CONSTRUCTION AND OPERATION OF AN ELECTRONIC RAM

by

IAN JAMES BILLINGTON

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ABSTRACT

A model of an electronic ram was built and operated in order to examine experimentally the principle of this proposed accelerator for charged particles.

The experimental work comprised several steps: production of a pulsed tubular electron beam; control of the axial velocity, space charge density, and cross section of the beam by a homogeneous longitudinal magnetic field; and use of a region of rapidly increasing magnetic field intensity to reduce suddenly to zero the axial velocity of the electrons, thereby converting electrokinetic energy of the beam to potential energy. This energy conversion was required to produce the "ram effect" (the raising of the front electrons of the beam to a high energy level.)

The results obtained are in accordance with theory and indicate the existence of the ram effect.

ACKNOWLEDGEMENT

I am pleased to express my thanks to Dr. W. R. Raudorf who developed the theory, which this experiment was an attempt to verify, of the Electronic Ram and under whose direction the research was carried out; also to Mr. J. Lees for valuable assistance with glass work for the apparatus.

I am indebted to the British Columbia Telephone Company for a Scholarship for the academic year 1951-52, and to the National Research Council for an Assistantship in the summer of 1952.

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I INTRODUCTION

A. General

Two years ago, a simple method was proposed[1] for accelerating electrically charged particles, preferably electrons, to high energies and for generating short and powerful electromagnetic pulses. The method depends upon the transfer of the electromagnetic energy of the total charge of a tubular beam of particles to a small fraction of that charge. The apparatus based upon this method represents the electrical analogue of an hydraulic ram, and for this reason is called the "Electronic Ram".

In order to achieve such an energy transfer it is necessary to produce a steady cylindrical stream of charged particles. The analysis by Brillouin[2] of the behaviour of high density electron beams under the influence of combined electric and magnetic fields predicts the conditions necessary for producing such a stream. However, no published report on experimental verification of the theory has been found.

B. Object of the Present Research

The purpose of the research reported here was to design, construct and operate a model of an electronic ram in order to examine the method experimentally. This involved the problem of producing and projecting a steady cylindrical electron beam of uniform space charge density and uniform axial velocity, and in which the space charge repulsive forces were exactly balanced by magnetic focusing forces. A beam having these properties could be made as long as desirable. A great part of the experimental work was devoted to the practical solution of this problem.

II THEORY

A. Basic Arrangement of Apparatus

A diagrammatical representation of the important components of an electronic ram is given in Fig. 1. Electrons from a highly emissive cathode, K, at a negative voltage V_0, are accelerated through this voltage and enter a grounded tube, T, around which is wound a long solenoidal coil to produce a uniform axial magnetic field within the tube.

The length of the tube T is great with respect to its radius, R, and the tube terminates at the entrance to another tube, T', co-axial with T and with radius $R' > R$. At the position of discontinuity in radius there also exists a region of rapidly increasing magnetic field produced by a sudden increase in the number of turns in the surrounding coil.

The cathode itself is in a region of weak magnetic field. The radial component of the fringing magnetic field at the entrance to the tube imparts an angular velocity to the electrons in the high density beam drawn from the cathode. A pulsed accelerating voltage is applied between the cathode and the tube T, producing current pulses, of predetermined average electron velocity, which pass along the tube. As each pulse reaches the junction of the two tubes, it experiences, due to the radial component of the increasing magnetic field, an increase of angular velocity at the expense of axial velocity and, due to the higher longitudinal component of the field, a radial compression. By adjustment of the magnetic field the axial velocity of the electrons may be reduced to zero, causing a high space charge density and a low potential. Thus a virtual cathode is formed at the entrance to tube T' and an axial electric field is induced in this tube. The front electrons then become accelerated into tube T' under the influence of this field.

B. Production of High Density Tubular Electron Beam

It has been shown[3] that a high density electron beam cannot be projected over large distances, under the influence of an electric field alone, without appreciable dispersion. Several papers[4,5,6], however, have discussed the possibility of maintaining high density beams of various types under the influence of magnetic fields.

The conditions required for the maintenance of high density tubular electron beams have been worked out[1,2]. The important assumptions and formulae will be summarized here. Cylindrical polar coordinates and rationalized m.k.s. units will be used.

Assume a beam of electrons of radius b and uniform charge density ρ, travelling axially through tube T of Fig. 1. Let T be maintained at a potential $V = 0$. Consider the beam to have been accelerated, from a magnetic field free region, through a potential difference V_o, and to have entered a region of uniform axial magnetic field B_o. Assume also that the electrons initially left the electron gun with negligible radial velocity, $\dot{r}$.

