate arrangement with a shorter drift tube microwave emission in the X-band was measured 2.0 m from the injection end. The use of 556 Tekronix dual-beam oscilloscopes allowed various pairs of these signals to be time-correlated. In addition, the entire tube was imaged onto the photocathode of a fast electronic sweep camera.

A set of recorded data, typical for all pressures, is shown in Figs. 1 and 2. In agreement with the results of Graybill et. al.[1], the magnetic pick-up loop signals show a pressure dependent rise time of 5-20 nsec and decay times of up to several hundred nsec. Relative delay times between various positions were determined from the initial rise of the signals. Both x-ray detectors at the tube wall exhibited double-peaked signals. Time delays derived from the initial rise of the signals or from the positions of the first maxima essentially agreed. At pressures above 800 Torr, the signal from the end x-ray detector, showed a flat precursor starting up to 35 nsec (at 2000 m Torr) before the main bulk of electrons arrived. Beam transit times are computed from the time delay of the beginning of this precursor with respect to the injection current. The microwave detector generally indicated a short, intense microwave burst. From the streak photographs, the propagation speed of the beam was derived from the average angle of the leading edge. As apparent from Fig. 2, the streak pictures exhibited a striation like periodic structure, the wavelength of which was inversely proportional to the tube pressure.

The transit times for the beam front derived from various measurements were normalized to the full tube length of 6.4 m assuming constant propagation velocity over the full path as indicated in Fig. 2. The results are shown in Fig. 3. The straight-path flight time for 350 keV electrons would be 26 nsec. The considerable larger measured values for the beam front transit time can be explained, to some extent, by the loss of electrons at the beam tip due to insufficient space charge neutralization. Taking an ionization cross section of 1.2×10^{-18} cm^2, the corresponding contributions to the transit time can be estimated as $\tau = 5/p$ nsec, where the pressure p is given in Torr. This estimate agrees in order of magnitude with the delays found. Also, its proportionality with 1/p could be fitted quite well to the results of Fig. 3. On the other hand, the calculated values are somewhat small. Even allowing for some uncertainty in the estimates the tip losses alone can neither explain the long transit times persisting at high pressures nor the delay times at low pressures, which are significantly larger than the sum of pulse length and straight-path transit time.

The transit time contribution due to the curvature of the electron trajectories in the self magnetic field of the beam can be estimated from the magnetic fields measured by our wall probes. These fields correspond to net currents, i.e. primary electron current plus plasma return currents, of about 10-20 kA for all pressures about 200 m Torr and the full tube length except the first 30 cm on the diode end. From this, an average transit time increase of about 6 nsec can be expected. However, due to current shielding effects of the plasma around the actual beam, the magnetic fields within the beam and thus, also, the corresponding effect on the transit times may be somewhat larger.[5] Still, it is hard to account for the transit times measured at large pressures.

Another contribution to the transit time may be associated with the mentioned structure in the streak photographs. A closer investigation of this structure indicates slight periodic fluctuations of the beam propagation velocity around its average. At pressures $\lesssim$ 150 microns this non-uniformity becomes very pronounced and almost step like as it may be produced[7] by coherent Cherenkov radiation of the fast electrons in the resulting plasma. Further investigations of this point are in progress.

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REFERENCES

1. S. E. Graybill and S. V. Nablo, Appl. Phys. Letters, 8,18 (1966) and S. E. Graybill, J. Uglum and S. Nablo, Bull. A.P.S. 13, 56 (1968).
2. W. T. Link, IEEE Trans. on Nuc. Sci., June 1967, 777.
3. H. Alfven, Phys. Rev., 55, 425 (1939).
4. J. D. Lawson, J. Elect. and Control, 3, 587 (1957); 5, 146 (1958).
5. D. Hammer and N. Rostoker, Bull. A.P.S. 13, 571 (1968) and paper submitted to Phys. Fluids.
6. J. J. Clark, M. Ury, M. L. Andrews, D. A. Hammer and S. Linke, 10th Symp. Electron, Ion and Laser Beam Technol., Gaithersburg, May 1969, San Francisco Press.
7. B. J. Eastlund, Bull. Am. Phys. Soc. 13, 555 (1968). and private communication.

