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ERA DEVELOPMENT AT BERKELEY*

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1. Introduction

The main interest at Berkeley in research on the electron ring accelerator lies in its ultimate use as a high-energy proton accelerator for elementary particle physics. In aiming towards this goal we are mindful of the possible application to nuclear chemistry, bio-medicine and other areas of research, and it is probable that in the course of the advances in electron-ring-accelerator developments it is in these latter aspects that the ERA could also be of value. Apart from some brief general studies a year-and-a-half ago[1] only a small amount of attention has been paid to the details of a large-scale accelerator; instead, the major emphasis has been on trying to establish the feasibility of the concept and in making experiments to obtain design information of use in future devices.

The major advantage of this type of accelerator will, of course, be its compactness. For reference, the typical rate of energy-gain per unit length of structure is 1 - 1.5 MeV/meter in a proton linac and about 40 MeV/meter in a proton synchrotron. In an ERA one limit is determined by the peak-field holding the ions within the ring, since

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the ring cannot be subjected to a greater acceleration without loss of the ions. This field is given by

$$E_{max} = k[N_e/R(a+b)],$$

where N_e = number of electrons, R = major radius, a, b, = minor cross-sectional dimensions and k is a form-factor that depends on the cross-sectional distribution of the electrons in the ring. In experiments by the Berkeley Accelerator Study Group, already reported[2], rings with a peak field of 12 MV/meter were formed. Improvement in this number by even a modest factor will thus lead to rates of energy-gain that seem very attractive. Of great importance, therefore, is the production of considerably more intense rings. Let me now describe the activities in this field that are underway at Berkeley.

Since the last conference in this series, two years ago at Cambridge, Massachusetts, when the report of the work by Veksler, et al.[3] caused heightened interest in pursuing research on collective-effect accelerators, the Berkeley group have built three devices for forming electron-rings and compressing them to small dimensions. Compressor I was in the nature of a learning device and was operated for a short time with a low-energy low-current electron linac as an injector. Compressor II was used for experiments on forming intense rings and trapping ions, and the results of these experiments are given in Ref. 2. Briefly the following parameters were achieved:

$$N_e = 4 \times 10^{12},\ R = 3.5\ \text{cm},\ a = 2.4\ \text{mm},\ b = 1.6\,\text{mm},\ E_{max} = 12\ \text{MV/m}\ .$$

In their final compressed state, however, the rings were held in a weak-focusing magnetic field with a field-index value of $n = -\frac{R}{B}\frac{dB}{dR} = 0.28.$

The lifetime of the stored rings, determined by the decay of the favorable focusing field, was about 7 milliseconds.

Fabrication of the most recent device, Compressor III, has just been completed at Berkeley, and it has been moved this month to Livermore for its first experimental testing. Experiments will be carried out for brief intervals over the next few months. The goal of these experiments is, first, to study the effects that occur with an ion-loaded ring as the field index gradient is allowed to approach $n \approx 0$, and, second, to extract the ring from the forming field and accelerate it in a "tapered"-solenoid field" ($B_z \gg B_\rho > 0$). A description of the design and testing of Compressor III is the main subject of this talk.

While an increasing number of people, outside the USSR, have made extensive calculations, and predictions (both optimistic and gloomy) and have described novel possibilities for electron ring acceleration during the last two years, it is my view that we have all suffered heavily by lack of direct experimental experience and information. In order to allow a suitable experimental arrangement compatible with ERA component-testing and the frequent shutdowns for equipment modification, we have begun construction of a high-current relativistic-electron source, which will be discussed later. In the meantime the Berkeley group has had limited access to the Astron injector at the Livermore branch of the Lawrence Radiation Laboratory, as an intense source of relativistic electrons.

Several theoretical efforts continue to be maintained. Some are directed to the more immediate problems associated with the experimental program, such as: the field and field-gradient effects on the electron ring due to the presence of neighboring dielectrics, the space-charge effects in the induction accelerator, the single-particle and collective instabilities that may be encountered, etc. Longer-range problems concern improvements to the method of ring-formation — such as static field compressors[4] and calculations on the long-standing problem of cavity radiation. Some of these topics will be discussed at other sessions at this conference.