Since the magnetic field in the tube is purely axial,

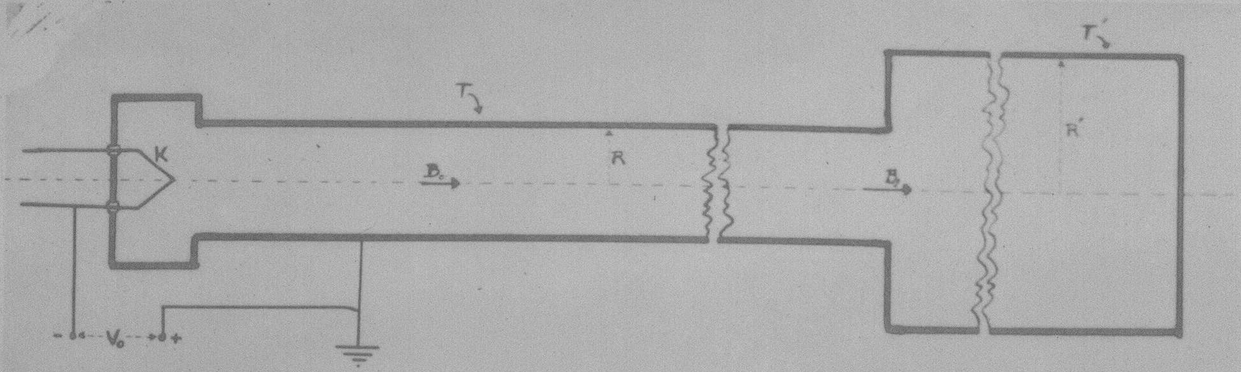


Fig. 1

Basic Arrangement of an Electronic Ram

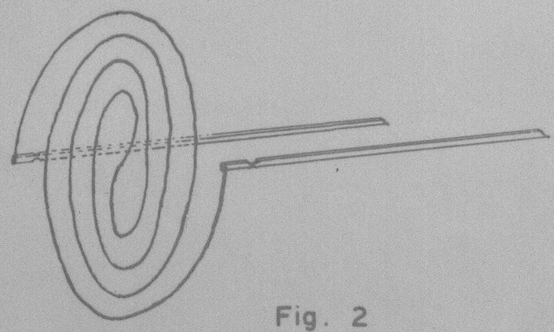


Fig. 2

Spiral Filament with Leads

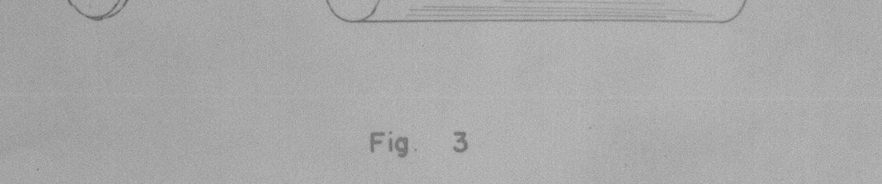


Fig. 3

Filament Winding Tool

the relationship $\vec{B} = \text{Curl}\,\vec{A}$ yields $A_r = A_z = 0$, $A_\phi = \frac{1}{2}rB_o$. The equations of motion for the electrons in the tube are then found to reduce to:

$$\ddot{r} = r\dot{\phi}^2 + kE_r + kr\dot{\phi}B_o$$

$$\ddot{z} = kE_z$$

$$p_\phi = mr^2\dot{\phi} + \tfrac{1}{2}er^2B_o = \text{const.} \qquad (1)$$

where p_ϕ is the generalized ϕ component of momentum, $\vec{E}$ the electric field intensity, and $k = e/m$ the charge to mass ratio for the electron. Conservation of energy requires that:

$$\tfrac{1}{2}(\dot{r}^2 + \dot{z}^2 + r^2\dot{\phi}^2) + kV = kV_o \qquad (2)$$

For a tubular beam with no dispersion we require that $\dot{r} = \ddot{r} = 0$. Thus the first of equations (1) is modified to:

$$mr\dot{\phi}^2 + eE_r + er\dot{\phi}B_o = 0 \qquad (3)$$

showing that the centrifugal force, the radial electric force, and the Lorentz force must balance each other. Since ρ is not a function of z, $E_z = -\frac{\partial V}{\partial z} = 0$. Thus the second of equations (1) yields $\ddot{z} = 0$, or $\dot{z} = \text{const.}$ Neglecting small initial velocities of the electrons, p_ϕ at the cathode must be zero; then conservation of momentum requires that $P_\phi = 0$ for all z. Thus the third of equations (1) reduces to:

$$\dot{\phi} = -\tfrac{1}{2}kB_o \qquad (4)$$

showing that all the electrons in the beam have the same angular velocity. This is the Larmor precession angular velocity. Equations (3) and (4) now give E_r as a function of r and B_o inside the beam:

$$E_r = \tfrac{1}{4}kB_o^2r \qquad (5)$$

However, E_r is related to the charge density by Poisson's Equation which in this case, may be written:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rE_r\right) = \frac{\rho}{\epsilon_0} \qquad (6)$$

First integration of equation (6) within the beam, and combination with equation (5) now yields a value for ρ:

$$\rho = \frac{1}{2}\epsilon_0 k B_0^2 \qquad (7)$$

Second integration of equation (6) yields the following value for the potential V inside the beam:

$$V = \frac{\rho b^2}{2\epsilon_0}\operatorname{Log}_e\frac{R}{b} + \frac{\rho}{4\epsilon_0}\left(b^2 - r^2\right) \qquad (8)$$

Combining equations (2), (4), (7) and (8) with $\dot{r} = 0$, an expression for the axial velocity of the beam in terms of the accelerating voltage, the focusing magnetic field, and the radii of the beam and tube is obtained:

$$\dot{z}^2 = 2kV_0 - \tfrac{1}{4}k^2b^2B_0^2(1 + 2\operatorname{Log}_e(R/b)) \qquad (9)$$

The total beam current is given by:

$$i_0 = \pi b^2 \rho \dot{z} \qquad (10)$$

From equation (9) it is seen that the axial velocity of the beam is reduced either by a decrease of the accelerating voltage V_0 or by an increase in the axial magnetic field in the tube. The axial velocity may be reduced to zero by the application of a critical "limiting field" defined by $B_0 = B_L$, where

$$B_L = \sqrt{\frac{8V_0}{kb^2(1+2\operatorname{Log}_e R/b)}} \qquad (11)$$

It is also seen from equation (9) that an increase in the tube radius R relative to the beam radius b will contribute to the reduction of axial velocity of the beam.

A beam of uniform electron density travelling axially down tube T of Fig. 1 under the conditions outlined, should be maintained without dispersion over a distance as great as may be required.

C. Production of the Ram Effect

Consider a pulsed high density cylindrical stream of electrons passing down tube T of Fig. 1, with radius b slightly less than R, and with B_o somewhat less than B_L.

As the stream reaches the junction of tubes T and T', the discontinuity in radius, combined with the increase in magnetic field intensity to a value greater than the limiting field, causes a compression of the front of the beam, and at the same time reduces the axial velocity of the electrons to zero in accordance with equation (9). The increase in space charge density lowers the potential at this point. The potential barrier which is set up blocks the passage of electrons in the rear of the beam and forms a space charge limited virtual cathode.

In tube T', an axial electric field is induced as the virtual cathode builds up. The front electrons, being ahead of the potential barrier and in a region of positive potential gradient, are accelerated into tube T'. Consideration of the conservation of energy during the bunching process[1] indicates that the energy of the accelerated electrons in electron volts varies from zero for the slowest electrons to V_x for the fastest, where V_x is given by:

$$V_x = V_0 \sqrt{\frac{8\pi\epsilon_0 \alpha^2 z_1}{C\left(1+2\log_e \frac{R}{b}\right)}\left(1-\frac{\alpha^2}{4}\,\frac{1+4\log_e R/b}{1+2\log_e R/b}\right)} \qquad (12)$$

where α is the ratio B_o/B_L, z_1 is the distance from the cathode to the junction of tubes T and T', and C is a measure of the effective capacitance between the virtual cathode and the tube T'. The value of C, which is a function of the tube and beam radii, can be determined by numerical integration.