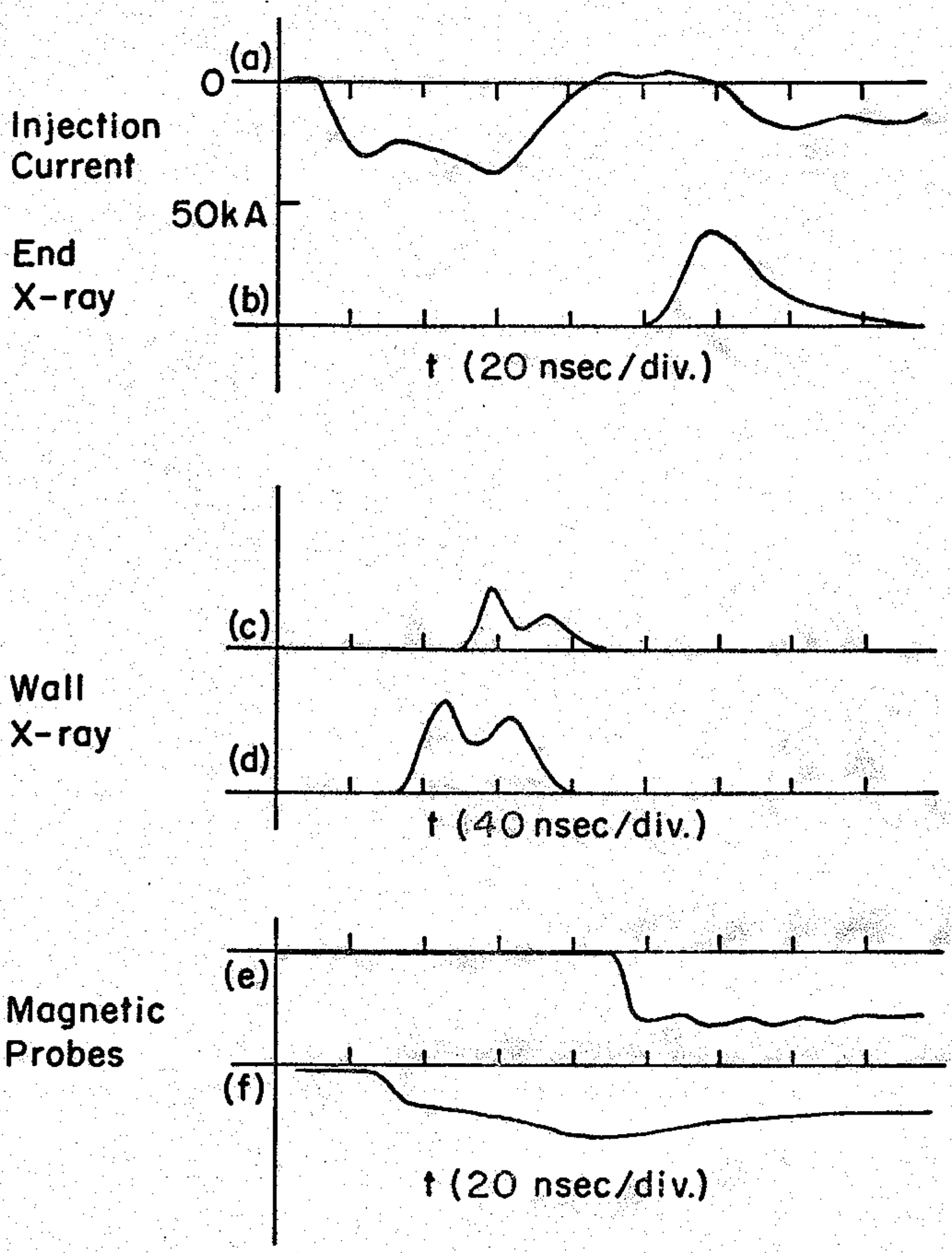

Fig. 1 Typical oscilloscope traces at 400 m Torr air
(Typical for all pressures)