2. Electron Linear-Induction Accelerator

During the past nine months we have examined the desirable parameters for an electron source suitable for ERA research purposes. The requirement of both a repetition rate of 1 Hz (or greater) and a low maintenance cost per pulse quickly eliminated the choice of any of the commercially-available flash X-ray machines. The desired parameters of the injector for the ERA test facility are as follows:

TABLE I

Energy:	2 — 4 MeV
Repetition Rate:	1 — 10 Hz
Current:	$\gtrsim$ 500 amps.
Emittance:	$\approx$ 0.06π cm-rad at 1 MeV
Pulse Length:	35 nanoseconds
Energy Spread:	Variable ($\geq$ 0.5%)

Design and development work has centered around an initial energy of 2.2 MeV with the future addition of further units to bring the energy up to 4 MeV. The basic element of the design is the pulsed accelerating cavity illustrated in Fig. 1. The four essential elements in this module are the cavity, the pulse-forming network, the switch, and the charging supply. In essence the cavity may be considered, in high-frequency terms, as a ferrite-loaded transmission line or, in a low-frequency analog, as a one-turn one-to-one ferrite-core transformer. No matter the point of view, the voltage appears across an accelerating gap of a few centimeters in width. A gradient higher than usual can be obtained because the voltage is on the gap for only 35 nanoseconds. Because of the short pulse-length the pulse-forming network has been chosen to be a rigid oil-filled Blumlein line, discharged by a pressurized spark gap. The charging supply is a quasi-d.c. ($\approx$ 1 μsec) Marx generator. A test module has been in operation for a few months ($\approx$ 200,000 pulses) in order to test certain design features, such as the choice of ferrite material and the behavior of the angled Lucite insulator that separates the oil-filled section from the accelerating gap in high vacuum. Each module is nominally rated at 250 kV and all the elements have been satisfactorily tested up to this time, with the exception of the high-voltage switch.

The accelerator is conceived to consist of a single-gap "gun" section of 1-1.5 MeV followed by an accelerating column of pulsed accelerating cavities whose apertures are determined by the beam size at their respective locations, and whose number is determined by the available finances. At this time, we believe the most desirable configuration for the gun is a compact stack of five cavity modules with a coaxial copper center conductor to carry the combined voltage pulse to the first gap.

In this way, these five cavities, each of a nominal 250 kV, should provide a high voltage terminal at 1.25 MV. We are hopeful that, at the repetition rate envisaged, a cold-cathode configuration of a cluster of needles will supply the desired current and emittance. If not, this high voltage terminal will allow the rather simple conversion to a hot-cathode source, such as lanthanum boride, without the complication of the heater supply being at high voltage.

The configuration of the accelerating column is not final, but in general terms will consist of pulsed accelerating cavities, solenoid focusing magnets spaced about one meter apart, and room for beam diagnostic equipment and pumping ports. Equipment will also be installed to select certain beam pulse lengths, and to allow the energy-spread to be varied.

The electron accelerator should be operating in late Spring 1970.

3. Compressor III

a. Ring-forming Stage

Mention was made in Ref. 2 of the difficulties encountered with Compressor II because of "single-particle" betatron resonances; in particular the values $n = 0.5$ ($\nu_R = \nu_z$), 0.44 ($\nu_z = 2/3$), 0.36 ($2\nu_z + \nu_R = 2$), 0.25 ($\nu_z = 1/2$), were suspected of leading to beam loss if encountered early in the compression cycle. These difficulties were solved by use of "n-correcting circuits" to trim the main-coil currents.

This experience suggested a desirable pattern of change of n with time and the coil configuration for Compressor III was redesigned accordingly. Four, instead of three coil pairs are used. (See Fig. 2.)

The additional coil pair, Coil 1B, is placed between Coils 2 and 3 and carries almost the same current as Coil 1A (hence the rather odd nomenclature). The method of exciting the coils is shown in Fig. 3 and the designed values of n versus time are shown in Fig. 4. It is intended to inject close to $n = 0.56$ ($\nu_R = 2/3$), to obtain three-turn injection, to dwell there for some time before crossing $n = 0.5$, and thereafter to cross the presumably dangerous values of n rather rapidly without dwelling too long near any of them. A computer program has been prepared that is capable of handling twenty coupled circuits and includes the effects of eddy-currents in the copper conductors of even the open circuit coils. Extensive magnetic measurements of n versus radius and time alerted us to the very large effects due to eddy currents and these empirical data have been well simulated in the computer program. Since one cannot, however, expect the final configuration to conform exactly to that planned, there is also provision for n-correcting circuits -- both active and passive -- to effect small modifications. The n-value at the end of compression will be $n \approx 0.1$ at a final radius of $R = 3.5$ cm.

Diagnostics during ring-formation will include those of Compressor II and some extra facilities. Two tantalum target probes can intercept the beam at different positions, scintillators detect the beam at entry and after three-quarters of a turn, an air-cored current transformer measures the circulating beam-current, while microwave and optical synchrotron radiation can be detected through a variety of sapphire windows placed radially around the compressor. Further probes that enter axially include a collector to detect the cold electrons emitted after the hydrogen gas has been ionized, a capacity probe to measure the ring current, a sequence of capacitance pick-ups to measure the velocity of the extracted ring. Finally, axially and within the ring, either a long dielectric image cylinder or a small high gradient coil can be introduced as desired. Some of the diagnostic probes and devices are illustrated in Figs. 5 and 6.

b. Ring Extraction and Acceleration

Perhaps mistakenly, we tend to believe that the stability of the ring and the technique of accelerating it once it is moving at high axial velocity, may present less difficult problems than extracting the ring from the forming field, loading it, and launching it to near-relativistic speed. It is to the latter problems that experiments with Compressor III are addressed.

