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IONIZATION INSTABILITY IN THE PROPAGATION OF HIGH-CURRENT RELATIVISTIC ELECTRON BEAMS IN GASES

by

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Abstract

Measurements on electron beams propagating in a gas filled drift tube show pressure dependent longitudinally periodic variations of light intensity, μ-wave emission, beam head velocity and net current. These results are consistent with an ionization instability, such as that proposed by Eastlund.

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Following recent technological developments in the generation of very-high-current beams of relativistic electrons, a number of theoretical and/or experimental publications appeared[1-7] concerning the propagation of these beams under various conditions. So far, all theoretical calculations on equilibria in established beams assume longitudinal symmetry along the beam axis. Also, when the propagation of these beams in neutral gases is considered, the collisional space charge neutralization at the beam tip is assumed to occur continuously and thus produce uniform propagation of the beam front. Similarly, most analyses of experimental results in cases where beam propagation is observed are based on these same assumptions. In only one case[8], under particular circumstances, was sudden beam stoppage found and accepted as an indication for the existence of the predicted upper limit (Alfven limit)[9] for the beam current.

In this paper, we report on first results of experiments in which axial periodicities in the light intensity are observed on beams propagating in gases. These periodicities are found to be correlated with periodicities in the propagation of the beam front, in the microwave activity and in the net current of the beam. These fluctuations appear to be caused by an instability in the ionization-neutralization of the beam in the gas. The reported beam stoppage seems to be an extreme case of this phenomenon.

The experiments were performed using the pulsed high-voltage transmission line and vacuum diode combination described earlier[10]. Typically beams of 30 - 40 kA having energies of 350 - 400 keV are launched through a titanium anode foil .02 mm thick. The drift tube, of 6.40 m length and

14 cm ID, consisted of lucite which was lined with Al-mesh to provide a return path for the beam current. For space charge neutralization, this tube was generally filled with air in the pressure range 0.1 - 2 torr. In some shots, helium was used as the filling gas.

For diagnostic purposes, the entire tube or parts of it were photographed using an open-shutter exposure. The entire tube was also imaged onto the photocathode of an electronic streak camera having the streak direction perpendicular to the beam direction. Integrating magnetic pick-up loops at the tube wall measured the self-field of the beam, i.e., its net current (beam current minus return currents flowing in the created plasma). In some cases some of these loops were used as μ-wave probes the signals of which, after passing through a X-band wave guide, were analyzed by a calibrated detector.

A typical example of resulting photographic and streak recordings is shown in Fig. 1. The periodic intensity modulations apparent in the photograph fully correlate with the structures in the streak, the bright areas of the photograph corresponding to the long bright lines of the streak. The wave length of this structure is quite reproducible at any pressure. Up to 25 "nodes" can be seen at high pressures. No significant variations with beam current and electron energies were observed in the investigated regime. However, as evidenced by Fig. 2, this wave length is inversely proportional to the air pressure P. Using helium filling exactly the same phenomena occurred, at pressures higher by a factor of 7.

Coinciding with this structure, periodic variations of the beam head velocity can be seen in the streak. At smaller pressures these become more pronounced, and resemble the mentioned beam stoppage[8] (Fig. 3). The beam head, after travelling almost with the velocity of the single electrons, slows down considerably and proceeds again only after a delay time which appears to be roughly proportional to $(1/p)^2$. In the case of Fig. 3, a similar delay was found in the rise of magnetic-loop signals before and after the "step". From a larger set of magnetic-loop measurements, it appears that the measured net current also correlates with the position of the probe relative to the steps. However, the average net current is more or less pressure independent.

Further confirmation of this structure has been observed in the μ-wave emission from the beam.[11] The peak intensity of the radiation builds up going downstream along the region initially bright in the streak. Then, this signal suddenly decreases by about 15 db in the vicinity of the steps, only to grow in magnitude again through the next bright region. Time resolved measurements of the occurrence of the emission record the same delay in step region as found with other diagnostics.

From streak pictures, it appeared that characteristics similar to the ones observed downstream occur at the injection end. This finding was substantiated by measurements in which all diagnostics were concentrated on the first two meters of the tube. It is found that the injection region actually is very similar to the step regions further down stream: the streak light level is low, the μ-wave emission if weak, and there is a delay between start of injection and beam propagation similar to the corresponding delays in later steps.

