

STATUS OF THE ERA RESEARCH AT BERKELEY

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I Introduction

This report will give a brief review of our recent activities at Berkeley in research on the electron-ring accelerator. In our first major high-intensity experiment two years ago at the Astron facility in Livermore, in which we used a ring-forming device called Compressor II, we succeeded in forming high-quality rings suitable for the acceleration of ions.¹ A year ago we returned to the Astron facility with a more elaborate device, Compressor III, which had additional capabilities that allowed the rings to be extracted and accelerated in a magnetic field. To our chagrin, in the short time allotted we were unable to re-create high-quality rings suitable for ion acceleration. In the interval between these experiments we were hard at work designing a high-current electron linear induction accelerator and in the last year have completed its construction. It is now an operational device at 2 MeV and ring-forming experiments are underway, on a regularly scheduled basis, with Compressor IV. Towards the end of the calendar year we will increase the energy to 4 MeV and begin acceleration experiments with Compressor V. We have also had a short study on the usefulness of an ERA for a high-energy proton accelerator with attention to the selection of parameters and technological feasibility.

II Compressor III Experiment

An axial section of the apparatus is shown schematically in Fig. 1. The alumina vacuum chamber is surrounded by four pairs of magnetic compression coils and the right-hand coil of the innermost set is developed into a solenoid about one meter long, inside which the ring can be accelerated axially to the right. The principle of the design was as follows. Electrons from the 3.6 MeV Astron accelerator were injected (into the plane of the paper) on an orbit of radius $R = 18.5$ cm, corresponding to a field supplied by Coil Set 1 of some 700 G. Sequential pulsing of the coils in an overall time of about 800 μ sec leads to compression of the ring to a final major radius of

$R = 3.5$ cm, as well as azimuthal acceleration of the electrons in the ring to about 18 MeV. If everything is well-behaved, the minor ring dimensions, a radially and b axially, should also shrink by approximately the same factor as the major radius. In this way a ring with high electric holding field, $E \propto N_e/R(a+b)$, can be generated. After compression to a field of 20 kG, an auxiliary circuit produces an unbalance of current between the left and right-hand solenoids of Coil Set 3. In about 100 μ sec the field in the left-hand coil rises to 45 kG; that in the right-hand falls slightly, and the plane of the closed orbit moves to the right, out of the compressor and well into the right-hand solenoid. With correct adjustments, the ring can be brought to a point where not only the radial component, B_r , but also $\frac{\partial B_r}{\partial z}$ vanishes, and if it thereafter experiences a small positive value of B_r , it will accelerate smoothly to the right. A dielectric image cylinder (see Fig. 1) helps provide axial focussing beyond this point.

This extraction and acceleration system appeared to function exactly as designed. Rings were moved out of the compressor and, at the release point, electrons were observed to be accelerated axially to the right. These electrons, however, were spread out axially and did not remain together in a compact ring for reasons which later became very clear. A careful study of ring dimensions and properties at different current levels revealed that the rings formed in Compressor 3 were of much poorer quality (i.e. lower N_e , larger a and b) than those in Compressor 2 (see Table 1).

TABLE I

Comparison of Ring Parameters

<u>Parameter</u>	<u>Compressor 2</u>	<u>Compressor 3</u>
N_e at 10 μ sec	$2 - 4 \times 10^{12}$	$2 - 4 \times 10^{12}$
N_e at 90 μ sec	$2 - 4 \times 10^{12}$	1×10^{12}
a (Syn. Light)	0.24 cm	> 0.24 cm
a (1/4 beam)	0.25 cm	0.3 cm
a (full beam)	————	0.6 cm
b (Syn. Light)	0.16 cm	0.5 cm
b (full beam)	0.15 - 0.3 cm	0.5 cm

With such diffuse rings, calculations show that a ring could not survive release and

acceleration and retain its compact integrity.