The total amount of charge accelerated into tube T' is CV_x. During the acceleration process, the virtual cathode recedes and diminishes as the electrons in the beam are scattered by the radial space charge repulsive force.

It can be seen from equation (12) that the ratio R/b should be close to unity if the maximum value of V_x for a given V_o is desired.

III DESIGN & CONSTRUCTION

A. Basic Design Considerations

In order to provide a wide range of experimental conditions, it was decided to allow the greatest possible variability to the three important factors: magnetic field intensity, accelerating voltage, and emission current. Also, the apparatus had to be so constructed that the major components were readily accessible for adjustment or repair.

Although all experiments were conducted under high vacuum, any adjustment to the cathode necessitated opening the apparatus to the air. Oxide-coated cathodes and Thoreated-Tungsten cathodes are highly susceptible to poisoning and easily damaged by positive ion bombardment[7]. Such cathodes require long and complicated activation procedures[8] before they can be operated. It is also important, when such cathodes are used, that all other tube components are thoroughly outgassed to guard against the liberation of gas and bombardment of the cathode during operation. For these reasons it was decided to employ a pure tungsten cathode.

In order to study the formation and maintenance of a steady tubular beam, preliminary experiments with a short tube immersed in a uniform axial magnetic field were conducted. Results obtained with this tube led to certain modifications in the construction of the final ram model.

B. <u>The Electron Gun</u>

Production of a tubular beam of uniform space charge density requires that the cathode should be plane, and perpendicular to the axis of the tube, and that it should form an equipotential surface in order that electrons emitted from all parts of its surface should be subjected to the same accelerating voltage. Since Tungsten must be maintained at a high temperature for good emission, a directly heated filament was employed.

In order to approximate an equipotential surface, the filament was wound in the form of a double spiral (Fig. 2) so that the low voltage end and the high voltage end came out from the center side by side. A special method was devised for winding spiral filaments of this kind. A thin slotted rod (Fig. 3) on the end of a bar of larger diameter was used to hold the center of a piece of filament wire. A metal disc was slipped over the rod and held in position with a set screw. The whole bar was then rotated slowly in a lathe, tension being maintained on both ends of the wire, until the filament was formed into a plane spiral between the disc and the end of the bar.

The ends of the cathode were spot welded to nickel leads of cross section considerably greater than that of the filament wire. Although nickel has a melting point of 1455°C, considerably lower than the operating temperature of the filament, the heat conduction of the leads was found to be great enough to prevent the welded junctions from overheating and melting apart. In fact, grooved heat chokes in the leads were used to prevent too great a heat loss from the cathode by conduction.

To assist in focusing the beam, the cathode was mounted inside a shielding electrode maintained at cathode potential. Experiments using electrodes of various shapes were conducted. The most satisfactory results were obtained using a cylindrical shield, of the same radius as the tube T, with a disc behind the plane of the cathode. One of the cathode leads made contact with the shield, while the other, to avoid shorting out the filament supply voltage, was brought through the shield in a small ceramic insulator.

Finally the whole cathode assembly was mounted in a glass ground joint as shown in Fig. 4.

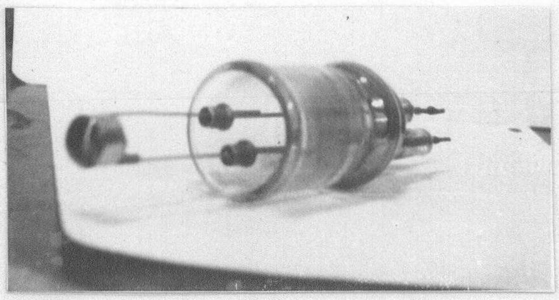


Fig. 4
Cathode Assembly

The filament leads were attached to tungsten leads, sealed into the glass, with clamps which allowed axial adjustment of the cathode position.

The filament was directly heated with A.C. from a Hammond Filament Transformer. A Variac on the primary side of the Hammond Transformer provided for control of the filament emission.

With a filament in the shape of Fig. 2, there was a danger of short circuiting the heater supply if two adjacent turns came into contact due to deformation of the spiral. To guard against this possibility, a fairly rigid spiral was required. Tungsten wire of 0.015" diameter was used to produce a cathode of reasonable rigidity; wire of larger diameter would have necessitated the use of very high heater currents.

C. Vacuum System.

For evacuating the system a mechanical forepump and a mercury vapour diffusion pump were used. The forepump was a Welch Duo Seal Vacuum Pump and the diffusion pump was one which had been made in the departmental glass blowing shop.

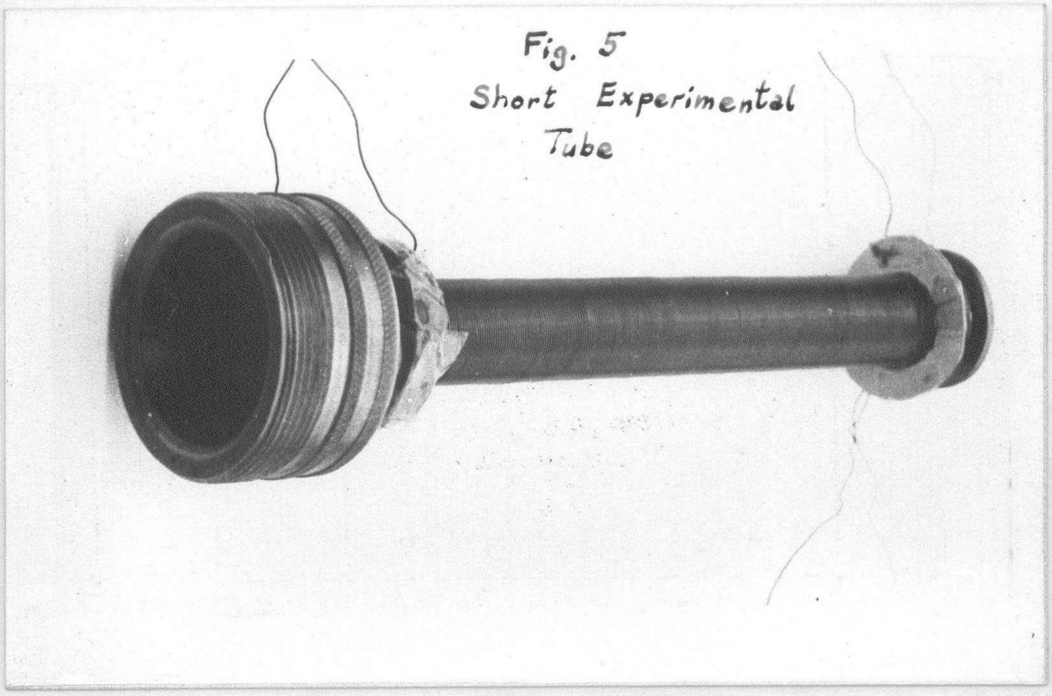
Pressures were measured with a Pirani Gauge, and the experiments were carried out at pressures below 0.1 micron Hg.