The basic technique planned for extraction is as follows. During compression, both left- and right-hand coils are excited with equal currents, but after compression a separate critically damped circuit (see Fig. 3) is switched to unbalance the currents in the left- and right-hand sides of Coil 3. The peak field in Coil 3L rises to about 50 kG while that in Coil 3R drops slightly to about 16 kG. During this time the median plane and the ring should move about 12 cm to the right into the long solenoid and the n-value at the ring decrease from 0.1 to zero. Control of the values of the currents in the other coils, 1A, 1B and 2, is necessary to achieve exactly the right condition. Beyond the spillout point a roughly-constant value of radial field, B_r, occurs to accelerate the ring at a constant rate. Values of B_r as low as ≈ 5 G over ≈ 50 cm should be achievable to provide gentle acceleration, if needed. The final axial speed of the ions emerging from the right-hand solenoid should be about 0.1 - 0.2 c.

Since during extraction, one must transfer the ring to a region where $n = 0$ and there is the danger of encountering the resonances $\nu_z = 0$ and $\nu_R = 1$. Because of collective effects, the axial and radial betatron frequencies are not simply $n^{1/2}$ and $(1-n)^{1/2}$, but involve many variables depending on intensity, ion-loading, magnetic-field shape, proximity of conductors and dielectrics, all of which in turn depend, generally, on time.

Table II is intended as a simplified chart of the effects contributing to the incoherent ν_z and ν_R, with an indication of the variables involved.

The full expressions for ν_z and ν_R are complicated and are given by L. J. Laslett.[5] In brief, however, one can appreciate from Table II that one can exploit many combinations of the parameters and in principle avoid difficulties at $\nu_z = 0$ or $\nu_R = 1$. In particular by arranging for images in an adjacent dielectric cylinder to be sufficiently strong it is possible, for small ion-loading, to maintain $\nu_z > 0$, $\nu_R < 1$. The first experiments with Compressor III will explore this regime of variables. It may be desirable to terminate the dielectric image cylinder once the ring has reached relativistic speeds, whereupon the ring should suffer an abrupt jump from $\nu_R < 1$ to $\nu_R > 1$, probably fast enough to avoid significant damage.

TABLE II

Outline of Terms Contributing to the Betatron Frequencies

Source	Typical Terms	ν_z	ν_R
Magnetic Field	$n = -\frac{R}{B}\frac{dB}{dR}$	+	–
"Linear" Space Charge	$\frac{1}{\gamma^2 a^2}$	–	–
Trapped Ions	$N_e \overset{\rightarrow}{\sim} N_e(1-f)$	+	+
"Toroidal" Space Charge	$\frac{N_e}{R\gamma\beta} \ln \frac{8R}{a}$	–	+ ($n < 1/2$)
Images in Dielectric	Proximity, Dielectric Constant	+	–

γ = total energy of electrons/rest mass

R = major ring radius

a = minor ring radius

f = fractional charge of ions

N_e = number of electrons

Because the preferred final state is with $\nu_R > 1$, considerable attention has been given at Berkeley to the design of a pulsed coil to change the gradient rapidly and so to jump across $\nu_R = 1$. If current is maintained long enough, the eventual accretion of ions would ensure $\nu_R > 1$ and the coil could then be turned off. Such a coil is being designed for later experiments with Compressor III. The power supply is somewhat complicated by the need for a long pulse length (hundreds of microseconds) and a short rise-time ($\lesssim$ 10 ns).

In the experiments now beginning, a small quasi-d.c. coil, with a radius smaller than the compressed ring, will be used to produce known changes in field-gradient. It can be used to study the behavior of the ring as the integral resonances are approached, for various values of ion-loading.

c. Results

Compressor III was moved in early August 1969 to LRL Livermore where the Astron linear induction electron accelerator will be used as an electron source. So far, less than 100 hours of useful beam time has been obtained. A special beam-transport line (see Ref. 2) was installed and after tuning, resulted in a peak injection current of 200 Amps at 3.4 MeV in a phase space area of approximately 0.06π cm rad. The acceptance of the compressor is approximately 0.02π cm rad.

Rings with $N_e \approx 3 \times 10^{12}$ have been regularly formed and compressed to final dimensions: $R = 3.6$ cm, $a_{RMS} \approx 2$ mm. The new coil configuration has resulted in very little trouble in crossing the betatron resonances previously of concern. The survival time of the rings was typically very long, viz, ≈ 20 milliseconds. During this first experimental run, the compressor pressure was about 6×10^{-7} T, considerably higher than ultimately planned. Nevertheless, no apparent deleterious effects due to the high background rate of ionization were observed.