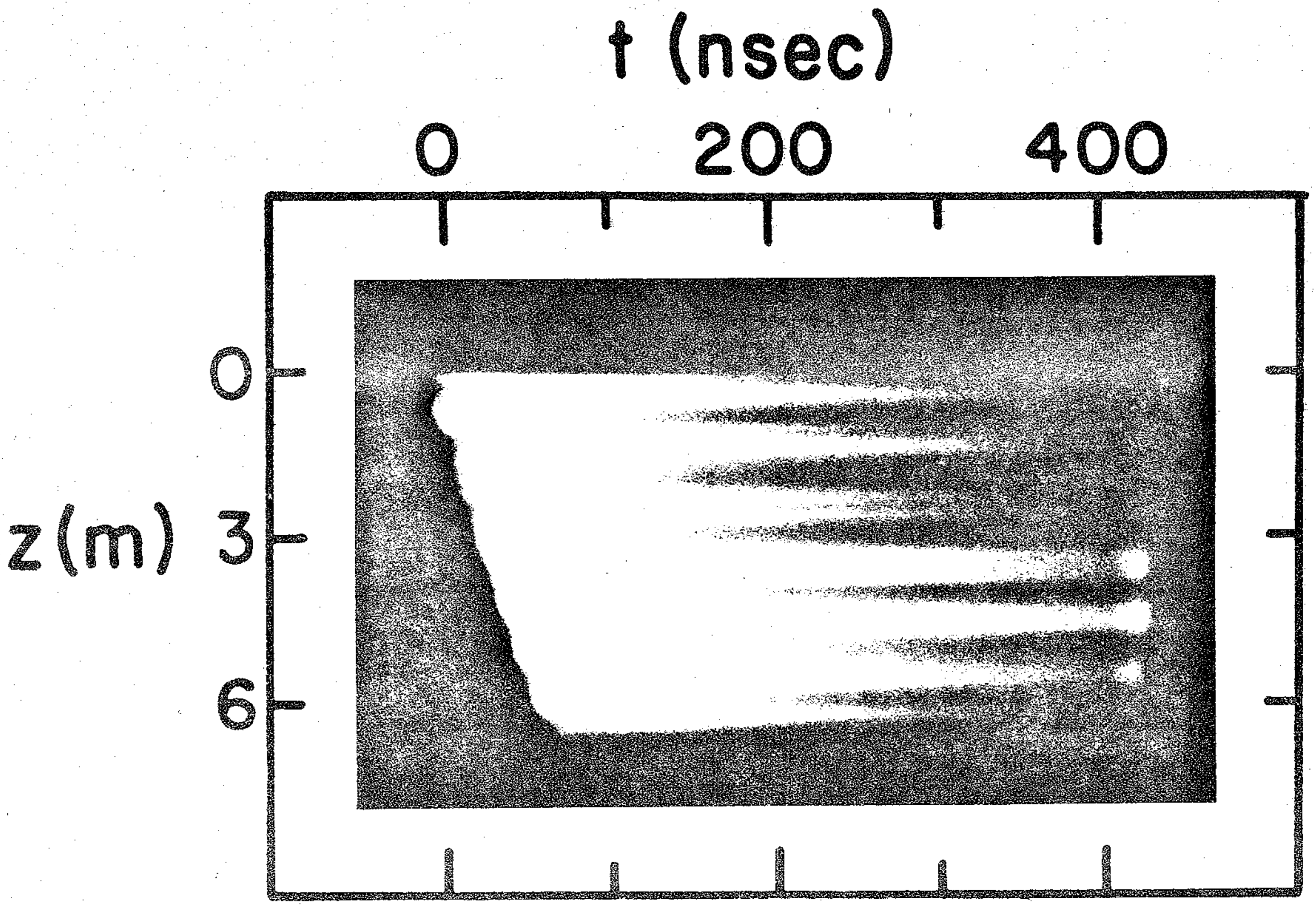

Fig. 2 Streak photograph at 400 m Torr in air.