Subsequent analysis of the data suggests that both collective and single-particle effects were to blame for the poor quality of the rings. The large radial spread is interpretable in terms of a severe negative mass instability near injection time leading to large momentum spread. In support of this, the momentum spread of the beam from the new version of the Astron accelerator was found to be smaller by a factor five or more than that from the old Astron accelerator used for Compressor II. (The Landau damping of the instability depends on the square of this quantity.) The harmonic field perturbations were larger in Compressor III and led to betatron resonances. Also the field derivatives $\partial^2 B_z / \partial r^2$ and $\partial^3 B_z / \partial r^3$ were larger and led to trouble with the homogeneous resonance at $n = 0.5$. It was not possible to study, disentangle, and cure these effects within the short run (three weeks), in time to accelerate ions. The experiment underway at present at Berkeley (Compressor IV) is addressed to separating and understanding the instability effects that were present in Compressor III.

III The Berkeley Electron Linear Induction Accelerator

The basic idea of linear induction acceleration is to use cores of magnetic material surrounding the beam, so that when a primary current pulse switched from a suitable pulse-forming network is applied to the core, the induction field appearing across a gap accelerates the electron beam, which acts as the secondary of the transformer. In the form built by Christofilos et al² and also used by the Dubna group, the cores are made of tape-wound iron alloy, each supplying 10 keV to the beam, and driven by a pulse switched from a pulse-line by a thyatron.

The appreciably shorter pulse-length needed for electron ring research eased the pressure for a large number of volt-seconds for the core and allowed the use of ferrite. In turn, the high voltage properties of ferrite permitted operation at a much higher voltage per core (250 kV compared with 10 kV), thus reducing greatly the number of accelerating units and consequently minimizing phasing, jitter, and maintenance problems. The energy-storage and pulse-shaping device for each core is an oil-filled Blumlein line with an electrical length of 45 nsec which is bolted directly to the accelerating unit. The switch is a 250 kV triggered spark-gap and during operation these gaps have been very reliable and fire with a relative jitter of less than one

nanosecond.

Figure 2 shows how two accelerating cavities can be stacked end-to-end to provide 0.5 MeV of energy-gain, and this cut-away sketch also illustrates the placement of the lucite insulators that separate the oil from the vacuum. In fact, we have chosen to stack five cavities together to form a 1.25 MeV gun section (Fig. 3). A stainless steel rod is placed axially within these five cavities, its end thus providing a high voltage terminal of 1.25 MeV, upon which is mounted a field emission cathode. A satisfactory long-lived cathode has been developed in the form of a small spiral (8 mm outside diameter) of half-mil tantalum foil. The anode is a high-transmission grid of fine tungsten wires. For later parts of the accelerator beyond the gun, we have chosen not to stack the cavities together, but arrange them singly with solenoids in between at a unit spacing of one meter. This provides extra space along the accelerator that is needed for diagnostics and for other devices to modify the beam properties.

Table II shows a comparison of the properties of the Livermore, Dubna, and Berkeley electron linear induction accelerators.

TABLE II
Parameters for Electron Linear Induction Accelerators

	Astron accelerator (typical operation) 1970	Dubna accelerator (typical operation) 1969	Berkeley	
			(design) Nov. '69	Operation Aug. '70
Energy (MeV)	6	1.5	2.25 (4 by late '70)	1.8*
Repetition rate (Hz)	5-30	1	1-10	1
Current (amps)	700	200	≤ 500	1000
Emittance at full energy in (cm-rad x π)	25 x 10 ⁻²	(1-3) x 10 ⁻²	≤ 20 x 10 ⁻²	20 x 10 ⁻²
Pulse length (ns)	≈ 250	≈ 200	35	45
Cathode	Barium Oxide (Hot)	Barium Oxide (Hot)	Field Emission (Cold)	Same
Core material	Nickel-Iron Tape	Permalloy Tape	Ferrite	Same
Voltage per core (kV)	9-15	10	250	≈ 200*
Number of cores	≈ 650	≈ 100	9 (later 17)	Same

* Temporary operation

The present Berkeley accelerator is capable of the design value of 2.25 MeV, but hitherto has operated at 1.8 MeV because of limitations in the temporary charging supplies. The changeover to the final power supply will take place in October. Operation of the accelerator - particularly with the tantalum - foil cathode - has been outstandingly simple and stable. After initial turn-on in the day, the tune-up time takes only a few minutes, operation can thereafter be interrupted at will and when turned on again, the beam is immediately reproducible. Single-shot operation at random firing times is also a stable mode of running.