Experiments were performed using the inner coil to change the gradient in the median plane of the compressed ring. By decreasing the local n-value from $n = 0.1$ towards $n = o$, the ring could certainly be destroyed but at this time the interpretation of the data is still uncertain.

A more interesting sequence of experiments involved activation of the left-right imbalance circuit at various currents, both with and without the image cylinder in place, and at various levels of gas pressure. As the level of the imbalance is increased, the ring is moved greater and greater distances axially to the right, later returning to the median plane where it can be inspected for survival. In this way, it was subjected to a variety of excursions in n-value eventually approaching $n = 0$, and with different conditions with respect to gas loading and image forces. There has not been time quantitatively to reduce these data, so that I can give only our hurried impressions. The effect of ions in increasing the betatron frequencies seems to be substantially less than simple calculations predict. Loss is believed to have occurred at $\nu_R = 1$ (incoherent), but its magnitude is uncertain. Neither the measurements nor calculations are yet precise enough to say how narrow the resonance width is but we think it is very small ($\Delta\nu < 0.01$). By activating the rest of the spillout circuitry, viz, the correcting currents in the other coils, the electron ring has been detected on a probe many centimeters beyond the spillout point, having perhaps suffered some small loss at the presumed $\nu_R = 1$ point. Whether the ring has remained a compact structure or contains accelerated ions is not yet known. There has not yet been time to determine the best combination of currents and ion-loading to achieve proper acceleration.

4. Conclusion

Experiments will continue with Compressor III to study and define the complicated interaction of variables needed to achieve extraction of a compact ring, either by staying below $\nu_R = 1$, or jumping quickly across this value. It is expected that a new electron accelerator will be ready by late spring 1970 to carry out further experiments.

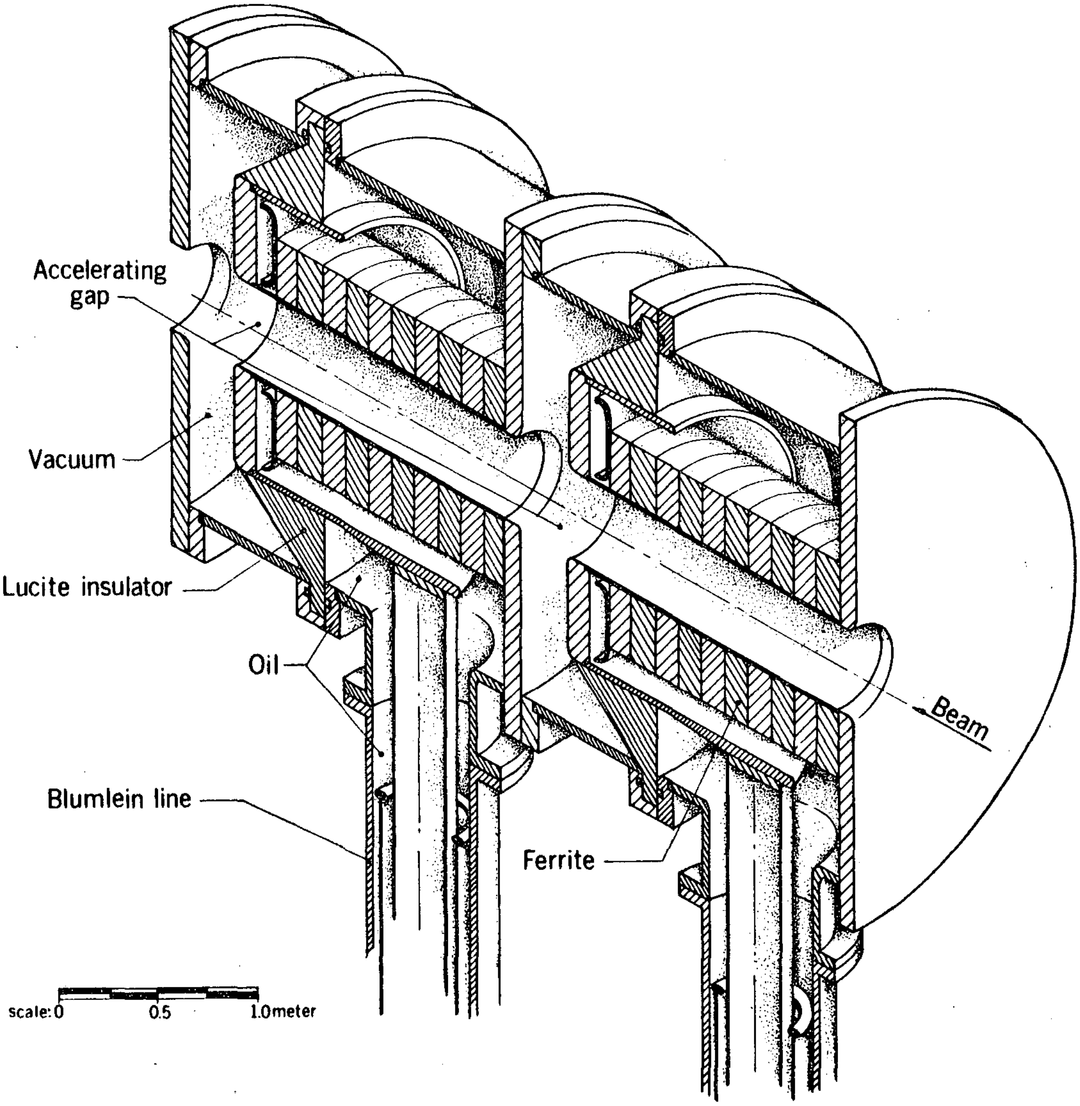
The Berkeley program on ERA, under the overall direction of E. J. Lofgren, is an effort in which many people are deeply involved. Among the principal members of the accelerator study group responsible for the work summarized here are:

