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ELECTRON RINGS: MEASURED PROPERTIES AND FUTURE APPLICATIONS

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ABSTRACT

Extensive measurements on the properties of electron rings and of the limiting nature of collective instabilities have been carried out at Berkeley. Peak collective fields of 5 to 10 MV/m have been regularly achieved; higher values should be attainable by improvement in the quality of the magnetic guide-field. Design parameters for an ion accelerator suitable for biomedical applications will be discussed. The design will be presented of an electron-ring device to contain ions for the spectroscopic study of atoms in a highly-stripped state.

The experiment at Berkeley on the use of electron rings to accelerate ions were suspended in June 1974 because of lack of research funds. This paper will describe a) the experimental results obtained up to that time, b) computational results on parameters for an electron ring accelerator for heavy ions that would be of value in biomedical diagnosis and possibly therapy, and c) plans for future work that we hope to start soon at Berkeley, in which relativistic electron rings will be used as a containment source for highly-stripped heavy ions produced by the ring.

I. Measurements on Electron Rings at Berkeley

Figure 1 shows the relativistic electron source at Berkeley which has been described elsewhere(1). It is a linear induction accelerator that uses ferrite cores driven by Blumlein lines. We have usually operated it at 3.6 MeV and about 500 amperes. The electron energy can be controlled quite accurately either to be constant during the pulse length, or to rise by a few percent during the injection time when we wish to stack a beam with an initially prescribed energy spread. Figure 2 shows the compressor and accelerating solenoid that we have been using for experiments for a year or more.

In the past, collective instabilities have severely limited the number of electrons that could be contained in the ring. The longitudinal (negative mass) instability proved the most intractable, the transverse coherent instability being amenable to more degrees of control; e.g., by manipulation of the shape of the magnetic guide-field. As a result of extensive experimental and computational work, we arrived at the design of metallic liner shown in Figure 3, which we felt would provide an electrical environment of adequate conductivity to allow reasonably large electron numbers to be stable and still would not interfere unduly with penetration of the pulsed magnetic field. The resistivity of the etched stainless steel foil averages 45 milli-ohms per square. By injecting a two-turn beam with

2% energy spread (full width), rings with electron number 6×10^{12} after injection were regularly achieved, without significant degradation by instabilities.

We did not feel it worthwhile to try experiments on extraction and acceleration of the ring unless we were confident that holding fields in the ring were at least a few megavolts per meter. Several lengthy experiments therefore were made on how to achieve optimum ring quality. Diagnostics used included: current pick-up loops to monitor the ring current near injection and near the end of compression; fast response loops to detect any high frequency rf signals if instabilities should arise; optical observation of the minor cross-section of the compressed ring both in the visible and infrared; an asymmetric pulsed magnetic field to kick the ring axially into the side wall -- the timing of the x-ray pulse giving a measure of the axial ring size; and an obstacle probe that could destroy the beam as it compressed -- the duration of the x-ray pulse giving a measure of the radial size.

The result of these observations was that in our compressor we could regularly form compressed rings with a holding field of 5 MV/m and more, without any problems from <u>collective</u> instabilities; the typical ring parameters being: $N_e \approx 2 \times 10^{12}$, $R \doteq 3.9$ cm, $2a = 3$ to 4 mm (FWHM radial), and $2b = 5$ to 6 mm (FWHM axial). A disappointing feature however, was the observation of serious broadening of the ring in the axial dimension, which led to loss of more than half the electrons during compression as a result of passage through single-particle resonances at $n \doteq 0.36$, 0.25 and 0.2. Both these actions have the result of reducing the holding field.

The main conclusion is that the design of the electrical environment used allows control of collective instabilities up to electron number $N_e = 6 \times 10^{12}$. With proper trimming of the magnetic field to reduce perturbations driving <u>single-particle</u> resonances, holding fields some six times larger than the observed 5 MV/m should be achievable with this apparatus.

No experiments were performed on the extraction and acceleration of the ring.

