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LAWRENCE RADIATION LABORATORY
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I. Introduction

The concept of the electron ring accelerator was very stimulating to us at the Lawrence Radiation Laboratory in Berkeley, California. After hearing about the exciting pioneering work of Veksler, Sarantsev, and other Dubna workers[1] at the Sixth International Conference on High Energy Accelerators at Cambridge, Massachusetts, in 1967, we examined the concept and its associated problems rather carefully. Although there seemed to be uncertainties and difficulties in the method, such as with beam instabilities and large radiation losses, none of these seemed insurmountable. The potential advantages of electron ring technology in producing considerably smaller and less expensive accelerators clearly outweighed the possible difficulties. Also the elegance of the electron-ring concept was most attractive. Early in 1968 we set up a research program under the direction of E. J. Lofgren and D. Keefe. A. W. Sessler, who leads the theoretical section of this program, also was instrumental in its initiation.

1 V. I. Veksler et al., Cambridge Electron Accelerator Report No. CEAL-2000, p. 289 (unpublished).

In February of that year we held at the Lawrence Radiation Laboratory a Symposium on Electron Ring Accelerators,[2] for the purpose of making another critical examination of this new concept. The participants of the symposium, who represented most of the accelerator laboratories of Europe and America, were fairly unanimous in their appraisal - namely, that the electron ring concept had great potential, that it had no obvious fatal defects, and that by all means the method should be pursued.

II. Experimental Program

The initial efforts of the Electron Ring Accelerator (ERA) group at LRL were experiments in simply forming and compressing electron rings. The first, a preliminary, low-intensity experiment conducted at the 4 MeV microwave electron linac in Berkeley, served mainly to get us acquainted with some of the electronic and diagnostic techniques that are involved with pulsed magnetic fields and nanosecond bursts of beams. The work with this preliminary equipment, called Compressor 1, was terminated when the apparatus for a high-intensity experiment became available. For such an experiment a very high intensity injector is necessary, and we were fortunate in that a very suitable injector existed in our own vicinity - namely, the Astron 3.5 MeV electron injector at LRL-Livermore. Thanks to N. C. Christofilos, this machine could occasionally be made available to us for periods of a few weeks.

The apparatus in this experiment, called Compressor 2,[3] is shown

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2 Symposium on Electron Ring Accelerators, UCLRL Report 18103 (1968)

3 D. Keefe et al., Phys. Rev. Letters 22, 558 (1969)

in the first slide (Fig. 1), in which both a radial and an axial cross section is illustrated. A weak-focussing magnetic guide field is provided by three pairs of pulsed coils situated outside a ceramic vacuum chamber. The compression cycle is illustrated in the next slide (Fig. 2). The three pairs of magnet coils are pulsed sequentially, the outermost pair serving to pick up the 3.5 MeV injected beam at a radius of 19 cm and to accelerate and compress it to a radius at which the next set of coils can pick it up, and so forth until the beam has been compressed to a radius of 3.5 cm and an energy of 18 MeV. The slide illustrates the time behavior of the ring radius, kinetic energy, magnetic field, and magnetic index n $\left(-\frac{R}{B_z} \frac{dB_z}{dR}\right)$ at the position of the ring throughout the 500 microsecond compression cycle.

The magnetic index n was the critical parameter in this experiment because of resonant single-particle instabilities. Generally, a particle orbit can become unstable when its radial and axial betatron frequencies, Q_r and Q_z, have a relationship of the form $aQ_r + bQ_z = c$, where a, b, and c are small integers (including zero), The importance of any particular resonance is related to the shape of the magnetic perturbation that drives the instability. Since the betatron frequencies Q_r and Q_z are determined by n, namely $Q_r^2 = 1-n$ and $Q_z^2 = n$, it is clear that, at certain values of n, resonances are possible and can cause large growth in beam size if the right magnetic perturbation is present and if the resonance is crossed slowly enough. In the Compressor 2 experiment it was found necessary to modify the n-trajectory of just the initial, large-radius portion of the compression cycle (where the magnetic perturbations are the largest) before a satisfactory compression could be achieved. After this modification the captured beam was compressed without loss.

The intensity of the ring was about 4×10^{12} electrons, and seemed to be limited by the injector rather than by any mechanism in the compressor. We observed no important intensity effects, aside from a helpful self-trapping mechanism, which occurred at incident beam levels greater than about 50 or 75 amperes. Furthermore, the compressed ring was stable for several milliseconds, being limited only by the decay of the magnetic field, which eventually brought it to the condition $n = 0$ and $Q_r = 1$, at which point the beam became unstable and was lost. The effects of ion focussing on the betatron frequencies also were observed. By means of a fast acting valve, a short puff of gas was admitted to the chamber, which served to load the ring with ions. It was very apparent that by adding a sufficient number of ions the beam could be brought to the $Q_r = 1$ resonance at a time before the field index n reached zero.