The pumping system could be used to evacuate either the main part of the equipment or an auxiliary cathode testing chamber in which anodes of various types could be mounted for investigating cathode emission. A standard size of ground joint was used in both sections of the apparatus, so that the cathode assembly, once mounted, could be easily inserted in either section.

The emission characteristics of the filaments, determined from experiments in the auxiliary chamber, were of use in designing magnetic field coils for subsequent experiments.

D. Short Experimental Tube

Preliminary investigations of the formation of electronic beams were carried out using a brass tube 1.33 cm. in inner diameter and 18 cm. in length (see Fig. 5).



To provide a uniform magnetic field inside the tube, a coil of #24 Formex Magnet Wire was wound on the outside of the tube along its whole length. This coil was four layers deep and 17.5 turns/cm. in each layer.

It was necessary to shield the cathode from the magnetic field so that the electrons would attain an angular velocity as they passed through a region of increasing field intensity after leaving the cathode. A small compensating coil (wound in opposition to and connected in series with the main coil) about one centimetre in length was added at the cathode end of the tube in an attempt to cancel out the magnetic field at the cathode. An approximate calculation of the number of turns required in the compensating coil was made, and tests were conducted at the cathode position with a sensitive compass needle and with a fluxmeter to check the field cancellation. The disadvantage of this method of cancellation was that it moved the region of increasing magnetic field further away from the cathode, allowing more time for dispersion of the beam before it entered the uniform field region. Eventually, experiments showed that a higher beam current was obtainable with the compensating coil disconnected. Fluxmeter measurements showed that the magnetic field intensity at the cathode position, due to the main coil alone, was only 10% of the maximum value inside the tube. Thus, for a given value of B_0, with current only in the main coil, electrons entering the tube experienced an effective flux density increase of $0.9B_0$.

A further small coil, which could be used to compensate for the falling off of the magnetic field at the end of the tube or to provide another region of increasing field intensity, was wound at the outer end of the tube. The coils were operated, in series with suitable variable resistors, on a 110 volt D.C. line powered by storage batteries in the building.

The outer end of the tube was terminated by a small brass flange. The cathode end of the tube was connected to a short brass cylinder (see Figs. 5, 6), large enough to fit over a length of glass tubing attached to the ground joint for the

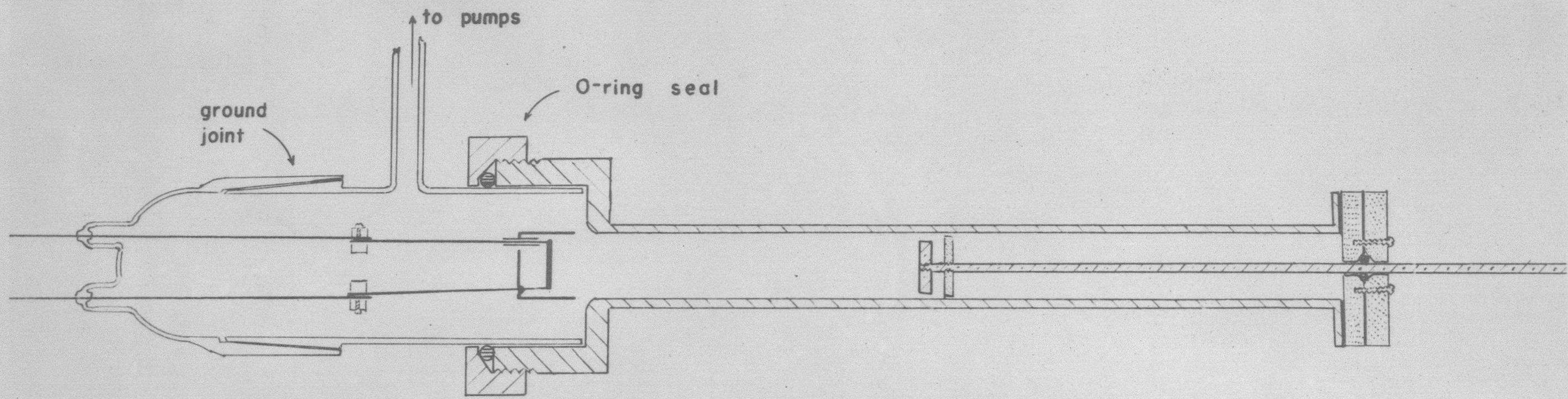


Fig. 6

18 cm. EXPERIMENTAL TUBE.

Beam detecting probe &
cathode assembly shown
in position.

cathode system. The glass tubing was also connected to the pumping system. The glass to metal vacuum seal consisted of a threaded ring which screwed on to the brass cylinder and held an O-ring rubber seal in place between the brass and the glass tubing.

E. Pulsing System

The voltage pulse was applied (see Fig. 6) directly between the body of the tube, which was grounded, and the cathode, which was at a negative voltage. For certain experiments a D.C. power supply, which was available in the department, was used.

For pulsed operation, the secondary of a 2.9 KVA Moloney Plate Transformer was connected directly between the tube and the cathode. The secondary of this transformer was modified by connection of the two secondary coils in parallel instead of in series, thus doubling the current capacity. The primary of the transformer was connected to a Variac to allow variation of the accelerating voltage. During pulsed operation the system operated as a half wave rectifier.

Child's Law[9] provides the relationship between the accelerating voltage V_0, the total current I_0 drawn from the cathode and the distance x between cathode and anode (in this case the anode was the entrance to the tube):

$$I_0 = (const.)\frac{V_0^{3/2}}{x^2} \tag{13}$$

Using the relationship of equation (13), for a given applied voltage the cathode can be placed in such a position relative to the tube that saturation current will be drawn for the greater part of each half cycle when the cathode is negative. Furthermore, the magnetic field can be adjusted so that, at the ends of the half cycle when less than saturation current is being drawn, V_0 is low enough according to equation (9) that the beam does not enter the tube. Using the system outlined above, the current pulses passing down the tube should be almost square wave pulses.