At present the beam is being used for one shift every day to inject into the Compressor IV apparatus (see Fig. 4). In November and December 1970 the energy of the accelerator will be raised to 4.25 MeV by the addition of eight more accelerator cavities.

IV Conceptual Studies for a High-Energy Proton Accelerator

While an electron ring accelerator has application in many fields, we have been most interested in its potential use for acceleration of protons to high energies. Early studies (Feb., 1968) were encouraging in suggesting that both a compact and cheap accelerating structure could be achieved. In Spring 1970 we pursued a more detailed study of a 100 GeV accelerator in which the ring is first accelerated in an electric column, and later in a magnetic solenoid of slowly-decreasing axial field^{3,4}. With such a combination, the final energy acquired by a high energy proton can be written very simply:

$$E = \eta e V_{\text{eff}},$$

where V_{eff} is the effective potential across the entire electric column, and η an enhancement factor that has a peak value of 80 for a ring loaded with 0.4% protons. Typically, V_{eff} would be 70 - 80% of the actual potential.

The high rate of energy gain possible in this type of accelerator arises for two reasons. First, the well-known advantage of accelerating the protons inside the electron ring leads to an effective mass-ratio enhancement, η , over the energy that a "bare" proton would acquire. Second, the very brief time of passage of the ring past an accelerating gap allows the use of voltage pulses that are short in duration and therefore can be very large.

The choice of ring parameters is a complicated matter, and the logistics of

handling the ring from formation and compression through the end of acceleration with avoidance of instabilities has been studied in considerable detail⁵.

For the electric column (320 m long) we chose to examine a rather conservative system derived from our experience with the linear induction accelerator. Fig. 5 is a schematic of part of the column and shows the placement of the solenoid guide-field coils and the ferrite. The voltage pulse, derived from a Blumlein line, is 15 ns long, which is probably too conservative because of the low jitter recently observed in operating the electron accelerator. The column should be capable of an average field of 5 MV/m and could well give a higher value. A great advantage of induction acceleration is that dimensional tolerances are extremely slack, allowing the use of rather cheap materials and fabrication methods.

The magnetic accelerating column is envisaged as a rather straightforward magnetic solenoid made up in sections to a total length of 150 m (Fig. 5). The field would decrease axially from 30 kG to about 5 kG.

The intensity of the accelerator would be 10^{11} - 10^{12} protons per pulse and repetition rates up to a few hundred hertz seem quite feasible.

References

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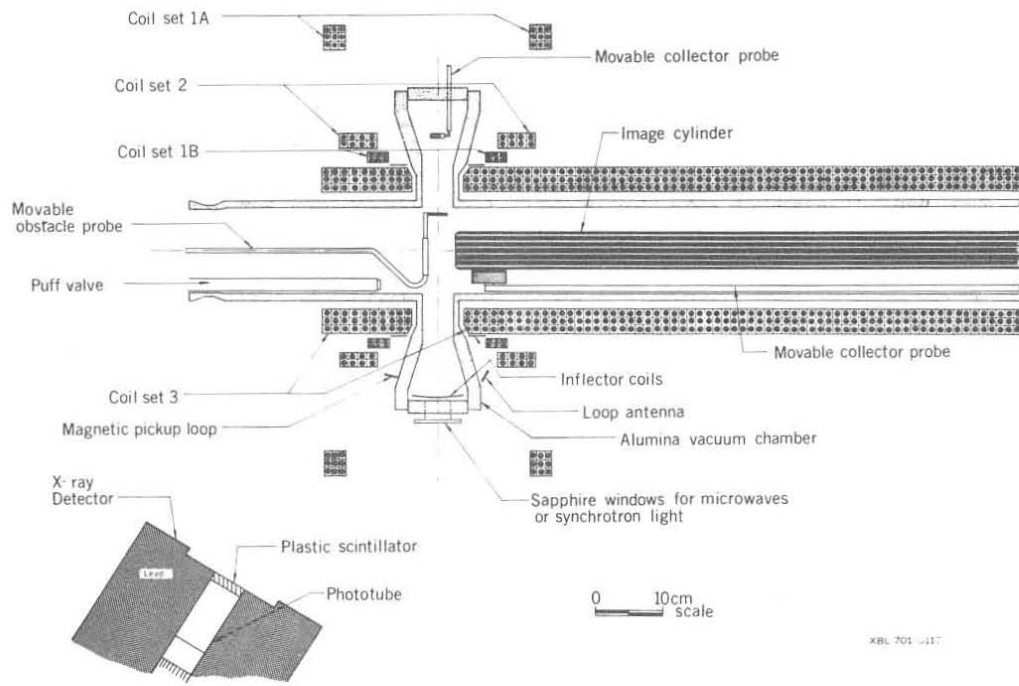