After compression to a radius of 3.5 cm the electrons have an energy of 18 MeV, and the synchrotron light from the ring is very bright to the eye, and can be photographed to show the spatial distribution within the ring. (Fig. 3) Such measurements showed that the density distribution was gaussian and gave minor ring radii of 1.6 and 2.3 mm (rms), which were in agreement with independent probe measurements. Combining the intensity and geometrical data gives a peak electric field of 12 MV per meter, which is not yet high enough to surpass the best types of present-day accelerators, but it encouraged us that such an intensity could be achieved without great difficulty and without barriers to higher intensities becoming apparent.

Out next effort was an experiment for accelerating an electron ring loaded with ions. In this experiment we wanted to form similar rings, load them with a few per cent of hydrogen ions, and accelerate them to a few MeV by magnetic acceleration over a distance of half a meter. The apparatus for this experiment, called Compressor 3, is illustrated in the next slide (Fig. 4). The design here differed from that of Compressor 2 in two respects (1) coil 3 was developed into a solenoid, the long side of which was the accelerating region for the ring, and (2) coil 1 was elaborated to provide a flatter initial n-trajectory - i.e., an effort was made to minimize the variation of the magnetic index n over the first few centimeters of compression. Unfortunately, this change resulted in an increase in higher derivatives of the field, which caused greater coupling to some resonances, as we shall see later.

Our greatest concern in the design of Compressor 3 was the problem of extracting the compressed ring from its magnetic well and starting it down the accelerating solenoid, where the magnetic field is essentially flat. Additional focussing must be supplied here to avoid both (1) axial spreading of the ring ($Q_z = 0$) and (2) radial blow-up as Q_r approached 1.0. Positive focussing in each direction is supplied by the positive ions being accelerated, but these forces are relatively weak for ion loading of only a few percent. Image focussing by a laminated conducting cylinder is more effective and also more satisfactory in that it raises the axial tune Q_z but lowers the radial tune Q_r, thus avoiding the $Q_r = 1$ instability.

This experiment was not a success because we could not form satisfactory rings in Compressor 3. As a result, we did not get a chance even to try acceleration of a loaded ring in the time we had available at the Astron accelerator. We had two difficulties, the first of which was the well-known "negative-mass" instability. As the intensity of the injected beam was increased to about 150 amperes, the radial width of the ring increased, corresponding to an energy spread of about 10%, which greatly diluted the electron density in the ring. This unexpectedly large negative-mass effect was due to the very narrow energy spread in the Astron injector, which had been completely rebuilt in the period between our two experiments. Whereas the energy spread of the injector had been about 0.5% in the Compressor 2 experiment, the new injector had no more than 0.1%, which was determined by using the Compressor 3 as a magnetic energy analyzer. Since the negative-mass threshold varies as $(\Delta p/p)^2$, this measurement indicated that the Compressor 3 situation had a 25 times smaller threshold for this instability.

Our second difficulty in the Compressor 3 experiment was an axial blow-up and loss of most of the beam because of single-particle resonances. The principal loss occurred at n = 0.5 (where $Q_r - Q_z = 0$). The coil system was flexible enough to inject below n = 0.5, but when this was tried, resonances at n = 9/25 and n = 1/4 also caused excessive beam loss.

These instabilities encountered in the Compressor 3 experiment are now understood well enough that we have, with some confidence, designed modifications which will avoid these troubles. For avoiding the negative-mass instability we shall first try a tapered foil in the incident beam line to provide a sufficient instantaneous energy spread. For avoiding the single-particle resonance instabilities, we have tailored the magnetic field so as to reduce the second and third radial derivatives of the magnetic field (d^2B_z/dR^2 and d^3B_z/dR^3), which drive the n = 0.5 resonance, and similarly we have reduced the angular magnetic perturbations that drive the n = 9/25 and n = 1/4 resonances. We expect to test these design features in a new compressor experiment starting in the last part of August. We plan to test the extraction and acceleration of electron rings loaded with ions later this year.

III. New Injector Facility

In order to carry out our ERA developmental program in a more systematic and orderly fashion, we have been building in Berkeley over the past several months a new injector accelerator. It is a linear induction accelerator, similar to the Astron injector except that it has a smaller pulse length (30 to 40 nanoseconds) and lower repetition rate (1 Hertz), which permit a simpler and cheaper type of design. The energy will be 4 MeV and the nominal peak current is 1000 amperes. The design is modular, consisting essentially of 17 induction cavities driven by 40 nanosecond pulses from Blumlein pulse-forming lines, each cavity providing 0.25 MeV across its gap. The next slide shows a typical cavity (Fig. 5). The induction cores here are ferrite rather than tape-wound iron-nickel ribbon as in the Astron injector. These cavities serve not only to make up an injector accelerator but also as models of the type of cavities that we visualize as useful for electric acceleration of electron rings in a high-energy proton accelerator. I shall speak more about this concept later.