Physics Aspects: W. W. Chupp, G. R. Lambertson, L. J. Laslett, A. U. Luccio, W. A. Perkins, J. M. Peterson, J. B. Rechen, A. M. Sessler.

Electrical Aspects: A. Faltens, E. C. Hartwig, C. D. Pike.

Mechanical Aspects: R. T. Avery, H. P. Hernandez, J. R. Meneghetti, W. W. Salsig.

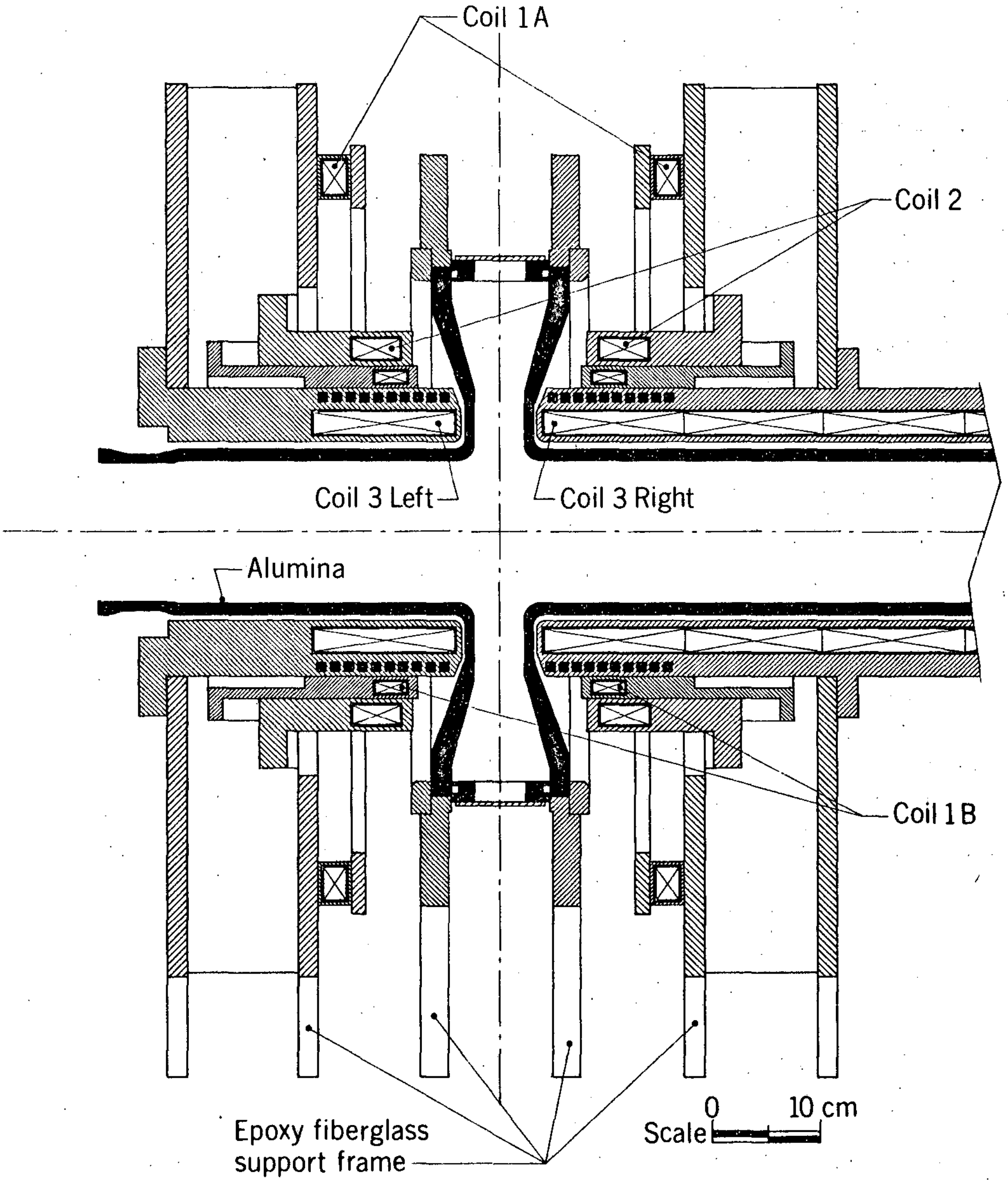
The experimental observations with Compressor 3 that are reported here would not have been possible without the enthusiastic cooperation of N. C. Christofilos who made available the unique facilities at the Astron installation in LRL Livermore. The hard work and help of the staff at the Astron accelerator were also indispensable.