The total delay incurred from these seems to explain the overly long transit time of the beam head found in our earlier measurements.[12] However, no hard explanation for this phenomenon can be offered at present. The strong pressure dependence of the periodicity indicated that it is not merely connected with some cavity mode of the mesh wall. Also, self-focussing betatron modes of the electrons can be safely excluded since the self-field is independent of the gas pressure. It appears that this structure results from a periodic reproduction of the injection process at the tube entrance. In the step region, the electrons first are deflected to the tube walls by their own space charge, (as indicated by X-ray detectors). Upon creation of sufficient ions, self-focussing of the beam occurs and propagation starts. Then, ionization and neutralization of the beam charge is increasingly aided by high-intensity plasma waves created by the beam. This is indicated both by the increasing μ-wave radiation and by the increasing light output which exceeds by far the light intensity resulting from the primary electrons at the darker initial phase of the propagation. In this phase, the beam head almost attains the velocity of the primary electrons, until for some reason, the wave activity subsides and the ionization has to be accomplished by the primary electrons alone. The primary importance of the ionization process is underlined by the mentioned pressure scale factor for helium filling which agrees well with the ratio of the effective ionization cross sections; i.e., the process seems to scale with the product of gas density and ionization cross section.

One such mechanism has been proposed by Eastlund.[13] According to this explanation, a catastrophic instability in the ionization process can result from the coherent Cerenkov radiation generated by the rapidly rising front of the charged-particle beams propagating in an initially unionized gas. As described by Eastlund, the radiated power and the plasma density produced by the radiation grow abruptly in time and therefore as function of distance as the beam traverses the tube. After reaching a certain plasma density, the radiation and thus the corresponding ionization of the gas is stopped and the entire process has to start anew.

