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THE BERKELEY ERA PROGRAM*

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Summary

The scope and status of the Berkeley Electron Ring Accelerator (ERA) program are reviewed.

Accelerator design studies carried out at Berkeley in the early 1960's convinced us that the practical energy limit for accelerators of conventional design was in sight. The conductivity of normal copper, the magnetic saturation of iron, and the breakdown strength of metallic electrodes seemed to place restrictions on the design of synchrotrons such that the cost was about one million dollars per BeV and the size was about one mile of accelerator structure for 75 BeV. Linear accelerators were substantially worse in both cost and size. With strict attention to design economies these figures could be improved, but the probable gains would be less than a factor of two. These large costs and sizes resulted in major financial and social problems for accelerators of a few hundred BeV. An order of magnitude increase in energy at the same rate would not be remotely reasonable. However, the scientific interest in and justification for experiments at higher energies seemed to be as great as ever. If accelerators of higher energy were to be built to satisfy this interest, new approaches to the problems would have to be explored. The possibilities known to us of going significantly beyond one or both of these limits were: a) clashing beam configurations, b) accelerators with superconducting guide field magnets, c) linear accelerators with superconducting cavities, d) accelerators based in some way on the collective electric and magnetic fields of aggregrations of particles. The report at the Cambridge Accelerator Conference by Kolomensky in 1967 on the work of Veksler, Sarantsev, et al.[1] focused our attention on (d) above. We were already carrying on a small project on superconducting beam transport magnets. We chose then, after a short intense study in the Spring of 1968 of the concept proposed by Veksler and Sarantsev and of other collective field phenomena, to go ahead on a program of advanced accelerator studies based upon two of the possibilities previously mentioned, namely superconducting magnet technology and collective effect acceleration. The objectives of the program were:

1. To explore the possibility of the eventual design of a very high energy, order of 10^{12} eV, accelerator whose cost and size were significantly less than that set by the previously mentioned rates.
2. A possible intermediate step of more modest energy that could serve both as a useful physics tool and as a vehicle to optimize design and to develop the technology leading to (1) above.
3. To explore the possibilities of heavy ion acceleration.
4. Such contributions to general accelerator theory and practice as might come from the program.

The particular concept of collective effect acceleration, which we called Electron Ring Accelerator (ERA), involved establishing an intense ring of relativistic electrons in a magnetic field with stability achieved by a combination of the self magnetic field of the ring, partially compensated space charge, and electric image forces. The electron ring would then be accelerated electrically or by expansion in a decreasing axial field. The positive ions carried along by the ring would then have an energy greater than the electron energy by the ratio of the mass of the ions to the relativistic mass of the electrons.

Two years ago at the previous conference of this series in Washington, Denis Keefe[2] reported on the beginning of this program. In particular he reported on the Compressor 2 experiment.[3] Stable rings of 18 MeV electrons had been formed. They contained 4×10^{12} electrons and the dimensions were 3.5 cm major radius and 2.3 x 1.6 mm minor radii. The peak holding field, E_H is proportional to $N_e/(R(a+b)$ where N_e is the number of electrons in the ring, R is the major radius and a and b are the minor radii. The calculated value for these rings was 12 MV/m. Loading of the rings with protons was demonstrated. This was accomplished by the Fall of 1968. Progress to this point had been rapid.

A second major piece of experimental apparatus, Compressor 3, was then designed and constructed, differing from its predecessor principally in that there was provision for expelling the ring from the compression field and accelerating it in a decreasing axial field. Figure 1 is a diagram of this apparatus. There were 4 sets of coils, 1A and B, 2, and 3 which with properly timed and proportioned pulsed currents would serve to compress the injected electron ring from the initial 18 cm radius to 3.5 cm. An additional pulse in coil 3 left side only would obliterate the magnetic mirror field on the right and the ring would move along the solenoidal field to the right. The image cylinder, a quartz tube with longitudinal conducting strips, would provide an inner wall on which an electrical image could form but a magnetic image could not, resulting in an additional axial focusing component. The vacuum chamber was alumina with a conducting coating, as before, and a gas valve and diagnostic devices were provided as shown in the figure. In the few weeks available for the experiment, it was not possible to form dense high intensity rings with this apparatus. The number of electrons was down by a factor of 4 and the minor dimension of the compressed ring up by a factor of 2 to 3 compared with the Compressor 2 results. These rings could be released into the long solenoid but the self-focusing forces were too weak to maintain the integrity of the rings. The results have been analyzed in a paper by Keefe et al.[4] and it is believed that there were two basic difficulties: a) single-particle resonances excited by magnetic field perturbations, and b) a negative mass instability connected with incompletely understood wall effects.