II. Possible Parameters for an Electron Ring Accelerator for Biomedical Use:

If it can be demonstrated that electron rings can be used to accelerate heavy ions stably over long distances (tens of meters), then an attractive application would be for therapeutic and diagnostic use in medicine since the ion energy needed could be achieved by magnetic acceleration alone. The possibility of this application was examined in detail by L.J. Laslett (2), and sets of possible ring parameters were derived by extensive computational work subject to the following input conditions:

i) The number of ions was adequately large to ensure positive axial focusing of the electrons.

ii) The momentum spread and the number of electrons in the ring were suitably chosen to remain below the threshold for the negative mass instability.

iii) The numbers of ions and electrons were such as to ensure stability for ion-electron oscillations of the type studied by Koshkarev and Zenkevich. Specifically, the numbers were chosen to avoid the lowest quadrupole resonance; whether this is limiting is not known yet.

Briefly, Laslett's results are as follows:

- The electron number, N_e, was typically (1-1.5) x 10^{13}.
- The ion number N_i, was typically $10^{11}/C$, where C is the charge state of the ion.
- The length of the solenoid required to accelerate ions to a certain energy depends on the selected charge state, C. (See Fig. 4)

- Alternatively, the final ion energy achievable with a solenoid of given length depends on the selected charge state, C. For example, a 35-meter solenoid would produce neon ions with 300 MeV/u for C = 5 and 100 MeV/u for C = 2.
- To produce neon ions mainly with C = 5 or more would require holding the ring for 3 to 4 milliseconds before release into the accelerating column. To produce ions mainly with C = 10 would probably demand very stringent control of background gas contaminants unless additional hardware features could be devised to shake loose periodically the undesired ions created from the background gas.

Thus, if the feasibility of ion acceleration over long distances can be established, these results show there are several choices of operating parameters which could reach useful energies without resort to electric acceleration of the ring (See Fig. 4). For the long d.c. solenoid needed, superconducting technology seems a natural application in order to reduce electrical power costs.

III. The Electron Ring as a Spectroscopic Source for Highly Stripped Ions:

A characteristic feature of the electron ring is that once an atom of neutral gas has suffered an ionizing collision, the ion remains trapped in the potential well of the ring and becomes the target for successive ionizing collisions so that it acquires a progressively higher charge state. In the process, the cold atomic electrons released are expelled by the potential of the ring and are not available for recombination. There is essentially no experimental information about the cross-sections for collisional ionization of ions that are multiply charged or the reverse process of electron pick-up from neighboring neutral gas atoms. There have been extensive calculations at Berkeley using theoretical models to determine how the mean charge and charge distribution of the ions contained in a ring progress in time, and how the velocity distribution of the ion evolves(3).

It is of considerable interest now at Berkeley to construct a special compressor for the specific purpose of creating intense compressed rings to be used for stripping and containing ions so that the spectroscopy of such ions can be studied as well as cross-sections for ionization and electron-capture. This field of physics is studied at present by the techniques of Beam-foil Spectroscopy in which ions travel at high speed through a stationary stripping foil. By contrast, the relativistic ring of electron acts like a moving stripper and leaves the stripped ions virtually at rest. Such measurements are of great fundamental interest in atomic physics but also are of great importance to solar physics and more recently to fusion research for the determination of the role of very heavy ions that can cool the plasma in a reactor.

In some respects such a compressor should be easier to construct than one from which it is intended to extract the ring and accelerate ions. One is freed from the requirement that the field index $\underline{n}$ has to change from its value at injection (in the neighborhood of $\underline{n} = 1/2$) to a value of $\underline{n} = 0$ at the release point; by keeping $\underline{n}$ constant during compression, problems arising from single-particle resonances can be avoided. Since a long containment time -- about one second -- is desired, the time for compression can be longer than usual; e.g., several milliseconds, thus allowing iron pole-tips for the magnet which can be used to shape the field, and moderately thick stainless steel foil for the vacuum chamber, which would provide a low coupling impedance and help in suppressing the negative mass instability. The most difficult feature will be the attainment of the very high vacuum ($P \simeq 10^{-10} - 10^{-11}$ Torr) which is needed both to avoid the ion-electron instability and to prevent charge transfer from the neutral background gas to the highly stripped ions under study. The possibility of an all-stainless-steel vacuum chamber is an aid in providing an easily-cleaned surface. A cross-section of a possible arrangement using cryopumping is shown in Figure 5.