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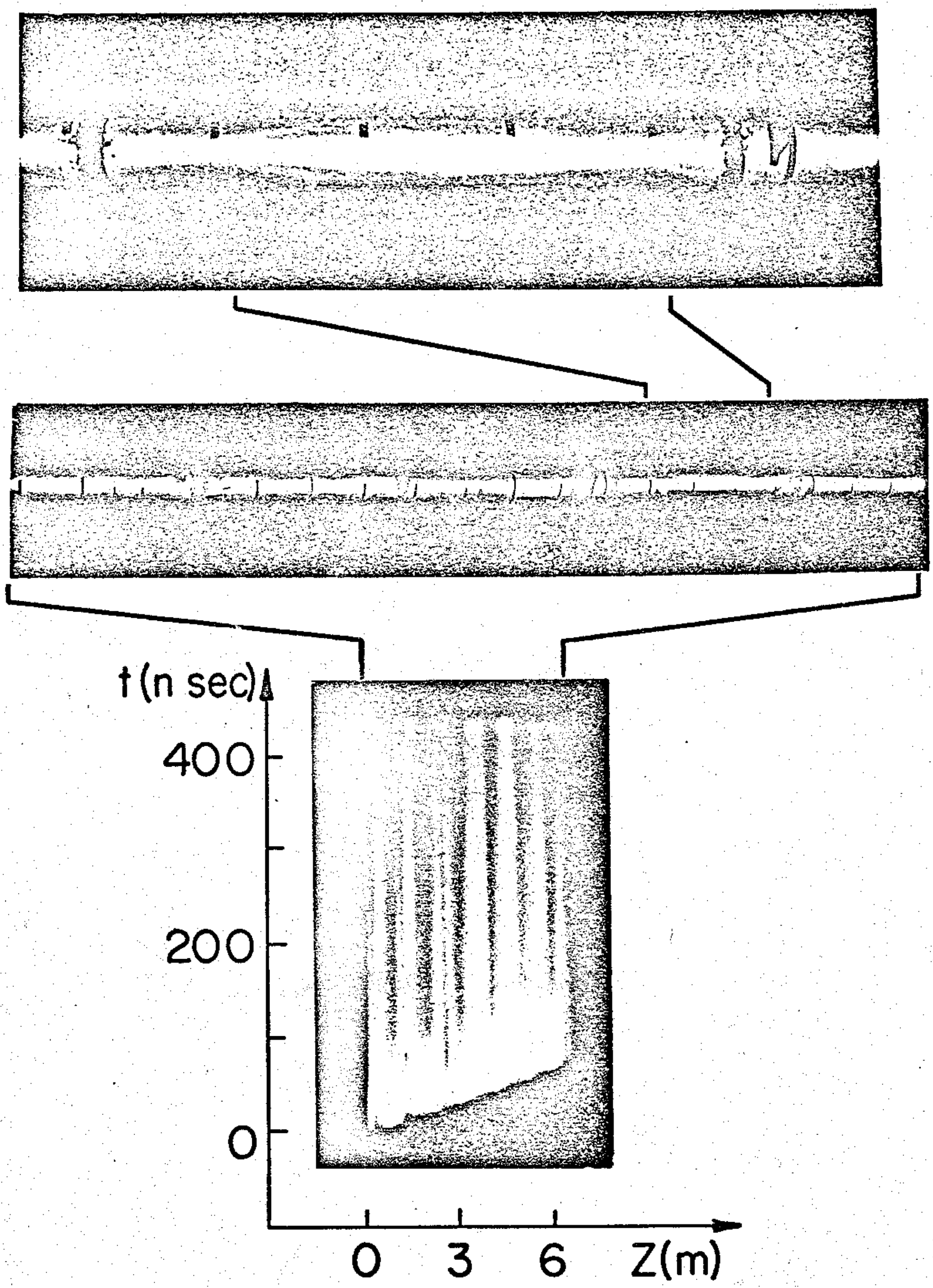
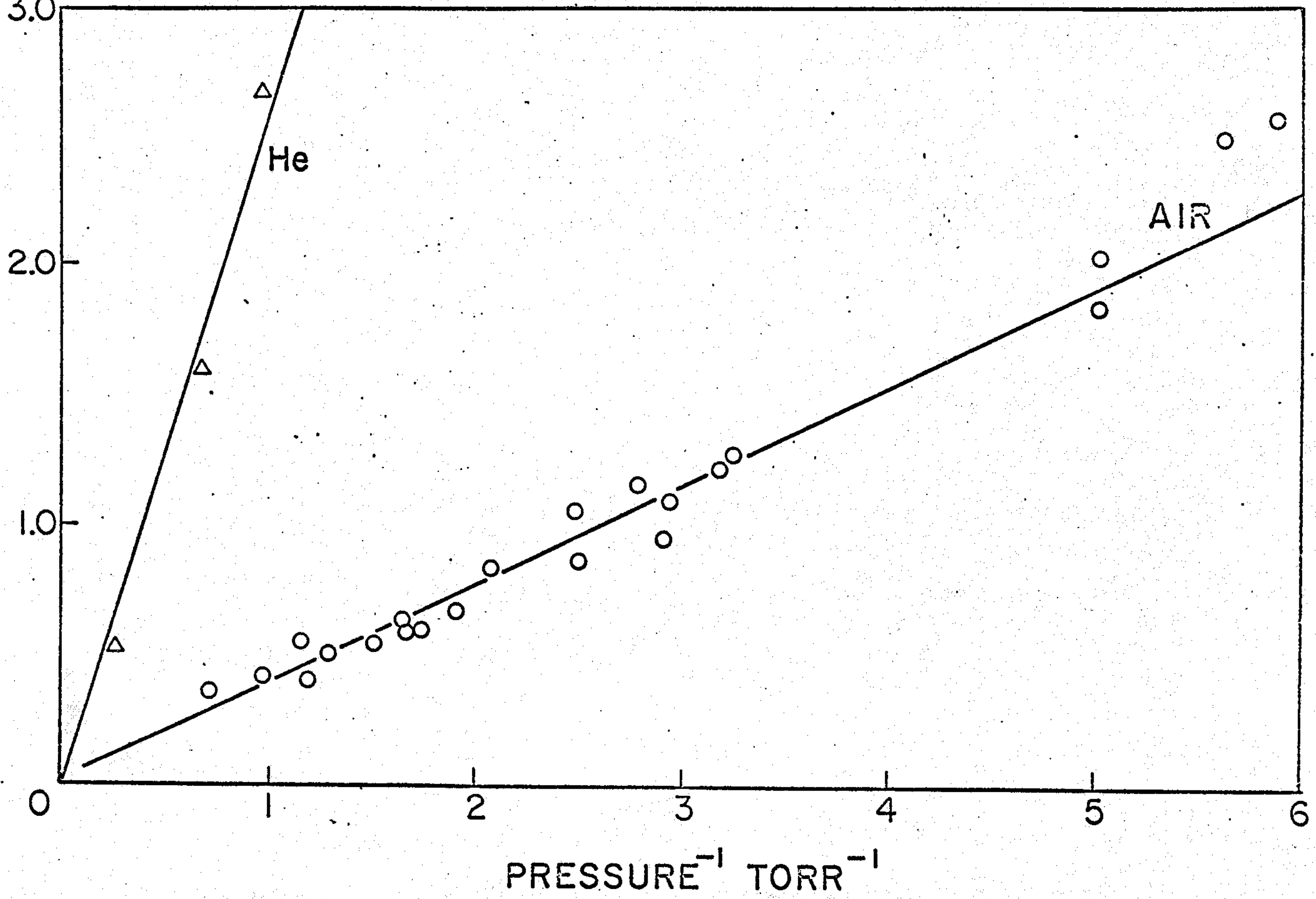


