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Electron Rings for Heavy-Ion Acceleration*

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I. Introduction

The most promising application of the electron-ring technology is for heavy-ion acceleration. Beam energies in the tens of MeV per nucleon for heavy ions seem quite doable, and indeed, energies even in the hundreds of MeV per nucleon are not out of the question in a simple, magnetic type of electron-ring accelerator.

In this report I shall speculate on the characteristics, the operation, and the problems associated with a heavy-ion type of electron-ring accelerator; I shall also indicate the status of the corresponding research program at the Lawrence Berkeley Laboratory.

II. A Heavy-Ion ERA

The three major components of a heavy-ion electron-ring accelerator are: (1) a high-intensity relativistic electron source, (2) a compressor for forming suitable electron rings and loading them with ions, and (3) a magnetic accelerating column, as indicated in Figure 1.

The injector must supply intense pulses of well focused electrons. Typical parameters are: peak currents of 1000 amperes for a pulse length of 20 or 30 nanoseconds at an energy of 3 to 6 MeV. The energy spread will be limited to 1 or 2 percent, and the beam emittance should be of the order of 50 milli-radian-cm or better. The injector will likely be a linear induction accelerator.

The compressor is a magnetic-field device for forming electron rings and manipulating them for maximum holding power. The holding power -- i.e., the maximum electric field (ϵ_{max}) -- of an electron ring is

$$\epsilon_{max}[V/m] = 60I/a\ [amp/m]$$

where I is the electron current and a the minor radius of the ring. It is apparent, therefore, that given an electron ring, its electric field can be increased if you compress it as much as possible. Many types of compressors have been proposed, but let us limit our considerations here to the pulsed type. For example, consider at the injection radius an electron ring with a circulating current of 100 amperes and a minor radius of 1 cm; the maximum electric field at the surface of the ring is 600 kV/m. If now the magnetic field is increased 100-fold, in a typical compressor the maximum electric field also will increase 100-fold, because the usual magnetic field shape is such that the major and minor radii of the ring both decrease approximately as the inverse square root of the field strength. Thus, the current increases to 1000 amperes, and the holding power to 60 MV/m, which is a level of interest for the practical acceleration of ions.

The next step in the sequence is to load the electron ring with ions, which can be accomplished simply by admitting a short puff of the appropriate gas and waiting for the desired degree of ionization. Typical sequences of ionization for argon and for uranium are illustrated in figures 2 and 3 for an electron ring of 10^{13} electrons, 3 cm in major radius and 1 mm in minor radius (I = 2.5 kilo amperes, ϵ_{max} = 150 MV meter^{-1}, electron density ≈ 1.7 x 10^{13} cm^{-3}). These calculations by G.S. Janes[1] of AVCO-Everett used approximate formulas for the ionization cross-sections; as a result the accuracy in the absolute times of ionization are somewhat uncertain, but hopefully they are within a factor of 2. The accuracy in relative times and in the distribution of charge states should be much better.

These figures show that by waiting for one millisecond one would produce argon ions with an average charge state of 9 ± 1.5. In this same period uranium atoms would be ionized to the average charge state of 23 ± 2.5. By waiting for 5 milliseconds the average uranium charge state could be increased to about 40.

These ionization times are one limitation to the possible repetition rate of such an accelerator. For example, if A^{+9} or U^{+23} ions were desired, a pulse repetition rate of, say, 500 Hz is possible, but for U^{+40} ions, because of the longer ionization time, a pulse rate of only about 100 Hz is doable with this electron density. We should note that these ionization times depend directly on the electron density in the ring, so that with an electron ring of, say, ten times lower density, the time scale would be ten times longer. Thus, with such a lower density ring, one would have either a ten-times lower repetition rate or, as seen from figures 2 and 3, for the <u>same</u> repetition rate a charge state that is lower by <u>a factor</u> of 2 to 2.5.

The next step in the accelerator sequence is to accelerate the rings by means of a slightly tapered magnetic solenoid. The electron ring is released from the compressor simply by removing one of the magnetic mirrors between which it has been confined during the compression and electron-stripping phases.

The axial acceleration of the electron ring is due to the Lorentz force $e\vec{v}\times\vec{B} = ev_\theta B_r\hat{e}_z$ where v_θ is the azimuthal velocity of the electrons and B_r the radial component of magnetic field. Only a small value of B_r is required -- or indeed permissible -- to obtain the maximum acceleration of the ions. For example, the proper value of B_r for a ring of 20 MeV electrons having a maximum electric field of 150 MV/meter and fully loaded with U^{+23} ions (total mass of uranium ions equal to total relativistic mass of electrons) is only about 8 gauss. At this value of B_r the phase area in the accelerating bucket equals the total phase area of the ions. At higher values of B_r the bucket area decreases and is zero for B_r greater than 20 gauss. That is, at higher values of B_r the ring is accelerated so fast that the ions are left behind. Since the axial field is about 20 kilogauss, the flaring of the magnetic field lines is very small indeed.