F. Beam Detecting Probe

In order to study the beam produced in the tube, a probe or travelling collector was designed. A metal disc (see Fig. 6) with diameter slightly smaller than that of the tube was attached to the end of a brass rod inserted in the tube. Attached to the rod behind the disc was a lucite spacer of slightly larger diameter to prevent the disc from making contact with the tube.

At the end of the tube, the brass rod passed through a vacuum seal consisting of two lucite discs clamped together and holding a rubber O-ring against the rod as can be seen in Fig. 6. This seal allowed the probe to be moved backwards and forwards inside the tube while the system was evacuated.

An ammeter between the shell of the tube and ground indicated the current due to electrons landing at the entrance to and on the walls of the tube. A second ammeter between the probe and ground was used to measure the beam current. By sliding the probe along the tube, the variation of beam current with distance could be studied.

G. The Final Ram Model

The main section of tubing for the Ram model had the same diameter as the short tube used for the preliminary experiments but was 100 cm. in length. The terminating tube (Tube T' of Fig. 1) was 7.2 cm. in diameter and 15 cm. in length. The outer end of this tube was closed except for a hole 1.6 cm. in diameter (see Fig. 7). The cathode end termination of the main tube was identical with that described above for the short tube and illustrated in Fig. 6.

Because of the much greater length of the coil required to produce the magnetic field in the 100 cm. tube, the resistance of the wire was great enough to prohibit the use of currents as great as those used in the 18 cm. coil unless a higher supply voltage could be used. The coils were wound, therefore, in a somewhat different manner. A first coil of four layers of #24 Formex Magnet Wire, similar to that used on the 18 cm. tube, was wound along the whole length of the tube. A second coil of the same wire was wound on top of the first. Two layers of this coil started 2.5 cm. from the cathode and extended to the end of the tube, and two more layers started 5.0 cm. from the cathode and also extended to the end of the tube. The first and second coils, connected to suitable variable resistors to control the current, could be connected either in series if a small current through both coils was required or in parallel to obtain a larger current in each coil. With the two coils arranged as described a uniform field could be obtained over most of the length of the tube except for the first few centimetres where a region of increasing field existed.

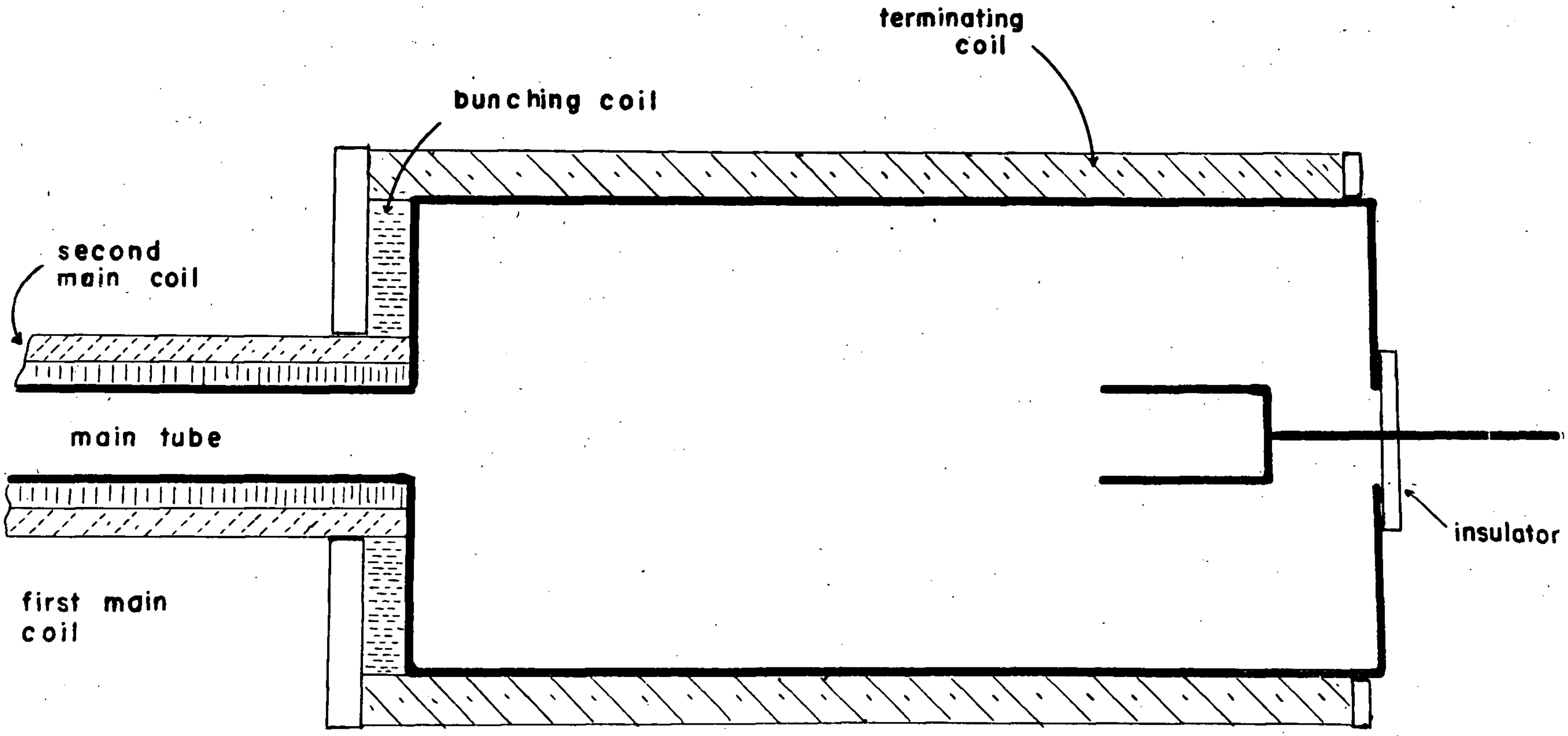


Fig. 7

TERMINATING TUBE, showing coil positions and internal collector.

At the end of the long tube, a "bunching coil" of about 300 turns was wound against the end of the terminating tube as shown in Fig. 7. This coil was designed to produce a field, of intensity greater than that of the limiting field, at the junction of the two tubes.

Finally, to provide a strong magnetic field in the terminating tube, a coil of eight layers of #24 wire was wound on the outside of this tube.

