THE ELECTRON-RING ACCELERATOR*

Denis Keefe
Lawrence Radiation Laboratory
University of California
Berkeley, California

For almost two decades there was sporadic interest(1,2,3,4) in the concept of acceleration of ions by collective effects and one unsuccessful experiment was reported as early as 1952.(2) A significant factor in creating recent active attention was the disclosure(5) at the Cambridge Accelerator Conference in 1967 of the experimental work at Dubna by Veksler's group on the specific form of collective effect device employing an electron ring as a vehicle for accelerating ions. With relativistic electrons in a ring configuration, and containing ions, there were reasons to believe that self-stability problems could be solved. Another factor of timely concern has been the rapid development in recent years of very intense ($\gtrsim$ 1000 A) sources of relativistic electrons which, of course, provide one of the essential tools. It was recently observed by Graybill at Ion Physics that the electric field close to the head of an intense pulse of 1.5 MeV electrons passing through gas caused acceleration of hydrogen ions to 5 MeV. While this is a mechanism that probably cannot be extended in an orderly manner to give high energies, it is an interesting practical demonstration for non-believers, that the collective-effect fields are really present and potent.

After the Cambridge meeting, interest in studying electron-rings ran high at the Lawrence Radiation Laboratory partly because of intrinsic interest on the part of the accelerator and plasma scientists and partly because of the availability of the 4 MeV 300 A electron source at the Astron facility, which would permit experimental work to proceed fairly soon. Properties and parameters for accelerators were studied and presented at a Symposium on Electron Rings held at Berkeley a year ago.(6) Interest in an electron-ring accelerator stems mainly from three reasons. First, it is a new and different way to accelerate particles and should be studied for its own sake; second, it should provide an intense source of heavy ions for Biomedical or Nuclear Chemistry research; and third, it may provide a compact means for accelerating protons to very high energy. In connection with the last point we should note for orientation that if we examine the acceleration-rate per meter of structure we find for present devices about 1-1.5 MeV/meter for proton linacs and about 40 MeV/meter for proton synchrotrons. By comparison we have achieved (at Berkeley) rings with enough holding power to accelerate protons at a rate of 12 MeV/meter. This number should continue to increase as the art of making more intense rings is developed and we have a long way to go before reaching a limit, imposed by the structure, of 500-1000 MeV/meter.

After the symposium, armed with a knowledge of the parameters we would like to have, we embarked on an experimental program to study what we really might hope to achieve, and of course, to investigate the feasibility of the principle.

The first piece of equipment to form rings was a rather simple device (Compressor I) made from a glass bell-jar. It had only two stages of magnetic compression coils and a very low repetition rate (one per minute). Since it was used in conjunction with a low-intensity electron-linac the number of electrons in the rings formed was too small ($\approx 10^9$) to encounter collective effects. Nevertheless it was a useful device for learning about single particle effects, for studying inflection, and for developing suitable diagnostic techniques.

A more sophisticated device (Compressor 2), intended to form intense rings with holding fields in the region of interest and to load them with ions, was constructed last year and operated for about 400 hours at the Astron injector(7) in Livermore last Fall. The results of these experiments are to be found in Ref. 8 and a description of certain details of the equipment is the subject of several papers at this conference(9,10,11,12) so that only a brief summary will be given in this text.

A rather elaborate beam transport line was constructed to transport the beam from the Astron linear induction accelerator to the ring-forming equipment. This included several sets of devices for sensing the beam position and current and for steering and focussing the beam. In addition, there was a fast chopper which selected a pulse 20 ns long out of the main pulse.(12) An emittance measurement device with a real-time television display allowed tuning of the beam to maximum brightness.(11)

The Compressor 2 equipment is shown schematically in Fig. 1 and a photograph of the apparatus is reproduced in Fig. 2. Although the high vacuum requirements would have been ideally met by use of a bakeable metal envelope the severe problems due to eddy currents dictated that no metal could be used; hence the vacuum chamber was chosen to be of alumina. The pulsed weak-focussing magnetic field was supplied by three nested coil-pairs pulsed sequentially in time. The compression from injection to the peak of the field takes 500 μsec and the behavior of several quantities of interest throughout this time is shown in Fig. 3. The magnetic field (at the ring) rises from 660 G to 17 kG; meanwhile the orbit radius is compressed from 19 cm to 3.5 cm and the electrons are accelerated azimuthally by transformer action from 3.3 MeV to 18 MeV. During this time the minor dimension of the ring shrinks from a few centimeters to a few millimeters. Of most concern during the course of the experiment was the behavior of the field gradient index