Energy loss of the electrons in the compressed ring by synchrotron radiation is an important effect, and to keep the radius of the compressed ring constant it is necessary to decrease the guide magnetic field. For an example case$^{(4)}$ in which the electrons are injected at 40 cm radius and compressed to 3 cm radius, the way in which the kinetic energy (T) and the magnetic field (B) decrease is shown in Figure 6 (a). Other relevant parameters are shown in Figures 6(b), and (c) as functions of time.

A preliminary experiment has been carried out in a previous compressor to study the feasibility of detecting characteristic x-rays from ions produced by the electron ring. The experiment was successful in showing that the K and L x-rays from xenon could be detected with sharp resolution with a high signal-to-noise ratio$^{(5)}$ despite the rather hostile radiation field of the compressor. We thus feel that the device described here will provide a viable new use for intense electron rings.

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(4) J. Hauptman, L.J. Laslett, W.W. Chupp, D. Keefe, Proceedings IXth Conference on High Energy Accelerators (SLAC, June 1974), p. 420.

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FIGURE CAPTIONS

Figure 1: View of the 4 MeV electron linear induction accelerator.

Figure 2: View of the compressor with magnetic accelerating solenoid on left.

Figure 3: Metal liner for compressor interior.

Figure 4: Examples of the relation between solenoid length and kinetic energy for magnetic acceleration only for the case of neon ions of various charge states.

Figure 5: Schematic of cryopumped compressor with laminated iron magnet.

Figure 6: Example calculation of variation in time of a) magnetic field, electron energy, major radius; b) RMS axial and radial minor dimensions -- betatron and synchrotron contributions shown separately; c) electron density (cm^{-3}).