The cathode and accelerating system used were unchanged from the short tube experiment. The probe previously described could be pushed through the terminating tube into the main tube to investigate the beam current (Fig. 8). To investigate the current in the terminating tube, two methods were used. A hollow cylindrical collector could be placed over the hole in the terminating tube as shown in Fig. 9, or a similarly shaped collector on the end of a rod could be placed inside the tube as shown in Fig. 7. These collectors were made hollow in an attempt to prevent secondary emission losses if high energy electrons were incident upon the collector. It is probable, however, that secondary emission was not well suppressed even with these precautions.

Design specification of the ram model are given in Appendix I, and the complete apparatus is illustrated in Fig. 10.

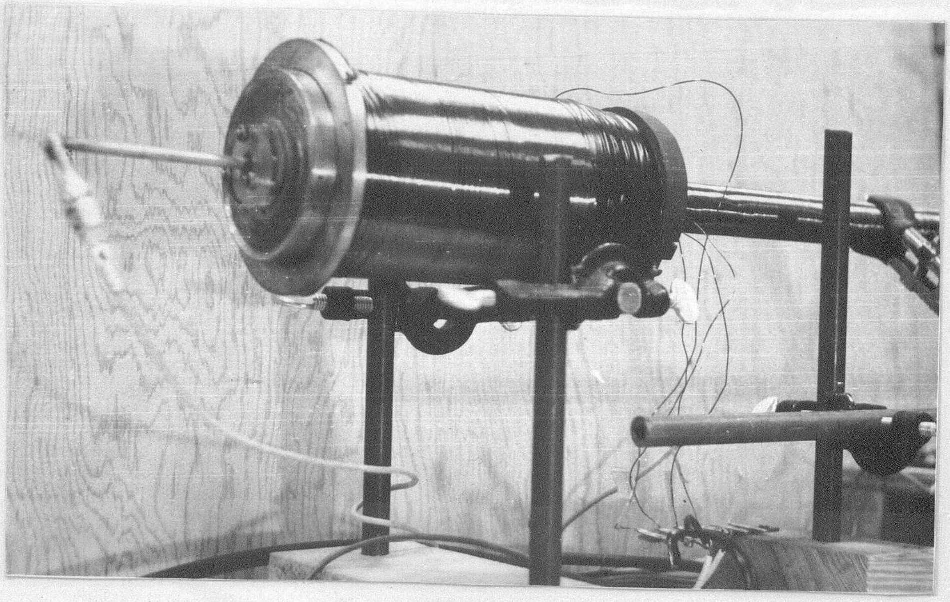


Fig. 8

Terminating tube with travelling probe in position.

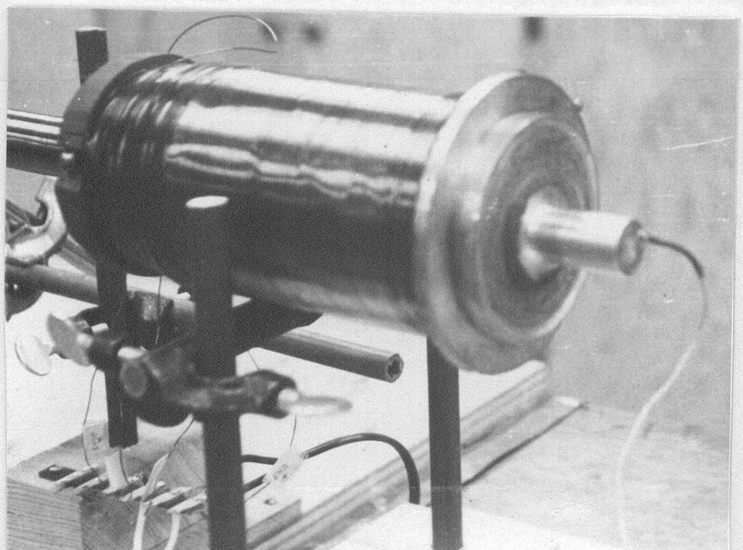


Fig. 9

Terminating tube with external collector.

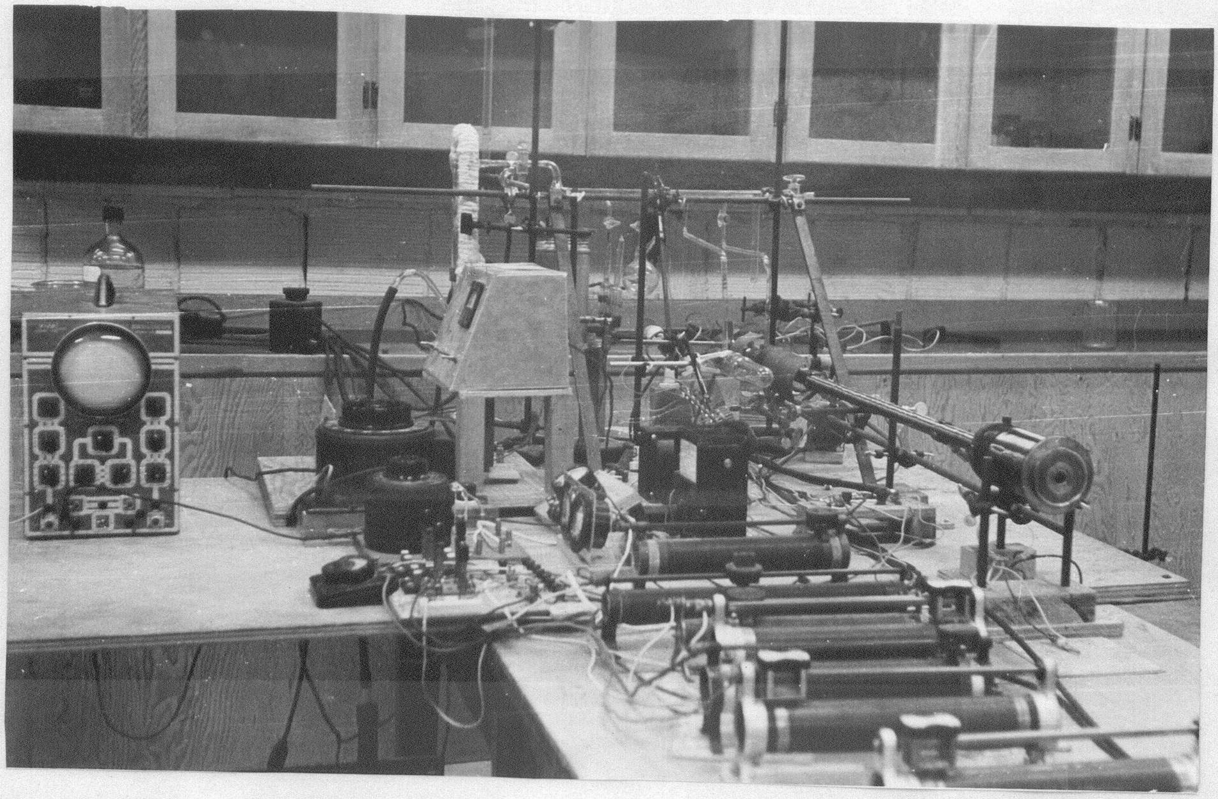


Fig. 10

Complete apparatus.