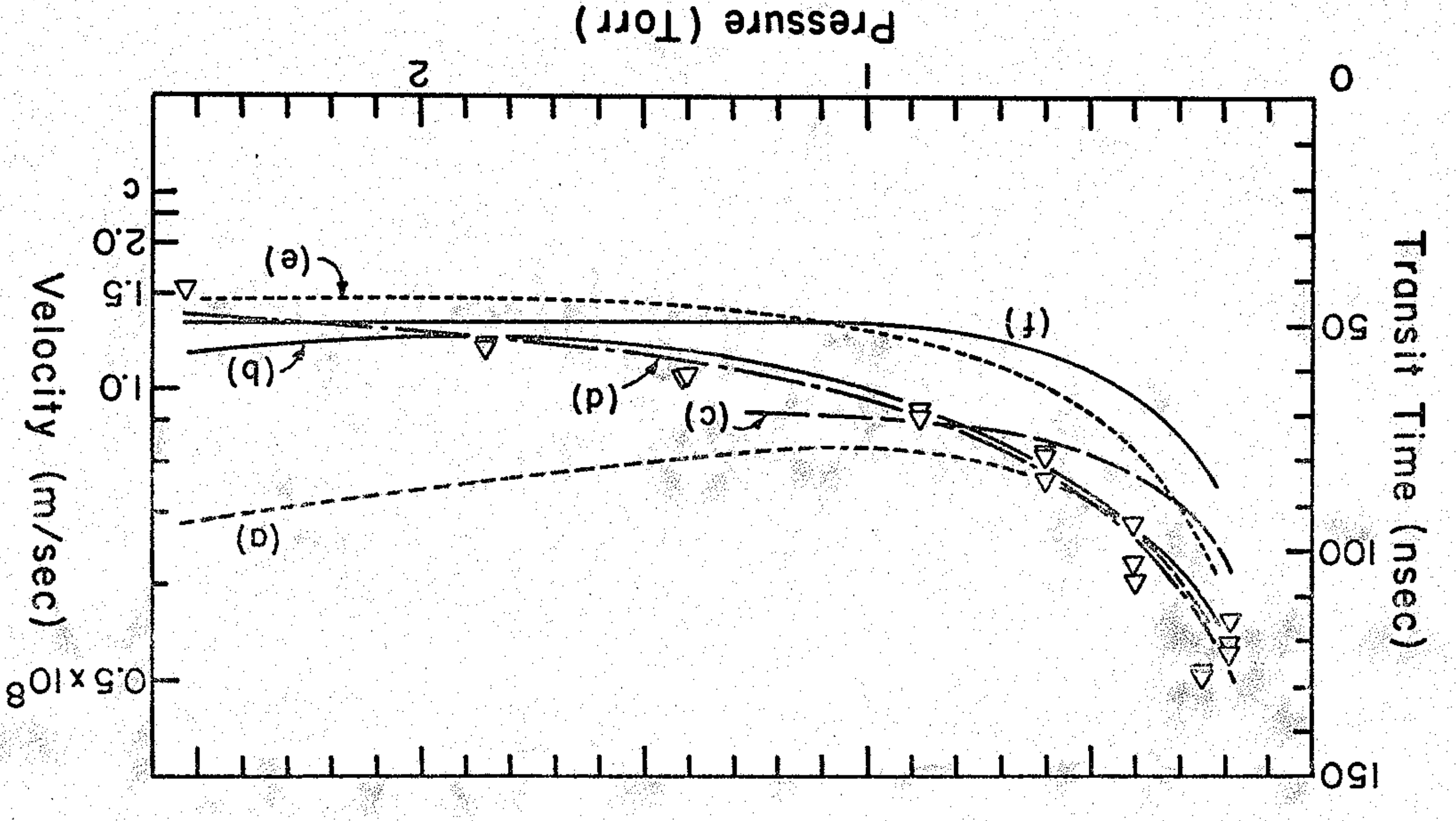

Fig. 3 Transit time of the beam front as a function of pressure, from (a) half-rise of end x-ray detector and injection current, (b) onset of end x-ray detector and injection current, (c) microwave detector and injection current, (d) streak photograph, (e) magnetic field probes, and (f) wall x-ray detectors. Experimental points indicated for case (d) only.