The two major experiments, Compressors 2 and 3, had been carried out at the Livermore Lawrence Radiation

Laboratory using the Astron Injector.[5] The existence of this electron accelerator and the opportunity to get some limited use of it was a key element in the rapid initial progress of the program. However the necessity of moving apparatus into and out of the Astron facility and the strict time limit imposed by the heavy schedule of that facility made it impossible to carry out the kind of painstaking investigation needed to understand the complicated behavior exhibited in the Compressor 3 experiments. We had already started to build an electron accelerator at Berkeley because it was clear from the beginning that the successful pursuit of this program would require an electron source dedicated to that purpose. All efforts were then concentrated on bringing the Accelerator Development Facility at the Berkeley Lawrence Radiation Laboratory to a sufficient state of completion as early as possible for use in the next phase of the experimental program.

Compressor 4 was designed to study the difficulties in ring-formation that had been encountered in the previous experiment without attempting to extract the rings. Figure 2 is a photograph of the partially assembled Compressor 4 in place. Provision was made for replaceable inner walls so that the surface impedance of the walls could be varied. Coil positions could be varied to give greater control over the value of n as the coils are pulsed. Diagnostic instruments were improved over the previous experiments. Experiments with this apparatus are partially completed and are the subject of a report to be given by Glen Lambertson at this conference.[6]

The Accelerator Development Facility is shown in Figure 3. It consists of an accelerator tunnel 100 feet long, 14 feet wide, and 24 feet high. A removable deck provides an upper level for an electron accelerator and a lower level for its pulsed power equipment. This accelerator is designed to provide electrons at 1 to 4.25 MeV in 40 ns bursts of about a thousand amperes, at a rate of 1 per second. A description of the accelerator and its performance will be given in a paper at this conference by Warren Chupp.[7] At the end of the tunnel is an experimental bay 40 by 40 feet and 26 feet high with a shielded block house for experiments in ring formation and acceleration. A basement is provided for pulsed power equipment. A control room and a screened room for observation is on the side. This facility has been in operation since August 1970 at 2-1/4 MeV and by May 1971 will operate up to its rated energy.

Although studies to establish definitively all of the scientific principles which would form the basis of a practical electron ring accelerator are only in mid-course, it is important to go through the exercise of a conceptual design of an accelerator and to examine the cost factors. Such an exercise reveals hidden problems and shows where inventiveness can make big gains. Since cost is one of the practical limits of present day very-high-energy accelerators one wants to be assured that when the scientific foundations for an electron ring accelerator are securely established the probability is high that an economical design can be produced. Accordingly we have made a conceptual design study of an electron ring accelerator which could operate in the 65-100 GeV energy range. We have assumed that all of the physics problems would be solved in agreement with existing theory and in that sense have made optimistic assumptions. However the assumptions of technology were rather close to present practice.

A study of the parameters to optimize the energy and intensity of the proton beam and to define a consistent set complying with all the known requirements for ring stability was made by Bovet and Pellegrini.[8] The accelerator here described embodies the results of that study.

Figure 4 is a schematic of the accelerator studied. The major components are: a) the source of relativistic electrons, b) the ring-forming device (compressor), c) the electric accelerating column, and d) the magnetic accelerating column.

The electron source would be an 8 MeV induction accelerator similar to the one which runs very reliably in our test facility and is described in another paper[7] of this conference. The current would be 150-400 amps in ~ 40 ns bursts at a repetition rate of 20 to several hundred per second. These requirements are within the range of present technology and present no serious problems.

The compressor is of course the component presently under intense experimental investigation. The assumed design is an extension of the present experimental compressors in which the number of electrons is increased by a factor of four and the major and minor radii of the ring are reduced by factors of two or three over the values achieved in the Compressor 2 experiments. It remains to be demonstrated that electron rings of this quality can be formed by this type of compressor. They are within the known theoretical limits and indeed the Soviet group have reported[9] results which indicate that they are approaching such values. Other types of compressor are also possible. In one type the rings are held for milliseconds in a high magnetic field to allow synchrotron radiation to further shrink the rings. Several different static field compressors have also been proposed[10] and may offer interesting advantages.

The next element is a uniform solenoid of 30 kG, 25 meters long. The timing signals for firing the spark gaps of the accelerating column are generated as the ring passes through this region. This coil as well as the other static field coils in the accelerator are superconducting Nb-Ti.