Fig. 1. Schematic section through the axis of Compressor 3. Acceleration of the electron ring is to the right.

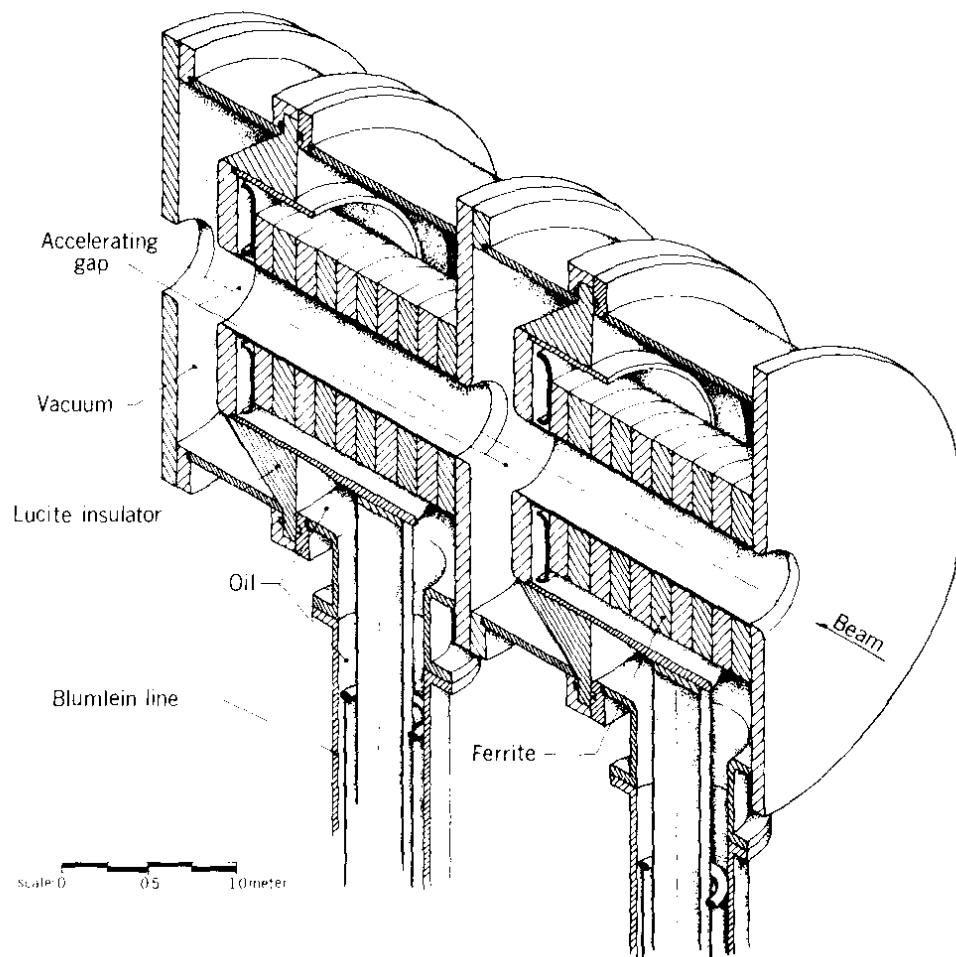
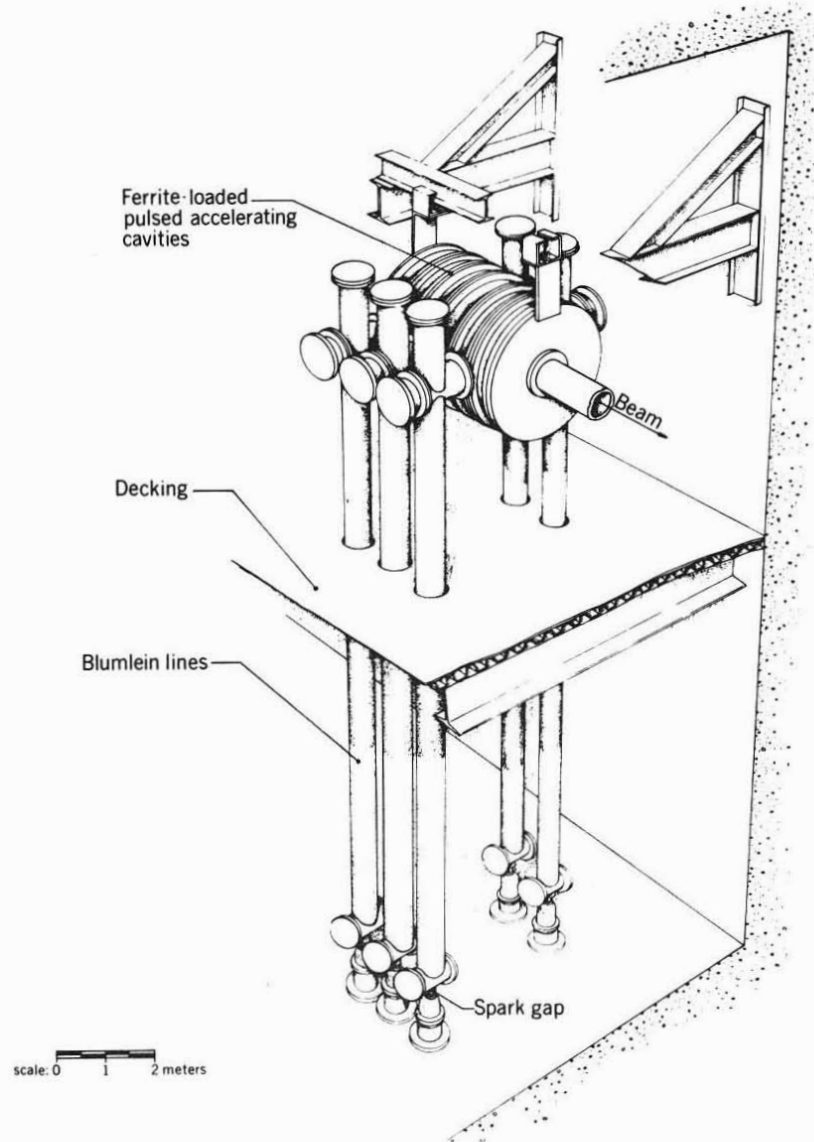