$$n = -\frac{R}{B_z}\frac{\partial B_z}{\partial R}$$

on the median plane. The curve shown in Fig. 3 represents the n-trajectory finally used to obtain successful compression without beam loss. When the experiment was begun, the curve did not look grossly dissimilar except that $n = 0.5$ occurred very close to injection and $n = 0.25$ was crossed during the cycle of the outermost coil-pair. Crossing either of these n-values early in the cycle caused loss of beam. When current correction programs were added to postpone crossing both these values of n until later, the previously severe beam losses were avoided.

The radial tune at injection was close to $\nu \approx 2/3$ so as to achieve three or four captured turns. The injection closed orbit was at $R = 19$ cm and prior to the moment of beam entry a fast beam bump was applied to push the radial position of the closed orbit out to the center of the injection snout. As beam entered and circulated for a few turns ($\approx$ 16 ns) the beam bump was diminished and the closed orbit returned to $R = 19$ cm.

Beam dimensions were examined with a variety of movable target probes. Loss of beam was detectable on x-ray photomultiplier counters. Presence of the beam was indicated by radiation in the microwave region and, also, near the end of the compression cycle by synchrotron light. Towards the end of the experimental run rings were regularly formed with

$$N_e = 4 \times 10^{12}$$

electrons, major radius $R = 3.5$ cm, minor rms dimensions $a = 2.3$ mm (radial) and $b = 1.6$ mm (axial). The axial and radial electron distributions in the ring were found to be Gaussian. These numbers yield a calculated peak holding field of 12 MV/m.

The rings survived for about 6 ms, the lifetime being determined by crossing $n \approx 1$ on the decaying magnetic field. Addition of a 3 ms flattop to the field(10) prolonged survival for a further 3 ms verifying that the beam loss was connected with the magnetic field and not the background gas. The lifetime of the beam could be modified by addition of hydrogen gas and in one case, by identifying the resonance at which beam-blow-up occurred, the tune shift due to the focusing of trapped ions was $\Delta\nu = 0.16$.

To return now to our current plans at Berkeley, we are at present constructing equipment for Compressor 3 which we expect to operate at Livermore in July this year. In this device we plan to study, first, the problems of turning off the external axial focussing field ($n \rightarrow 0$) simultaneously loading with ions to add focussing and so provide axial stability. In the process the integral resonance

$$\nu_R = 1$$

must be negotiated rather rapidly. A long solenoid (1 meter) has been added to allow acceleration of the ring and ions to an axial energy of about 10 MeV/proton. This process of acceleration depends on the decrease in axial field along the solenoid (radial component $B_r > 0$) to transfer some of the azimuthal energy of the electrons into axial energy of the ring.

The exact course of further experiments at Berkeley and Livermore depends on the outcome of the upcoming experiments with Compressor 3. If it works and we learn how to accelerate ion-bearing rings with confidence, then one change in approach that would become immediately possible is to abandon our present system of crow-barring the magnetic field. Instead, the pulsed fields would be supplied in a resonant fashion and the power losses per cycle cut down by a factor of five or ten. An obvious element of the on-going program is, of course, to study the formation of more intense rings and how to circumvent the instabilities or other factors that may limit the holding power. The advantages of the ERA concept are directly related to the holding power of the ring.