The electron gun of our new accelerator consists of five of these cavities stacked close together and coupled by means of a central conducting rod that terminates at the fifth cavity and carries the emitting cathode. The cathode voltage thus is the sum of the voltages of the five cavities, which is 1.25 MeV.

This electron gun has been tested successfully now for two or three months. Only field-emission types of cathodes have been used thus far, although the geometry is compatible with the use of thermionic cathodes as well. Field-emission types have been used initially because of their greater simplicity, and thus far they seem satisfactory, except possibly in regard to life time. Peak currents of 1000 amperes or more are easily obtained. Furthermore, the brightness of the beam seems adequate for electron ring formation. The instantaneous energy spread has not yet been measured precisely; it is known only to be less than 0.5%.

The physical layout of this injector and experimental facility is shown on the next slide (Fig. 6). Apparatus for the formation and acceleration of electron rings are being prepared for installation in the experimental hall at the end of the injector enclosure.

IV. Future Possibilities for ERA

For the future we are optimistic that the electron ring accelerator will prove to be a successful competitor to the more conventional types of accelerators, both for medium-energy heavy-ion acceleration and for high-energy proton accelerators. We have been greatly encouraged by the results of the electron-ring group under Sarantsev at Dubna. Our own analyses of the technical and economic aspects of the problem have also been encouraging.

We recently made a study of the feasibility of an 80 GeV proton-type electron-ring accelerator. The design considerations for an electron ring accelerator are quite different and more involved than for a synchrotron. For a synchrotron the only important parameters to be chosen for a given final energy and intensity are the machine radius and injection energy; whereas for an electron ring accelerator the final proton energy depends critically on the ion loading ratio and the geometry of the ring itself.[4]

In our study we considered only a high-energy proton-type of electron ring machine consisting of a compressor, a section of electric acceleration, and a final section of magnetic-expansion acceleration. The next slide shows the layout schematically (Fig. 7). The electric acceleration column consists of a series of linear induction cavities similar to those in our injection accelerator. The average external accelerating field supplied by the cavities is 5 MeV per meter. The solenoid guide field of 30 kg is provided by superconducting coils which are interspersed between the cavities, as indicated in the next slide (Fig. 8). Although the radius of the electron ring is only of the order of 2 or 3 relatively large bore radius of 19 cm is provided in the electric cavities to keep down the radiation loss due to the interaction between the electrons and the accelerating structure. Since this radiation loss increases as the square of the number of electrons in the ring, this effect limits the number of electrons to a few times 10^{13} per ring in this situation. It also prevents the use of a focussing image cylinder, which in an electric column could at best occur only intermittently, which would greatly increase the radiation loss.

In this example, the electron ring has a maximum electric field of 500 MV/meter and is loaded typically with 1/2% of protons. The protons gain energy by electric acceleration at the average rate of 125 MeV/meter, thus gaining a total of 40 GeV in the 320 meter length of the electric column. In the electric column the average accelerating rate for the protons is maintained at only one quarter of the maximum electric field at the ring in order

4 C. Bovet and C. Pellegrini, LRL internal report ERAN-73, June 1970.

that polarization effects within the ring should not become severe. Since in the electric column the integrity of the electron-ion ring is maintained only through ion focusing, there is the great danger that the system can become unstable if the centers of the positive and negative charges become too much separated. A self-consistent solution of this problem has not yet been found.

The problem of time jitter between the voltage pulses appearing at the cavities is manageable by conventional electronic techniques. Relative jitter times of 1 ns or less have been achieved in the firing of the five cavities in the electron gun section of our injector accelerator although the jitter will be larger for the much larger number of cavities in the electric acceleration section, it should be adequately covered by the 15 ns pulse length applied to the cavities.

The last section of the accelerator, a magnetic-acceleration column 150 meters in length, is simply a slightly tapered, superconducting solenoid. This is placed after the electric-acceleration columns because, as was pointed out by Keefe,[5] magnetic acceleration acts as a multiplier of energy, while electric acceleration is additive. In the magnetic-acceleration column the proton energy increases by a factor of about 2, entering at 40 GeV and reaching 80 GeV at the end. In this magnetic column the protons are allowed to gain energy at a rate of one half the maximum electric field of the ring (rather than 1/4 as in the electric column) because here the polarization of the protons from the electrons is less important. The focusing of the ring system is dominated by the forces from an image cylinder, so that polarization of the ions and electrons does not threaten the integrity of the ring.