IV OPERATION

A. Preliminary Experiments

The total emission current expected from a 4" length of 0.015" diameter Tungsten wire at various temperatures and also the filament power required in each case had been calculated on the assumption of no temperature gradient along the wire. Investigation of spiral cathodes in the auxiliary testing chamber, however, indicated that the practical results differed somewhat from those predicted theoretically.

Examination of heated filaments with an optical pyrometer showed that there was a considerable cooling effect in the outer turn of the spiral, probably due to heat conduction by the cathode leads.

Experiment also showed that for a given filament current the total emission current which could be drawn was considerably less than the calculated value probably because of the non-uniform temperature distribution. It was found that total emission currents suitable for beam forming experiments could be obtained using filament power of 90 to 125 watts. Some filaments were found to deform when first heated to operating temperatures, so new cathodes were tested before being put into operation.

B. Experiments with Short Tube

In the 18 cm. tube with the travelling probe, and with a D.C. accelerating voltage, measurements were taken to determine the variation of beam current with distance along the tube, and the distribution of emission current between probe and tube.

A number of measurements, with the probe at positions between 5 cm. and 18 cm. from the cathode end of the tube, indicated no appreciable variation of beam current with distance. However when the probe was at the entrance to the tube, effectively changing the shape of the accelerating electrode from a ring to a plane, approximately 80% of the total emission current was registered on the probe. With the probe withdrawn to the end of the tube, beam currents as high as 65% of the total emission current and as large as 100 ma. were detected. Passage of larger currents was limited only by the capacity of the D.C. power supply used.

A.C. measurements, using the pulsing system previously described, were taken to determine the pulsed beam current passing down the tube. Average currents measured were of course smaller than in the D.C. case because of the half wave operation of the system. The waveform of the pulses arriving at the end of the tube was examined on a cathode ray oscilloscope and was similar to that shown in Fig. 11.

C. Operation of the Ram

A preliminary experiment was carried out with the ram model to compare the beam current in the main tube with that passing through the 18 cm. tube. The beam detecting probe was placed at the end of the 100 cm. tube; the current in the field coils and the accelerating voltage were adjusted to give the same conditions as those governing the short tube D.C. experiments. The beam to tube current ratios showed no appreciable difference from those determined in the 18 cm. tube. With pulsed operation, the probe current pulses were examined with a cathode ray oscilloscope. Fig. 11 shows a photograph of the waveform as displayed on the oscilloscope screen.

Measurements were taken, with pulsed operation, of the beam current received by the cylindrical collector at the end of the terminating cylinder as shown in Fig. 9. With current flowing only in the main tube coils, no beam current was registered at the collector obviously because of dispersion due to centrifugal forces in tube T'. However, with current flowing in the terminating coil also, a small beam current (about 5% of the total emission current) was detected. Similar results were obtained using a collector inside the terminating cylinder. A current flowing in the bunching coil produced a slight decrease in the beam current received.

Examination of the collector current pulses with an oscilloscope showed evidence of a ram effect. The unperturbed current pulses appeared like those of Fig. 11. Increase of the magnetic field or decrease of the accelerating voltage produced small oscillations at both ends of each pulse as shown in Fig. 12. Since a sine wave accelerating voltage was used, equation (9) predicts that the effect should be first noticeable toward the ends of the pulse, where V_0 is low enough to be critical. Further increase of the magnetic field or decrease of the accelerating voltage caused the oscillations to spread across the whole pulse, resulting in the condition shown in

Fig. 13. Calculations (see Appendix II) indicated that the bunching effect occurred under conditions very close to those predicted by equation (9).

Efforts were made to determine the energy of the electrons received by the collector. An electrostatic voltmeter was placed between the collector and ground but registered nothing. In another experiment a peak accelerating voltage of 200 volts was used, with magnetic field adjusted to produce the bunching effect. The collector was maintained at a negative potential of 1000 volts relative to the grounded tube. Examination with an oscilloscope indicated that some collector current may have been received, since small current pips were observed on the C.R.O. screen. However, it seems probable that the results of both these experiments may have been modified by secondary emission from the surface of the collector.

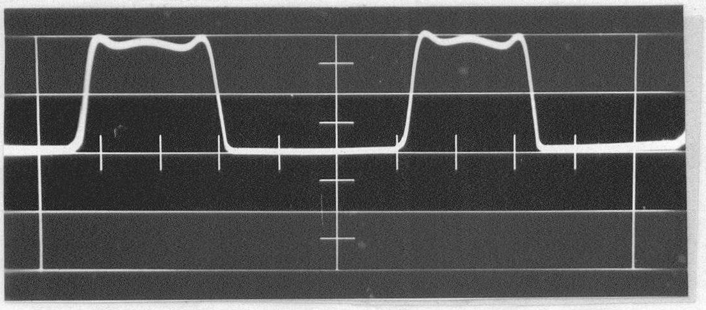


Fig. 11

Unperturbed pulses in main tube, as displayed on screen of Tektronix Oscilloscope, model 514-D.

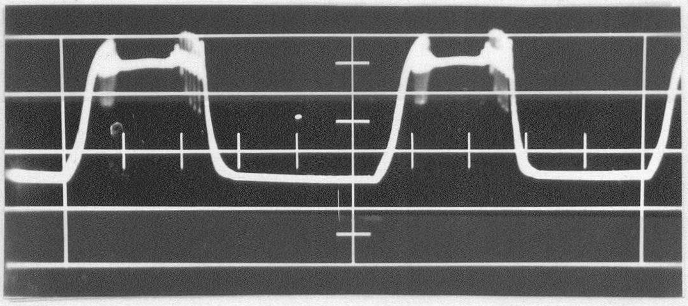


Fig. 12

Pulses in terminating tube, showing small oscillations at the ends of the pulses as critical conditions are approached.