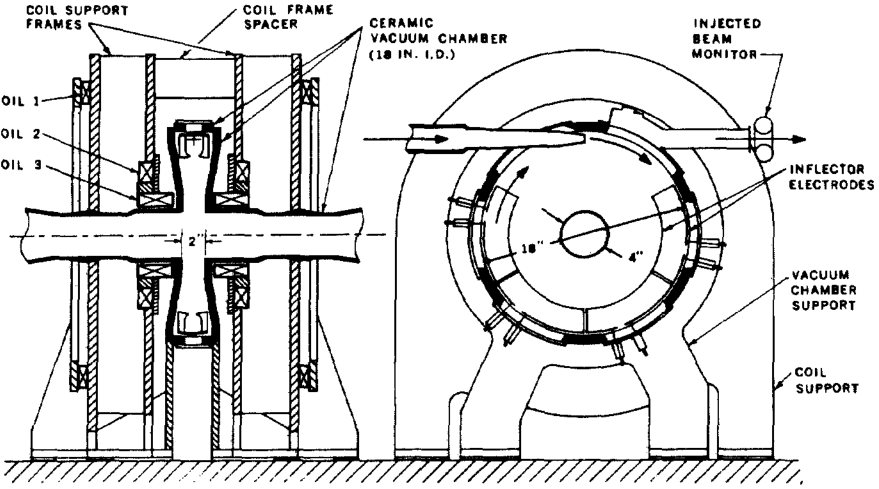
Two major topics to be studied in the future are electric acceleration and static-field compression. A form of electric acceleration that sounds very attractive for a high-energy proton accelerator was proposed by E. C. Hartwig and co-workers at the Berkeley Symposium.(6) This so-called "pulsed line" system envisages acceleration of the ring by an induction field that is present in the accelerator only in the immediate neighborhood of the ring, and is therefore only a few nanoseconds in duration at any one location. In other words instead of the electric accelerating energy being stored in the entire structure at any one time (as in a system of RF cavities), it is propagated along the structure at the speed of the ring and occupies only a few feet at any one time. This is a system we intend to model soon. The subject of static-field compression is one of considerable topical interest and there will be two papers at this meeting bearing on this subject.(13,14) The object here is to use dc magnets — — which could be superconducting — — to compress a ring of large dimensions and shrink it to a ring with small major and minor dimensions and therefore of high holding power. The ring would then be launched into a dc accelerating solenoid field and later, if desired, accelerated electrically. This would supply considerable relief from the problems of supplying considerable quantities of pulsed power to the guide-field structure. In addition superconducting coils would almost certainly be used which would permit considerably higher fields to be employed and also help in the achievement of high vacuum. A central advantage of this form of compressor is the possibility of achieving very high repetition rates. Since a static field compressor would not result in azimuthal acceleration of the electrons in the ring they would have to be injected at quite high energies (several tens of MeV). A linear induction accelerator to supply such high injection energy would be quite ungainly and it is probable that a high-current betatron would be the type of injector employed. Since the compressor used in the Dubna and Berkeley experiments were, in essence, high-current betatrons this form of injector could be relatively compact.

In conclusion, we should note that there was just one paper on electron rings at the Cambridge Accelerator Conference eighteen monghs ago while at this meeting we notice thirteen papers submitted on this topic. This is certainly a rapidly-emerging subject that should become in the future a more significant part of accelerator conferences. At least we at Berkeley hope that is the way the future lies.

References

*Work done under the auspices of the U. S. Atomic Energy Commission.

1. R. B. R-S-Harvie, AERE Internal Memo GM/87 (March 1951).
2. H. Alfvén and O. Wernholm, Arkiv Fysik 5, 175 (1952).
3. V. I. Veksler, CERN Symposium on Accelerators, 1956, Vol. 1, p. 80.
4. G. I. Budker, CERN Symposium on Accelerators, 1956, Vol. 1, p. 68.
5. V. I. Veksler, et al., Collective Linear Acceleration of Ions, in Proc. of the Sixth International Conference on Accelerators, Cambridge, Mass., September 1967, CEAL-2000, p. 289.
6. Symposium on Electron Ring Accelerators, Berkeley, February 1968, Lawrence Radiation Laboratory Report UCRL-18103, February 1968.
7. N. C. Christofilos, et al., Rev. Sci. Instr. 35, 886 (1964).
8. D. Keefe, et al., UCRL-18671, December 1968 (to be published in Phys. Rev. Letters); also R. W. Allison, Jr., et al., UCRL-18498, October 1968.
9. R. T. Avery, et al., UCRL-18538, March 1969.
10. W. R. Baker, et al., UCRL-18447, March 1969.
11. R. W. Allison, Jr., et al., UCRL-18522, March 1969.
12. A. Faltens and C. Kerns, UCRL-18564, March 1969.
13. L. J. Laslett and A. M. Sessler, UCRL-18589 February 1969.
14. N. C. Christofilos, Collective-Ion Acceleration at Very High Energy in a Static Magnetic Field, UCRL Report, March 1969.