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5 D. Keefe, Particle Accelerators I, 1 (1970)

The constraints put on the parameters of the electron rings in this study were quite severe. In addition to the radiation loss limitation imposed by the ring-cavity interaction already mentioned, ring stability was required throughout the whole process of ring formation and acceleration. The number of electrons in the ring was kept below the thresholds for the negative-mass instability, the resistive-wall instability, and the transverse incoherent space charge effect. With all these constraints plus that of achieving 80 GeV protons in a total length of 470 meters, the range of possible compressor designs is quite limited. (One interesting alternative solution to the problem of compressor design suggested by Pellegrini utilizes shrinking of the ring dimensions through the action of synchrotron radiation; this possibility is under investigation.)

Although I have characterized this electron ring accelerator in my talk as an 80 GeV machine, one should realize that in this type of device the actual output energy is a strong function of the amount of ion loading and the detailed properties of the electron ring. For a fixed set of hardware in the electric and magnetic columns, the output energy could be 100 GeV at an average intensity of 5×10^{12} protons per second (assuming 100 Hz repetition rate) but only 60 GeV at an intensity of 2×10^{13} protons per second (assuming optimum operation in each case).

One constraint imposed during this conceptual study was to assume that only state-of-the-art technology would be used, e.g. voltage holding capabilities, jitter times, etc. that have commonly been achieved. We are still, however, in the learning process and technological advances are being made quite rapidly. For example, the peak applied electric field assumed in the studies (5 MV/m) is now thought to be too low by a factor of two; thus protons of perhaps 200 GeV could be produced in the accelerator described.

Cost estimates for construction of electron ring accelerators cannot be very reliable, particularly in view of the rapidly changing technology, but our studies of costs have convinced us that an electron ring accelerator has a potential economic advantage over a conventional synchrotron, and that its development should be pursued with vigor.

FIGURE CAPTIONS

Fig. 1. Longitudinal and transverse sections of Compressor 2.

Fig. 2. Ring radius (R), kinetic energy (T), magnetic field (B), and field index (n) versus time (t) in Compressor 2.

Fig. 3. Synchrotron light from electron ring in Compressor 2. Each exposure consists of 15 pulses. The structure of the images is caused by a grid in the image multiplier used.

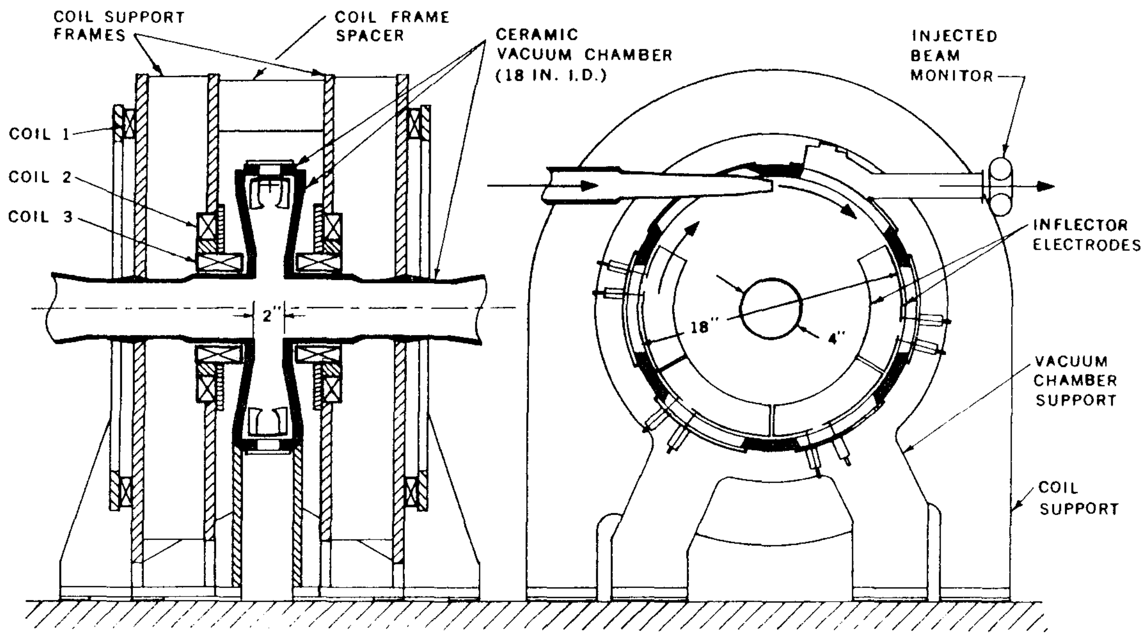
Fig. 4. Longitudinal section of Compressor 3.

Fig. 5. Accelerating cavity of Berkeley injector.

Fig. 6. Berkeley injector and development facility.

Fig. 7. Schematic diagram of a proton accelerator.

Fig. 8. Electric and magnetic accelerating columns.