Electron Induction-gun Ferrite Cavity

XBL 698 4871

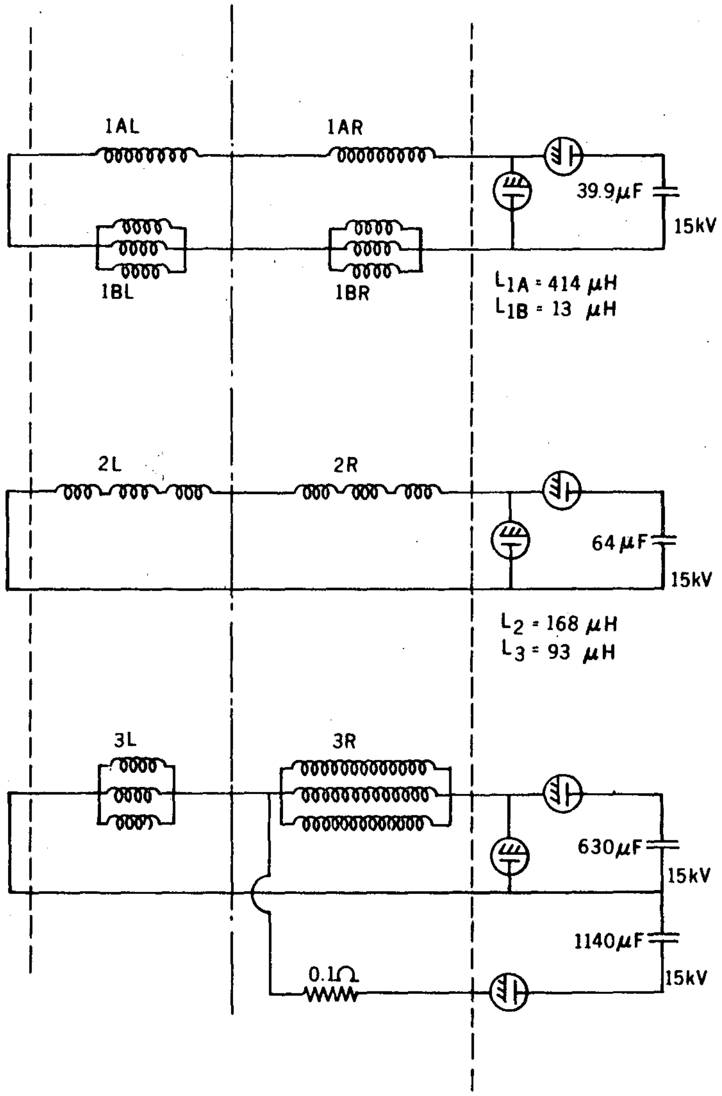
Fig. 1



ERA Compressor III
Compression chamber and coil arrangement

XBL 697 4861

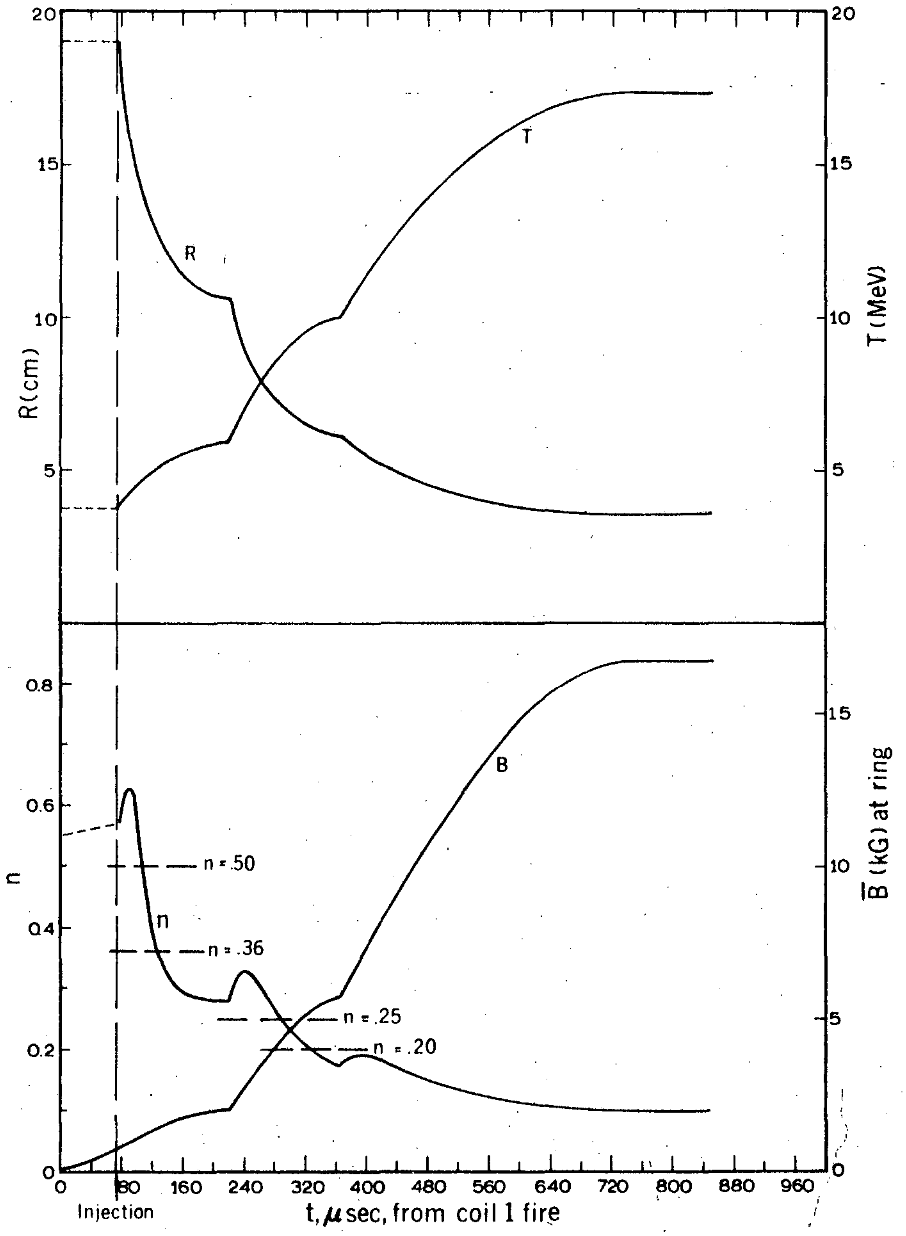