The electrical column is 230 meters long and would be excited by the spark-gap discharge of Blumlein lines and would provide an accelerating field 1500 kV per gap or an average of 6 MV/m over the column. A fraction of the energy gain is lost in radiation as the ring crosses the accelerating gaps. This loss is an inverse function of the bore which was fixed at 19 cm radius to hold the loss to 10%. Recent experiments with the electron beam at SLAC have confirmed the calculations by Eberhard Keil at CERN upon which this estimate was made. The ring whose radius is here about 2 cm is contained by the field of superconducting coils built into the structure.

The final section is an axial magnetic field which decreases from 30 to 5 kG in a length of 150 meters. The ring expands as the axial field decreases and the radial component of the field accelerates the ring converting rotational to translational energy.

A more extended discussion of the mechanical and electrical features of this design concept will be published in the proceedings of this conference.[11]

The pulse rate of the accelerator would be 20 Hz with provision for an increase by a factor of ten. An accelerator of this type has no fixed energy. The energy of the ions depends upon the fraction of ion loading (~ 1%), the magnetic field containing the compressed ring, and how close one can successfully approach the coherent transverse instability limit. The range for this design is from 30 GeV at $1.4 \cdot 10^{14}$ protons per second to 100 GeV at $1 \cdot 10^{13}$ protons per second.

The estimated cost for this design is about one quarter of one million dollars per GeV. This figure is not to be taken as a serious estimate, but as an encouragement that the ERA may be a direction of reduced accelerator costs. As further experience is gained with this novel concept new inventions and better optimization are bound to be made. It is also expected that for higher energies the cost per unit energy will decrease significantly because of the large number of repetitive units.

Progress in the ERA studies has not been as rapid as the earliest successes seemed to promise. In retrospect it should not be surprising. The ERA world is a strange one – the effects that are used to make ERA work are the very ones that limit the performance of conventional accelerators – the best performance is close to the limits of stability – and it does take time to sort things out. However very substantial progress has been made in both the theoretical understanding and the experimental control of many of the complicated interactions between the particles and the apparatus. The prospects seem as bright as ever that it will be possible eventually to design a practical high energy proton accelerator and that before that it will be possible to design a versatile and useful lower energy accelerator capable of accelerating a wide range of ions and serving as an indispensable tool for the development of this new method of acceleration.

The physicists and engineers who have taken part in this program are: Physicists: R. W. Allison, Jr.,[+] W. W. Chupp, A. C. Entis, A. A. Garren, D. R. George, D. Keefe, G. R. Lambertson, L. J. Laslett, R. G. Nemetz, W. A. Perkins, J. M. Peterson, J. B. Rechen, A. M. Sessler, L. Smith; Engineers: R. T. Avery, A. Faltens, E. C. Hartwig, H. P. Hernandez, J. R. Meneghetti, C. D. Pike, W. Popenuck, W. W. Salsig; Physicist Visitors: A. U. Luccio,[+] A. J. Nakach,[+] C. Pellegrini,[+] C. Bovet,[+] D. Möhl.

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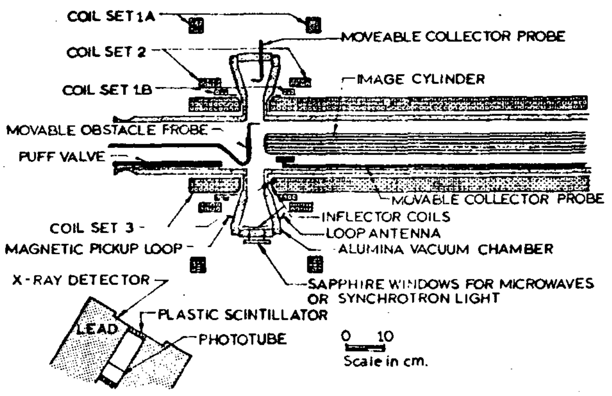

Fig. 1. Cross Sectional Diagram of Compressor 2.

[+] Former members of the group.

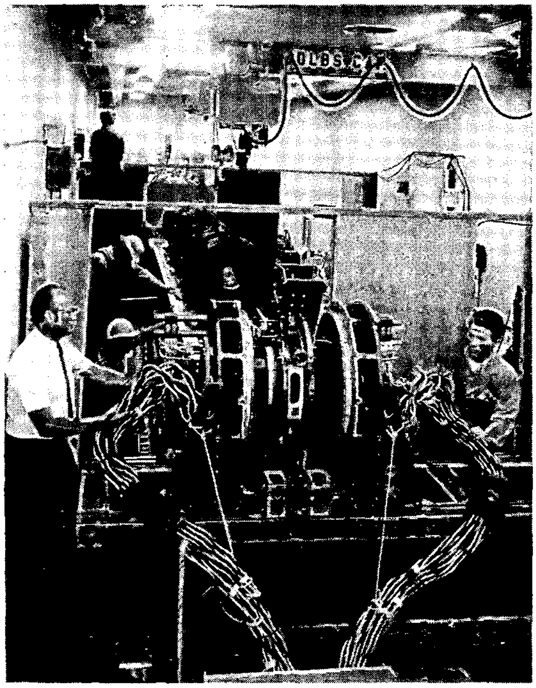

Fig. 2. Photograph of the Compressor 4 apparatus being assembled. The electron accelerator is in the background.