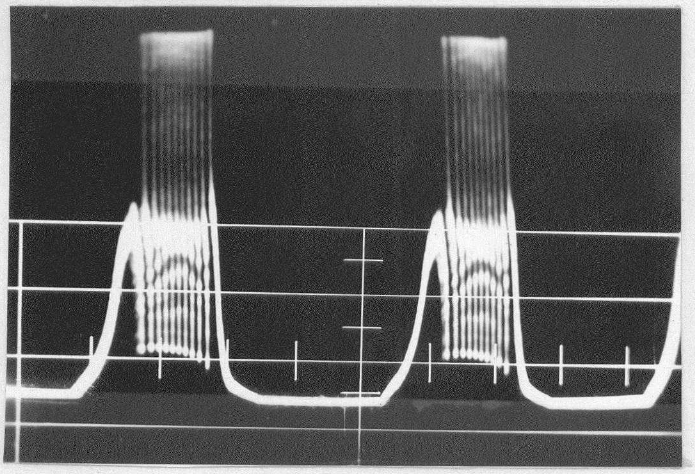


Fig. 13

Pulses in terminating tube under critical conditions.

V. CONCLUSIONS

The preliminary experiments with the short tube and with the 100 cm. tube of the ram model demonstrated that electron beams of high density can be maintained over large distances under the influence of axial magnetic and radial electric fields without appreciable dispersion, as predicted by the theory. The fact that the current passed through the larger terminating tube was smaller than that passed through the smaller diameter tube is in accordance with the work of Smith & Hartman[3] who predicted definite upper limits for the amount of current which could be passed in a beam through cylinders of various radii.

Loss of emission current due to electrons reaching the shell of the tube seemed to occur only in the region near the entrance to the tube where the beam was being formed. The distribution of emission current between probe and tube was found to depend to some extent upon the strength of the magnetic field, indicating that the fringing magnetic field near the cathode had a focusing effect upon the beam. Unfortunately this meant that the axial field in the tube could not be varied without an accompanying variation in the total beam current.

It is apparent from Fig. 11 that the current pulses in the main tube were not perfect square wave pulses; in particular they did not have sharply defined ends. However, the effects shown in Figs. 12 and 13 indicate that a ram effect was probably obtained. The fact that the amplitude of the short current pulses of Fig. 13 is considerably greater than that of the current traversing T' under steady conditions (Fig. 11) indicates that the electrons which constitute these pulses possess on the average higher axial velocity than the electrons within tube T. It appears that each half wave pulse was of sufficient duration for the electron beam to undergo the bunching several times in each cycle. With each bunching a sharp current pulse was ejected into the terminating tube, and the potential barrier was dissipated rapidly enough for the succeeding electrons to become bunched. It can be seen in Fig. 13 that the short pulses do not extend down to the base line of the trace, indicating that the axial velocity of the electrons was never reduced absolutely to zero as predicted by equation (9). It is probable that the initially axial beam with negligible radial velocity and the uniform space charge density assumed in the derivation of equation (9) were only approximated with the simple accelerating system used in the experimental apparatus.

The efforts made to measure the energy of the electrons traversing the terminating tube were indecisive. Accurate energy measurements could probably best be made with an analyzing magnetic field; incorporation of such a field in the ram model, however, would have entailed considerable redesigning of the equipment, and the measurement of energy distribution was beyond the scope of this work.

In the light of experience gained with the ram model several useful modifications of equipment can be suggested for possible future experiments in this line.

Various special types of cathode (such as the Philips L-cathode[10]), which will produce very high emission currents at relatively low operating temperatures, can be obtained. Such cathodes require activation before operation but would be much superior to a pure tungsten emitter if they could be used in a system which need not be frequently opened to the air.

Furthermore, the use of an electron gun[11], entirely separate from the main tube would be of great value in reducing losses at the entrance to the tube and would produce an initially axial and monokinetic beam. A gun of this type could be completely screened from the axial field in the tube, so that the magnetic field could be adjusted independently of the beam current.

For pulsed operation, the use of a higher frequency square wave accelerating voltage instead of the 60 cycle sine wave used in this model should produce short, well defined, pulses of beam current with sharp fronts.

The improvements mentioned above were not incorporated in the original apparatus for the sake of simplicity in design and because the main purpose of this work was to investigate experimentally the basic principle of the new acceleration method.

APPENDIX I.

SPECIFICATIONS OF THE RAM MODEL.

CATHODE:	Tungsten Filament Wire:	Length:	4.0 in.
		Diameter:	0.015 in.
	Diameter of cathode spiral:		0.9 cm.
	Diameter of cylindrical shielding electrode:		1.3 cm.
INTER-ELECTRODE SPACING:			
	Cathode - main tube entrance:		0.5 cm.
	Shielding electrode - main tube entrance:		0.25 cm.
SHELL:	Main Tube:	Length:	100 cm.
		Inner Diameter:	1.33 cm.
		Outer Diameter:	1.68 cm.
	Terminating Tube:		
		Length	15.0 cm.
		Inner Diameter:	7.2 cm.
		Outer Diameter:	7.6 cm.
FIELD COILS: (#24 Magnet wire giving 17.5 turns/cm.)			
	First main coil:		4 layers
	Second main coil:		4 layers
	Bunching coil:		300 turns
	Terminating coil:		8 layers
BEAM DETECTING PROBE:		Diameter:	1.1 cm.
CYLINDRICAL COLLECTORS:		Inner Diameter:	1.3 cm.
		Length:	3.0 cm.

APPENDIX II.

COMPARISON OF RESULTS.

Since the value of the beam radius, b, could not be determined experimentally, calculations were made to determine for what beam radii various values of V_0 should be critical, for given magnetic field intensities, according to equation (9). Some of the calculated results are listed below.

B_0	V_0	b
166 gauss	greater than 280 volts	none
" "	280 volts	0.66 cm. (= R)
" "	200 volts	greater than 0.4 cm.
276 gauss	greater than 800 volts	none
" "	800 volts	0.66 cm. (= R)
" "	700 volts	greater than 0.5 cm.
" "	600 volts	" " 0.4 cm.
" "	400 volts	" " 0.3 cm.

The waveform of Fig. 12 was obtained using an accelerating voltage of 800 volts r.m.s. and a field intensity of approximately 276 gauss. It can be seen from the above table that for no beam radius could the field be critical during the peak of the voltage cycle. However, at the ends of the pulse where V_0 is lower, the field is critical for any reasonable value of b. Thus, the results obtained are in accordance with these calculations.

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