Fig. 2



Schematic of Coils and Power Supplies for Compressor III

XBL 698 4866

Fig. 3



XBL 698 4873

Fig. 4

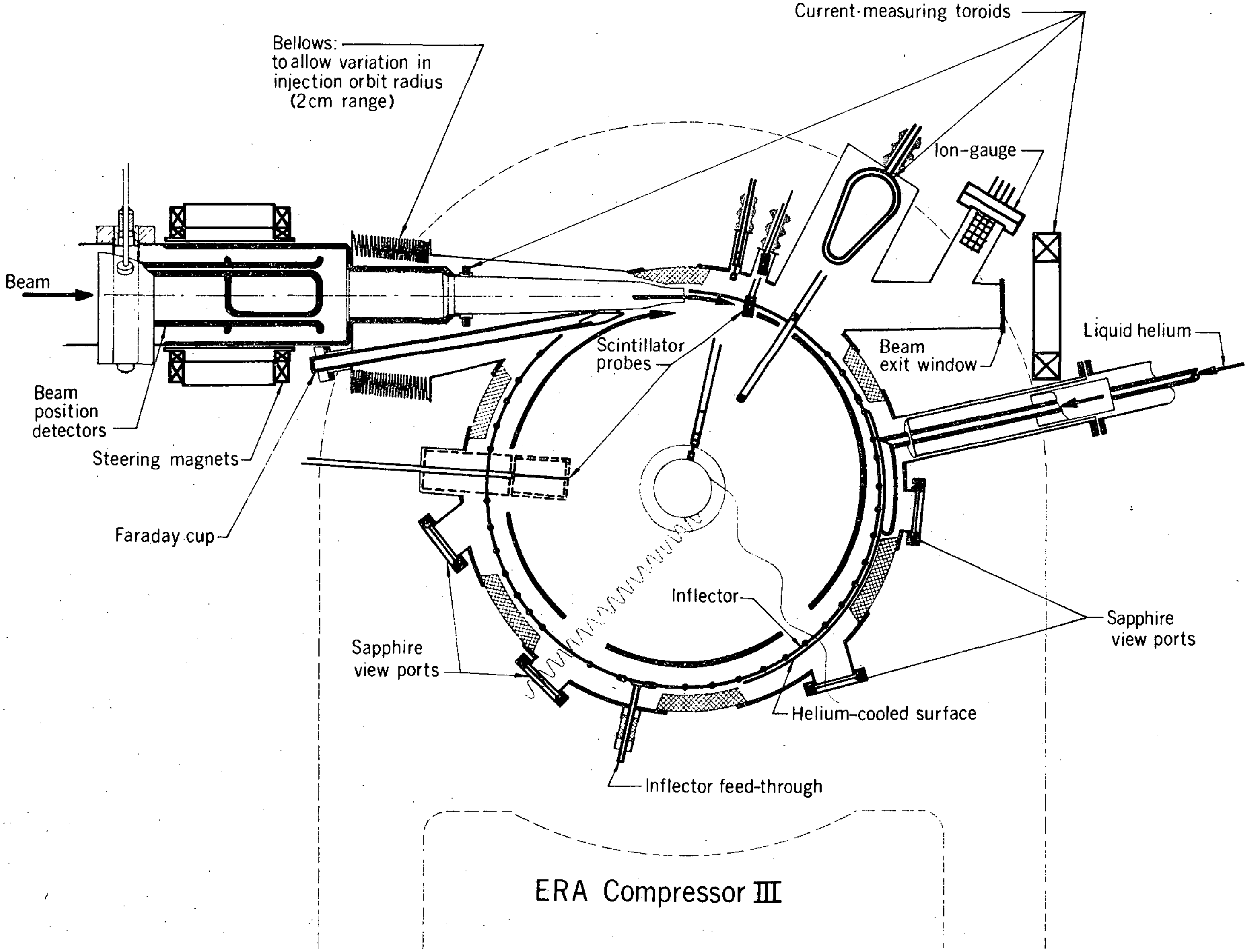


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