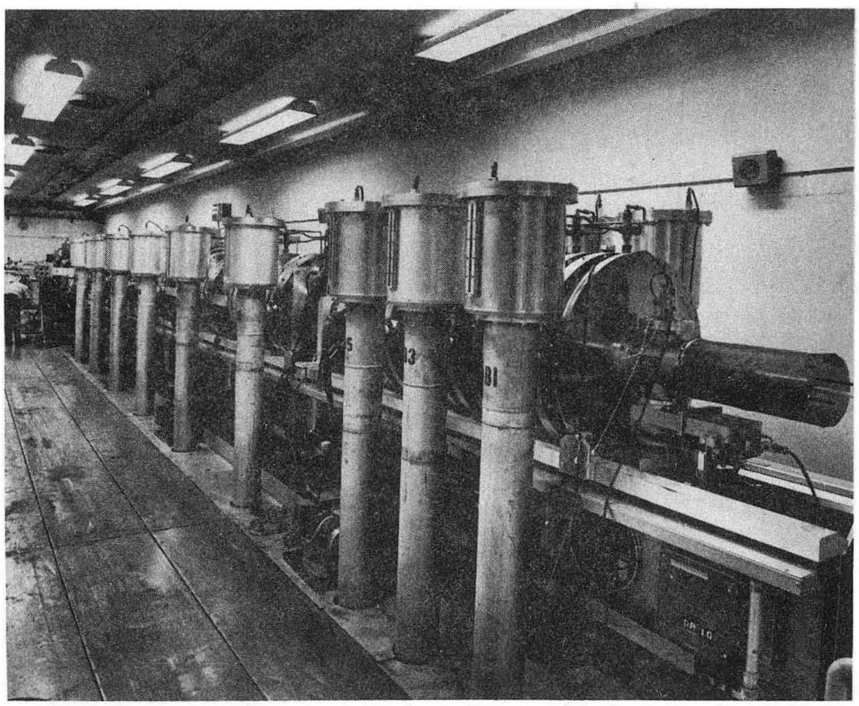

Fig. 1. XBB 747-4400

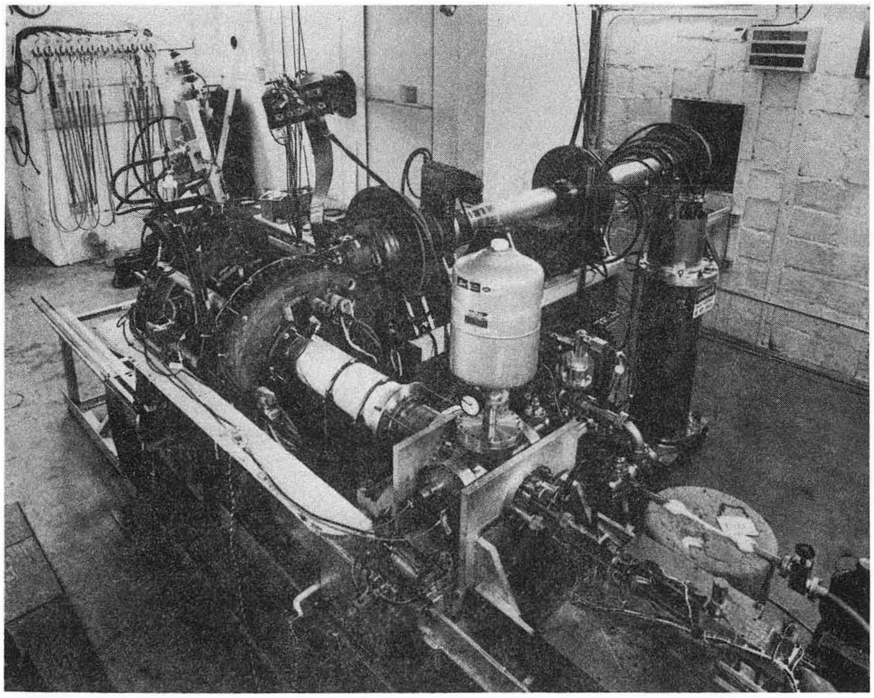

Fig. 2. XBB 747-4401

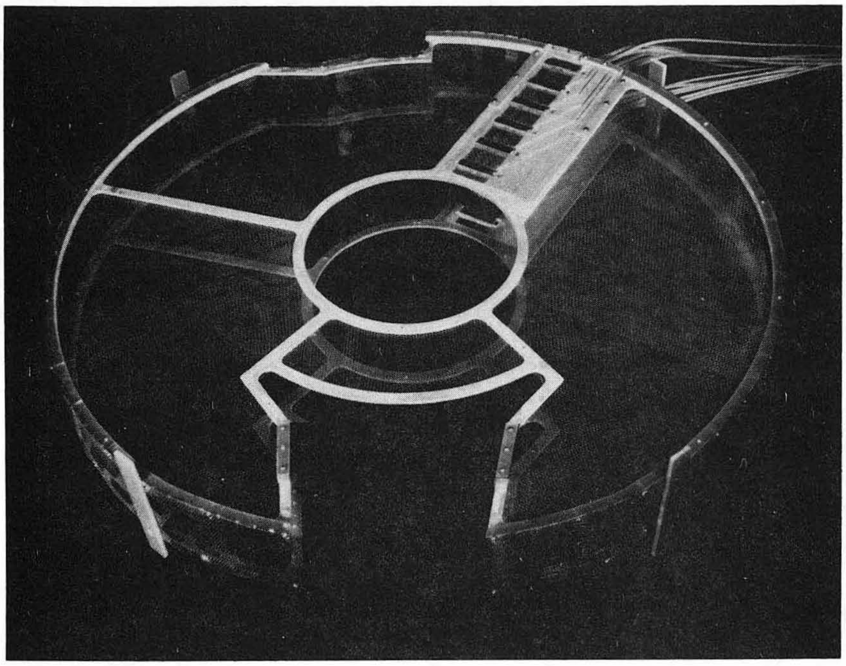

Fig. 3. XBB 7412-7579

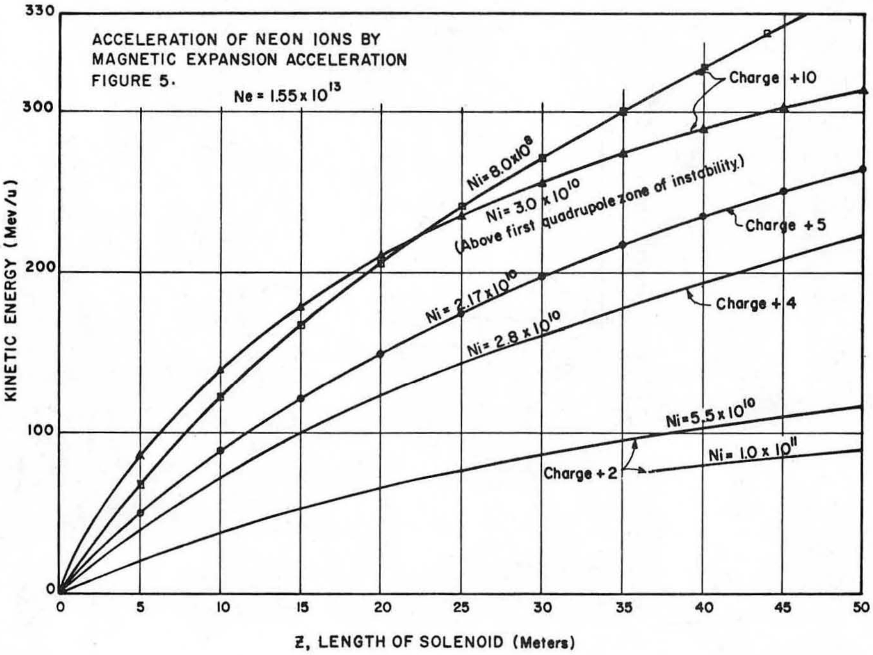

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Fig. 4.