Fig. 2. Cut-away view of two stacked induction cavities showing the placement of ferrite and the lucite insulator. (The feed-through detail from the Blumlein line is an early design, later discarded.)



1.25 MeV Electron Induction-gun

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Fig. 3. The arrangement of five stacked cavities to form the 1.25-MeV gun section.

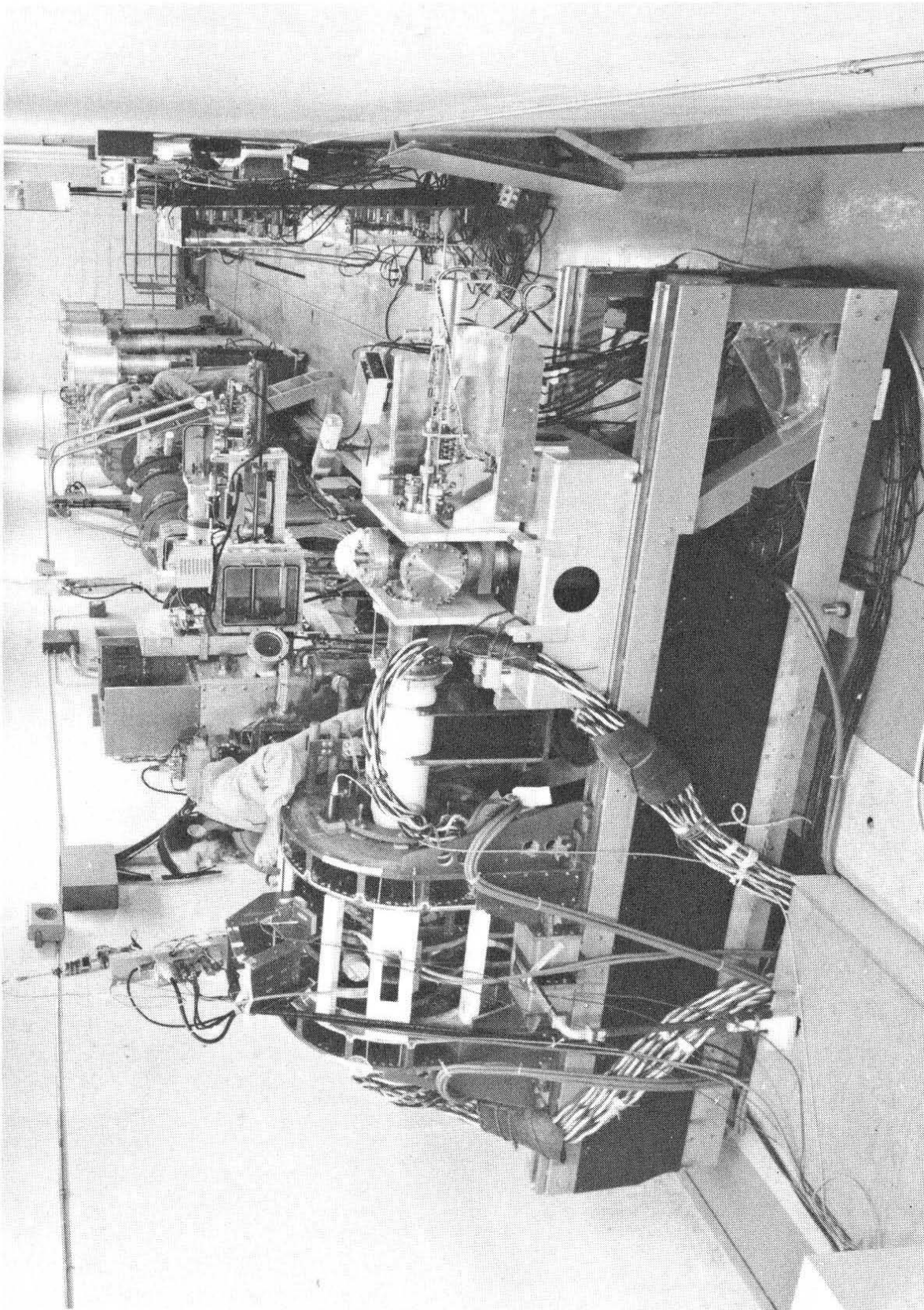
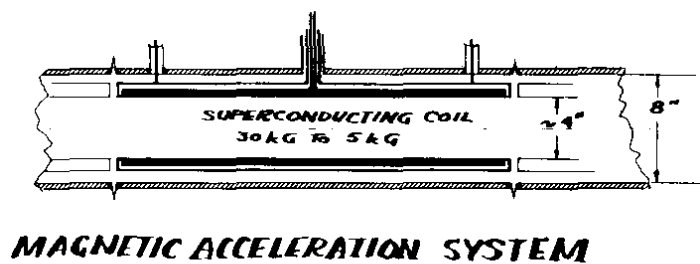
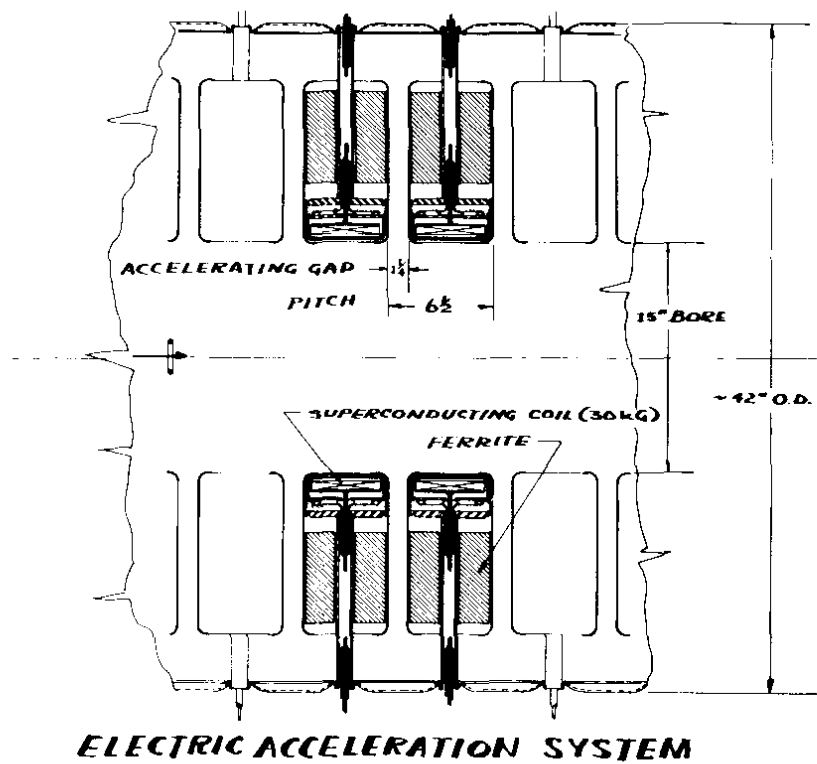