Figure 1. Time integrated and streak photographs showing axial periodicities in beam propagation.



Figu . Nodal wavelength for Air and Helium plotted a function of the ambient pressure.

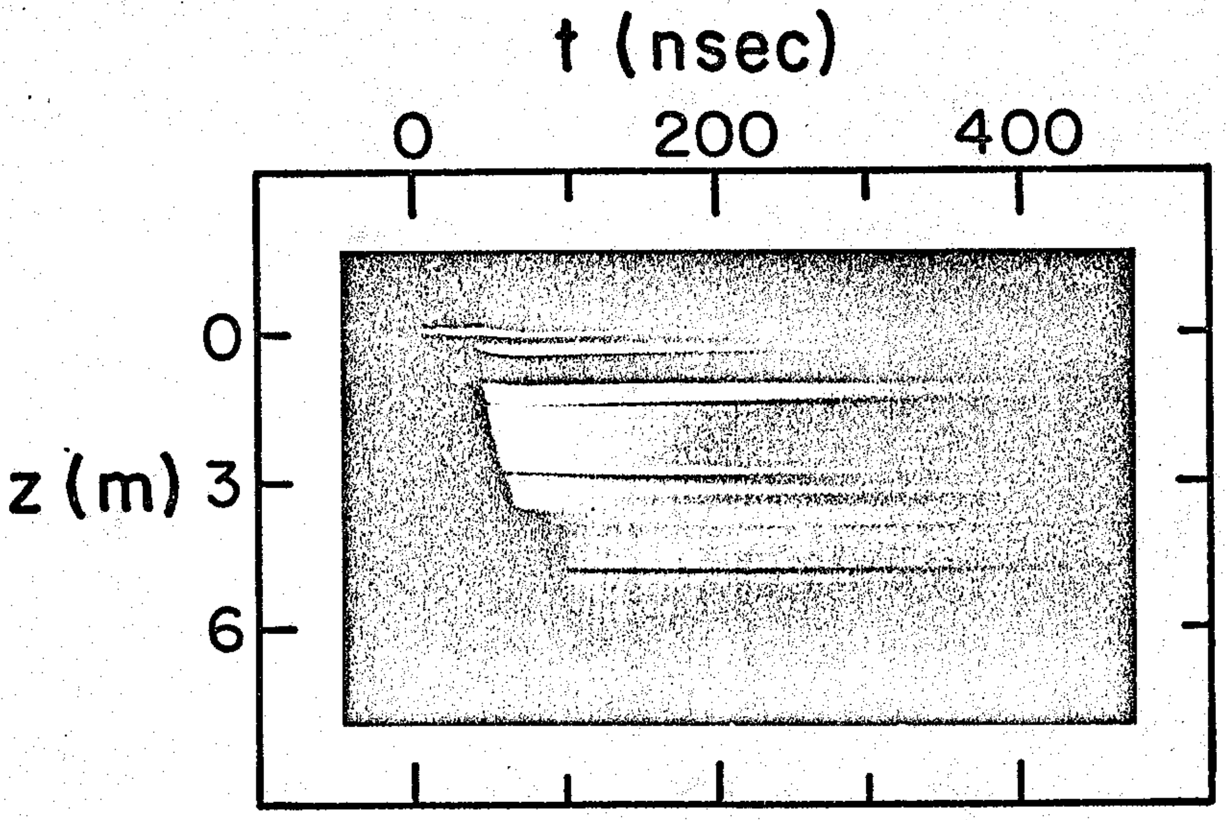


Figure 3. 'Low pressure' (150 mTorr in air) streak photograph showing a single beam discontinuity.