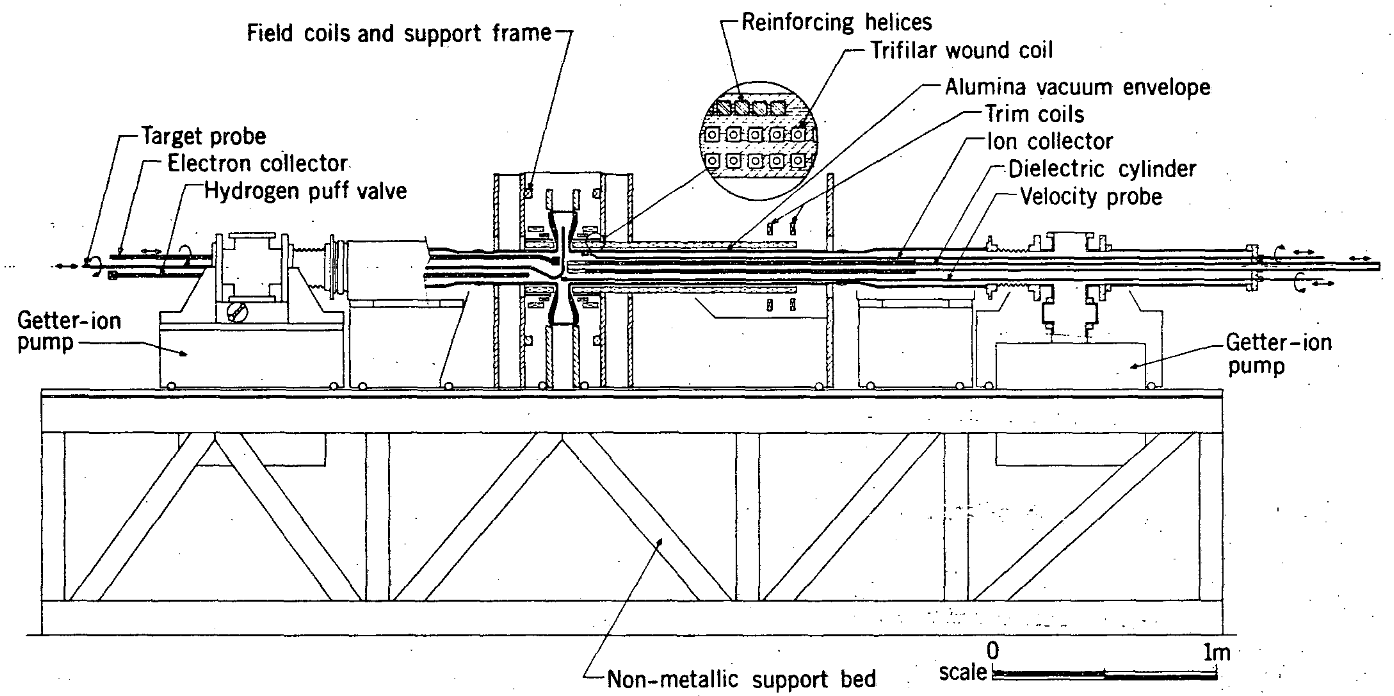
Fig. 5



ERA Compressor III — Longitudinal section

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Fig. 6

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