ELECTRON RING ACCELERATOR - COMPRESSOR II

Fig. 1.

XBL 689-4921

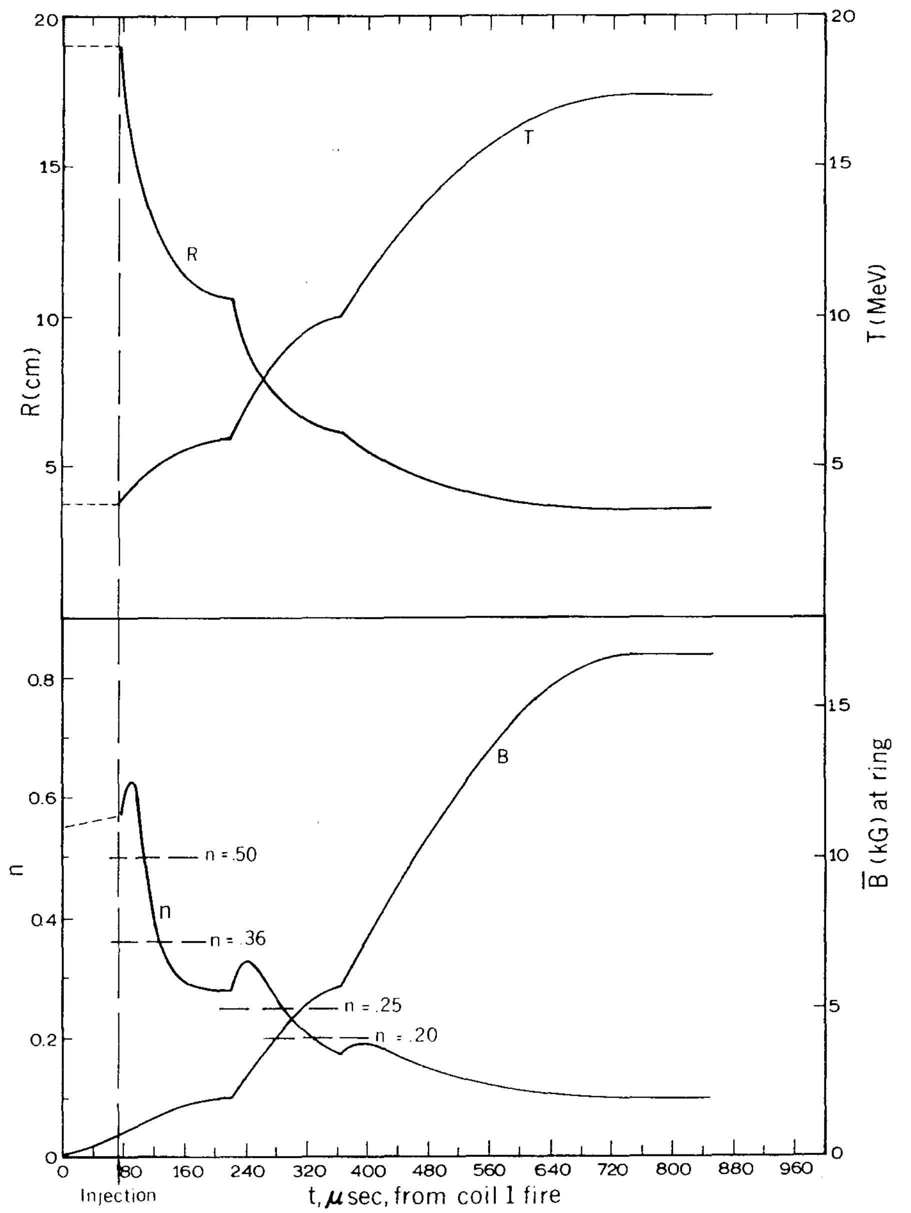
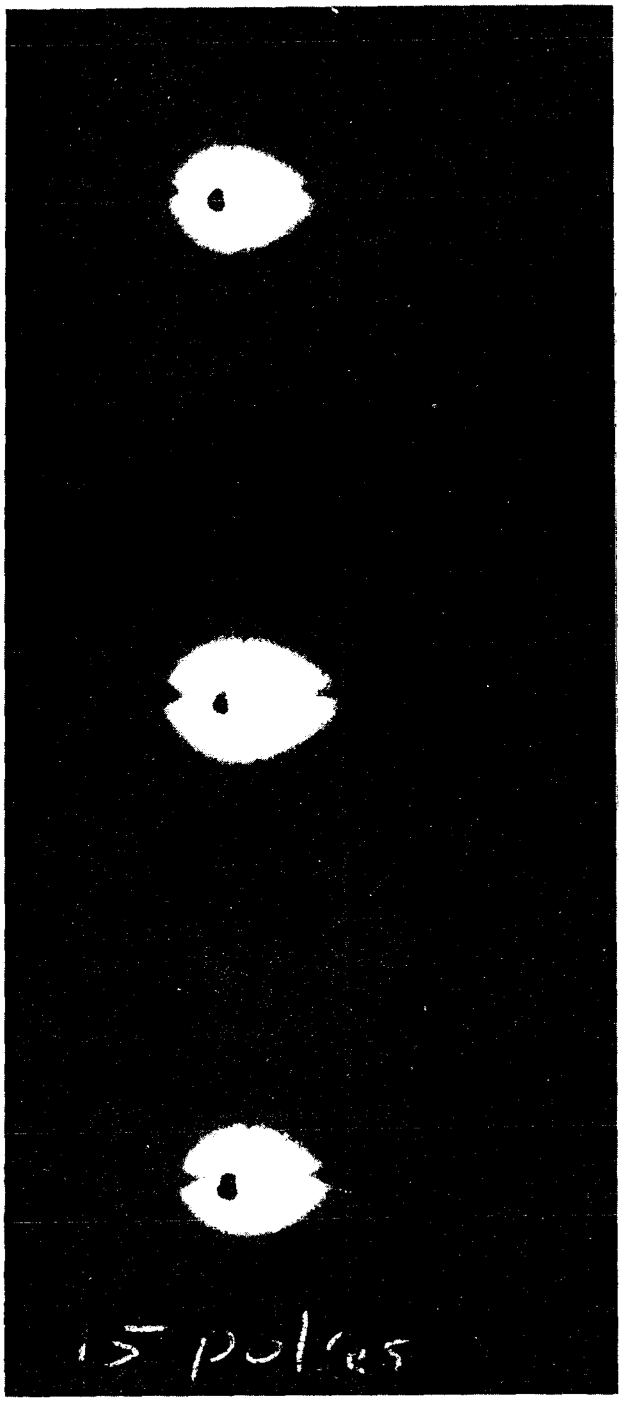