Fig. 4. The 2-MeV accelerator (upstream of ladder) and the beam transport and diagnostic section leading into Compressor IV.



XBL 703 6164

Fig. 5. An axial section of possible induction accelerator cavities and magnetic solenoids for ring acceleration to high energies.

DISCUSSION

L. C. Teng (NAL): I noticed that your superconducting solenoid is an integral part of the accelerating system; what part of it is cold?

D. Keefe (LRL): Just the region surrounding the coil is cold. The coil itself is a small cryostat with some super insulation and so forth, but the ferrite is warm.

L. C. Teng: Did you look into what the accelerating field does to the superconductor of the solenoid?

D. Keefe: The solenoid is outside a metal surface and eddy currents damp the accelerating field completely.

J. Claus (BNL): What are the advantages of field-emission cathodes?

D. Keefe: The cold cathode is a much simpler device (by many orders of magnitude) than the hot cathode for a current on the order of 1000 A. The cathodes used by Christofilos are of the order of 6 to 8 inches in diameter, and it takes quite a long time to shape electrodes, cathode, and so forth. All we do is wind up a small piece of ribbon about 3/10 of an inch in diameter. We can make it in about a half an hour and put it in in another half an hour. It's just the simplicity of getting 1000 A.

J. Claus: Do you have any comparative numbers for field emission versus hot cathodes?

D. Keefe: There has been no careful study of this. I could quote you two numbers, one for the emittance of our accelerator is substantially brighter than the emittance of the ASTRON accelerator which uses a hot cathode. I believe that by modifying the cold cathode we can make it still brighter.

J. Claus: It seems to me that the gap capacitances in the electron accelerator are very large. Is there any reason for making them so large?

D. Keefe: Indeed, you are right. The capacitance is rather large at those gaps. It can be made smaller by increasing those gaps, but it is no longer the dominant thing in the risetime of the pulse. We have not attempted to make it any smaller.

J. P. Blewett (BNL): In answer to Claus' question about brightness, the thermionic cathode has been studied in connection with the electron microscope, and there it seems to have an advantage of a factor of about 1000 over the field-emission type.

G. A. Loew (SLAC): Do you have any new ideas on static compressors? My second question is--in this magic number of 80, what is the range of variation of the expansion column depending on what you do in the accelerating column?

D. Keefe: The new idea in static compressors which has been studied in the last year is to arrange for the ring to be held after compression in the field with a suitable n value, so that synchrotron radiation causes damping of the minor dimensions; in this way the holding power can be greatly increased. This has been studied by Pellegrini,

and he has written a report on it. However, independently, the Dubna group have also been studying this. It is more complicated than just letting the ring sit and radiate. They also supply energy by a radiofrequency field.

R. L. Martin (ANL): Do you have any ideas of predicted effective emittance of the ejected proton beam if one were to use it as an injector into a synchrotron?

D. Keefe: From the point of view of emittance, it is not bad. It's within some small factor of what one eventually gets for an equivalent energy from the synchrotron.