ELECTRON RING ACCELERATOR - COMPRESSOR II

XBL 689-4921

Fig. 1. Simplified schematic of the Compressor 2 equipment.

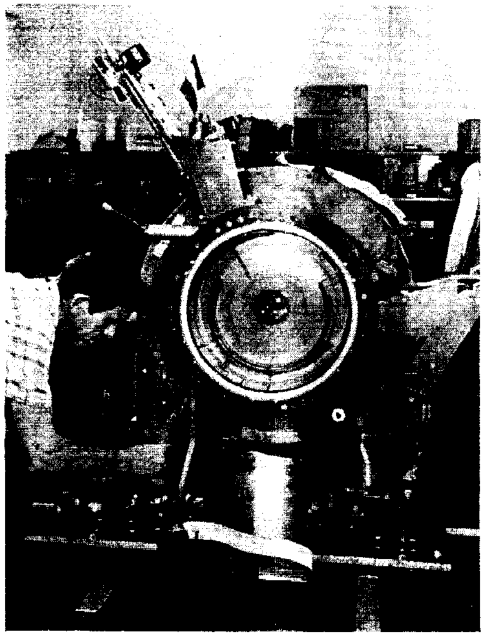


Fig. 2. Photograph of Compressor 2.

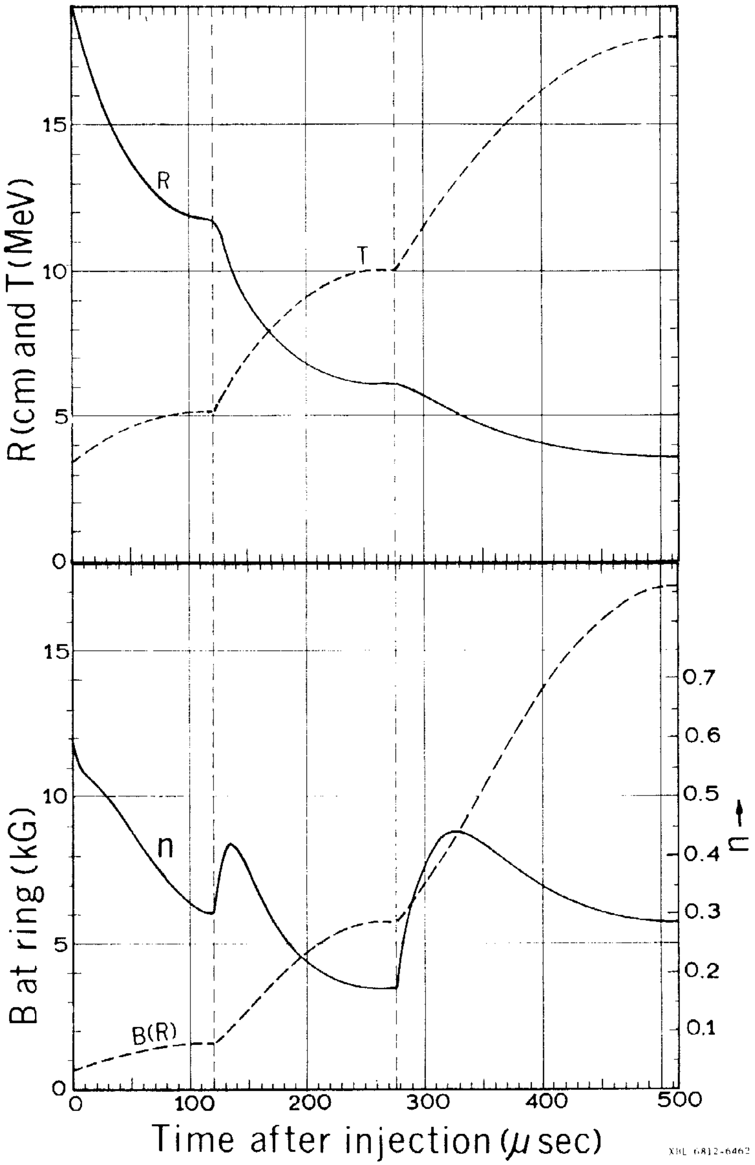


Fig. 3 The major radius (R) of the ring, the kinetic energy (T) of the electrons, the magnetic field (B) at the ring, and the magnetic field index (n), as functions of time during the compression of the ring in a typical cycle.