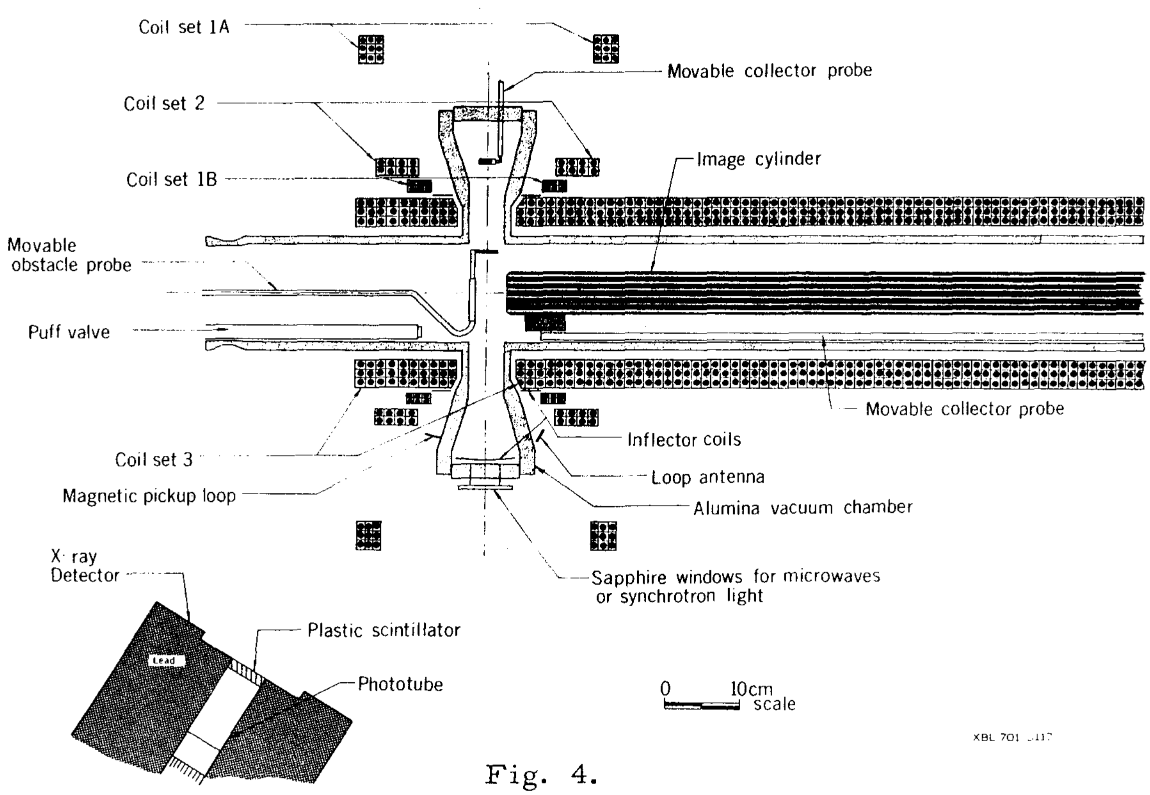
Fig. 2.