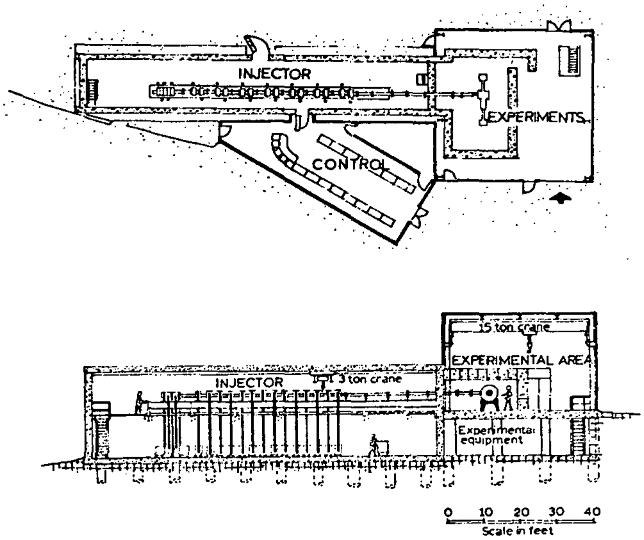

Fig. 3. Accelerator Development Facility, Plan and Elevation.

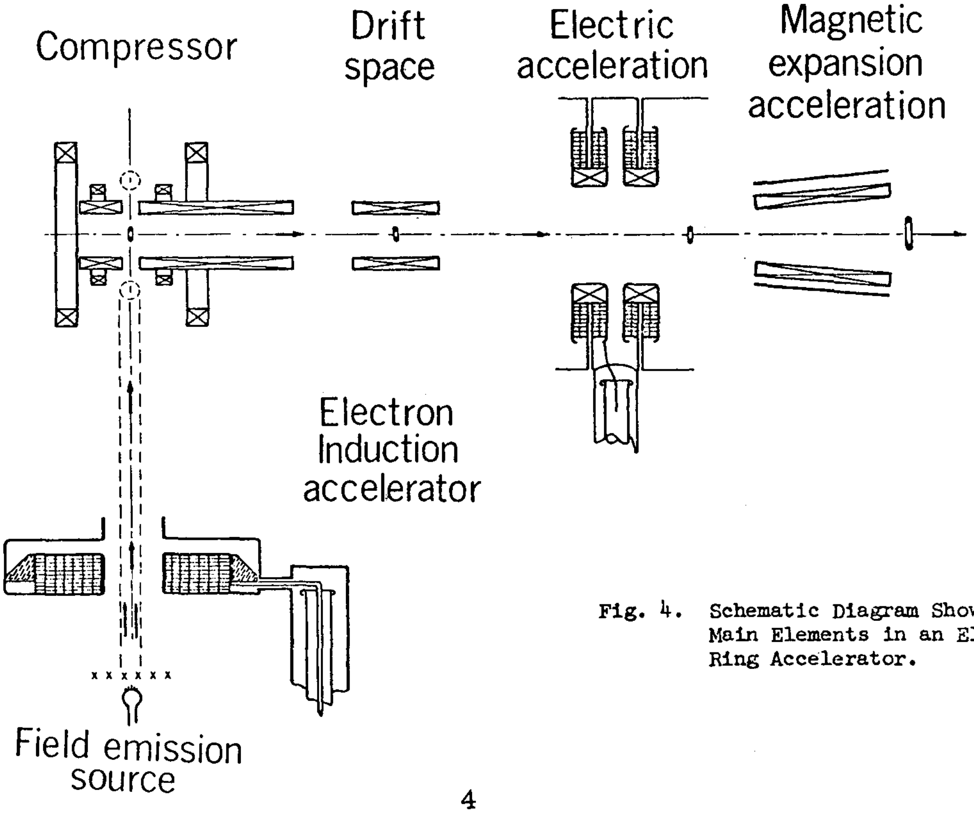

Fig. 4. Schematic Diagram Showing the Main Elements in an Electron Ring Accelerator.