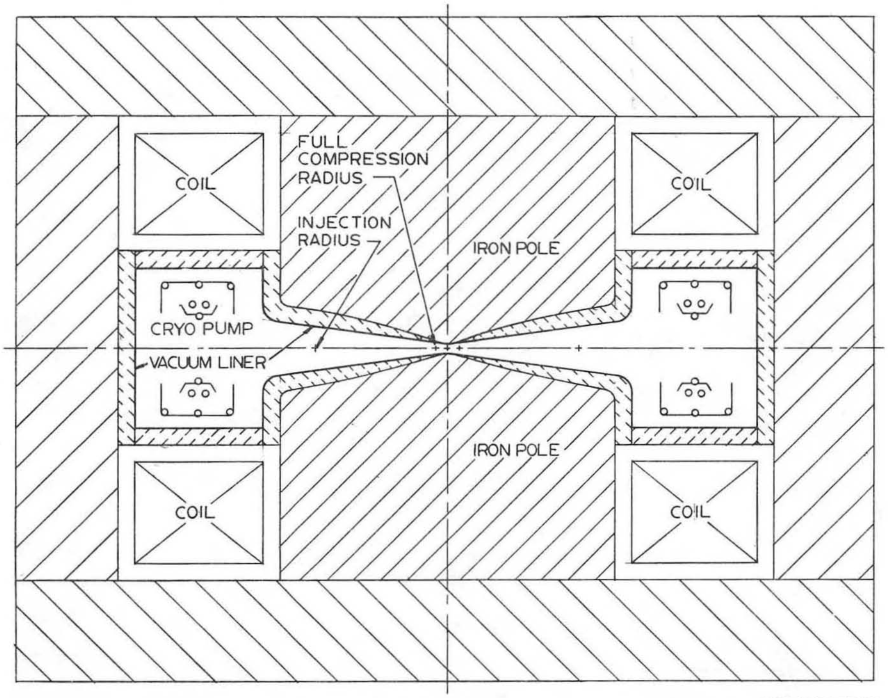

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Fig. 5.

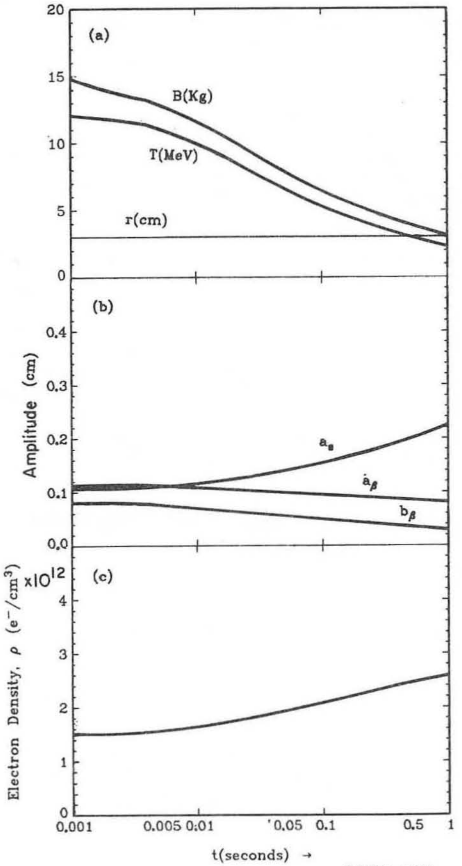

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Fig. 6.

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