XBL 698 4873



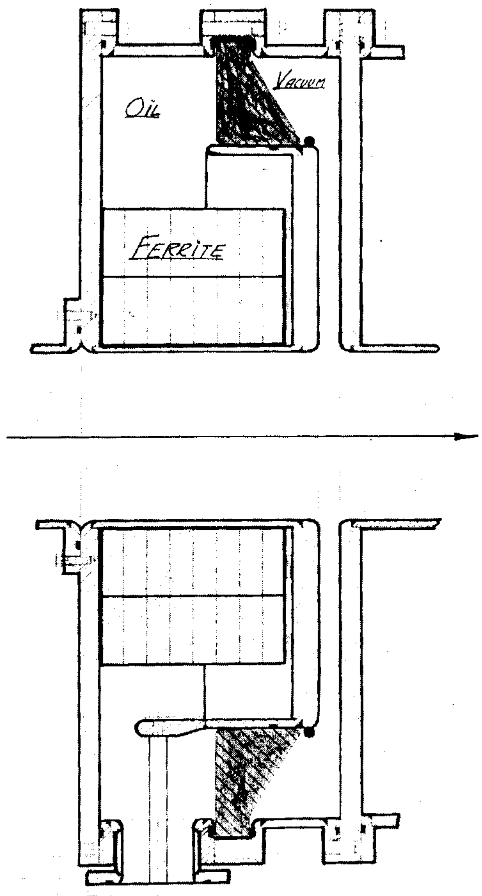
XBB 6811-6842

Fig. 3



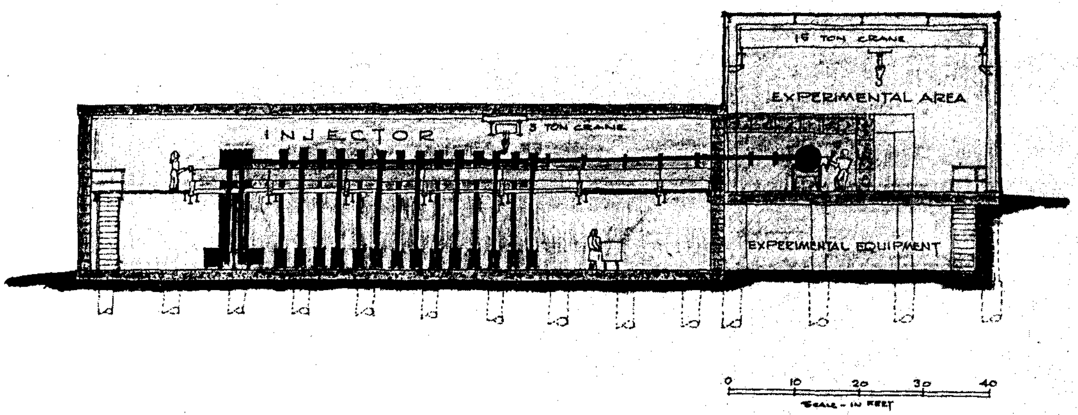
XBL 701 -117

Fig. 4.



BBC 701-319

Fig. 5

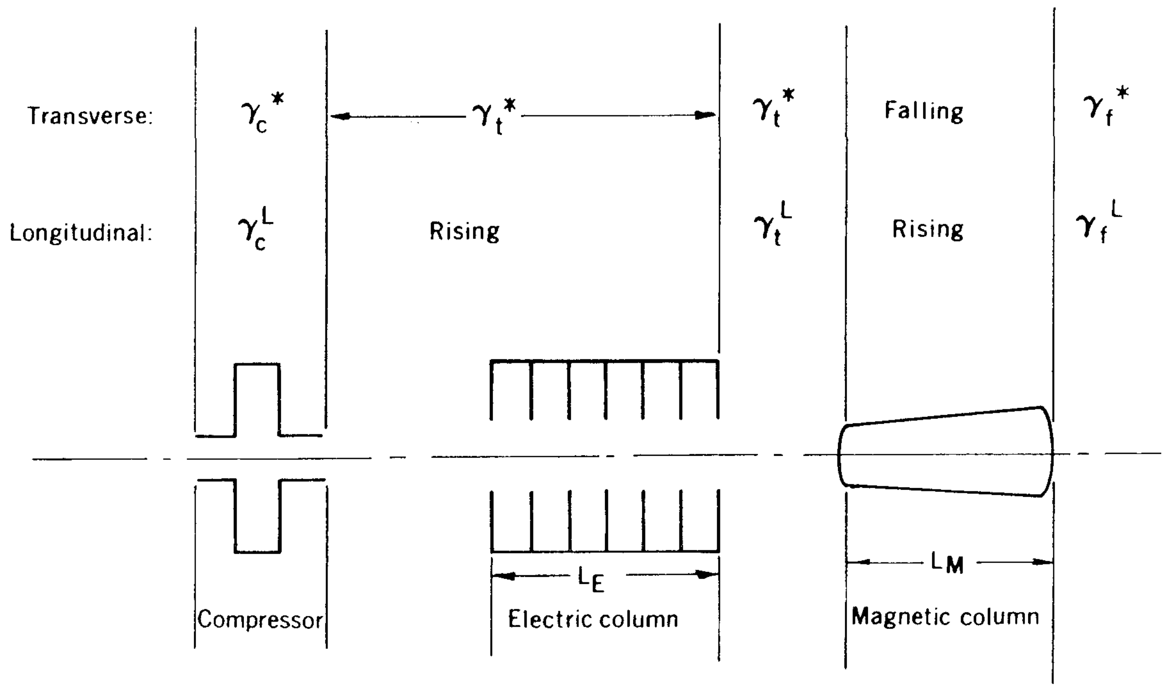


ACCELERATOR DEVELOPMENT FACILITY

SECTION THRU INJECTOR TUNNEL AND EXPERIMENTAL AREA

XBC 701-409

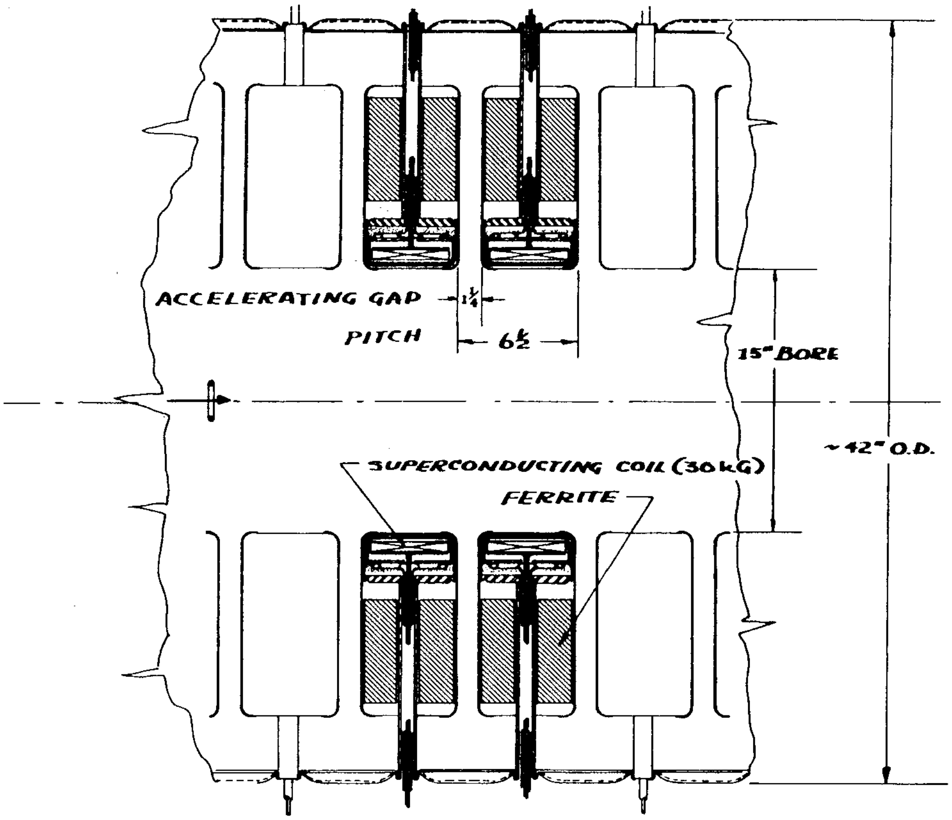
Fig. 6



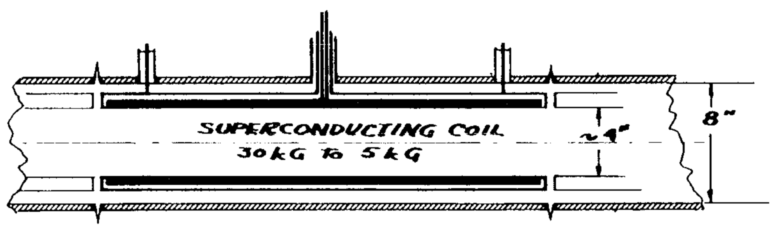
Schematic ERA to show Parameter Nomenclature

Fig. 7.

XBL 703 6160



ELECTRIC ACCELERATION SYSTEM



MAGNETIC ACCELERATION SYSTEM

Fig. 8.

XBL 703 6164