In such a field (B_r = 8 gauss) the U^{+23} ions gain energy at the rate of 23 × 150 Mv/m × 0.4 × 1/238 = 5.8 MeV/m/nucleon, so that the energy of 10 MeV per nucleon can be reached with only 1.7 meters of solenoid acceleration. At this length the magnetic field will have decreased about 4%, and the radius of the ring will have increased by 2%.

This type of acceleration can be carried much further. However, as the electron ring expands radially, the electric field decreases so that the rate of acceleration must be correspondingly reduced. If we take this effect into account, we find that we can accelerate the U^{+23} ions to about 300 MeV per nucleon with a 120 meter solenoid. At the end the magnetic field will have dropped by a factor of 4 and the radius of the ring will have doubled. If fewer ions are accelerated, the ring expands less so that a greater average rate of acceleration can be used. With small ion loading, the average ion energy can be made as much as 440 MeV per nucleon with the same length of solenoid.

If we limit the ion loading (for reasons of stability in the accelerating process) to a total ion mass N_iM_i equal to the total electron mass $N_e\gamma_o m_e$, then for a ring of $N_e = 10^{13}$ electrons of 20 MeV energy (γ_o=40) the number of ions N_i is equal to about 10^9 ions per ring for uranium and about 6×10^9 for argon. With an accelerator operating at 100 H_z pulse rate, the corresponding average beam rates would, of course, be 10^{11} and 6×10^{11} ions per second.

The beam structure from an electron-ring accelerator has an extremely low duty cycle. A typical pulse length is only 10^{-10} second, so that some coincidence-counting experiments would be severely limited. However, other types of experiments such as time-of-flight and short-half-life experiments can greatly benefit from this time structure.

The beam emittance and energy spread are determined largely by the ion motion in the potential well of the electron ring. For the ring we have considered the spread in the U^{+23} ion energy is about ± 6% at 10 MeV per nucleon and about ± 0.7% at 300 MeV per nucleon. The inherent emittance ($\pi a\theta$) in the ion beam is about 10 milliradian-cm for the U^{+23} ions at 10 MeV per nucleon and about 2.5 milliradian-cm at 300 MeV per nucleon.

III. Developmental Problems in the ERA

The principal problems in developing this type of accelerator have to do largely with beam stability in the compressor system. The injector, although its parameters are impressive, has not been a severe problem. The Astron injector in Livermore was more than adequate for our first ERA experiments,[2] although it was built for quite different pruposes. We recently built a new 4 MeV electron source[3] in Berkeley designed for ERA work. It is seen in Figure 4. It is a linear induction system consisting of 17 pulsed, ferrite-filled, induction cavities, each adding about 1/4 MeV energy to the electron beam. From a relatively crude field-emission cathode it produces several hundred amperes of monoenergetic electrons in a beam that is adequate for our present experiments. Furthermore, this system has potential for higher currents, finer emittance, and higher repetition rates, should they be needed.

The compressor system used in Berkeley is illustrated in Figure 5. The ring is formed at a radius of 18 cm in a weak-focussing magnetic guide field formed by the outer pair of coils. The three sets of coils are pulsed sequentially to compress the ring by factor of about 5 in both major and minor radii. Rings of good quality at intensities of up to 4×10^{12} electrons with electric fields of 12 MV/m have been formed, and we are optimistic about achieving better results.

In our investigations we have encountered a rich variety of beam instabilities, some of which seem to be sensitive to small changes in the ring environment. First, we have single-particle resonances,[4] which occur when the radial and vertical betatron tunes (ν_r and ν_z) are related by small integers, as $a\nu_r + b\nu_z = c$ (a, b, and c being integers). Such resonances are well known in accelerator lore and can usually be avoided or mitigated in a fairly straight forward manner.

Second, we have unstable oscillations of the transverse coherent type having the characteristic frequency $(m-\nu_r)f_o$, where f_o is the electron revolution frequency and m is the mode number. The $(1-\nu_r)f_o$ instability can be driven by ions produced from the background gas. The time of the onset of this instability was found to correlate with the background pressure as shown in Figure 6. These times correspond to complete neutralization. Although this is an interesting instability, it is of concern only at compressor pressures that are much higher than the normal. A heavy-ion machine will normally operate in the 10^{-10} or 10^{-11} torr region in order to avoid contaminating the ring with too many unwanted ions from the residual gas. More importantly, this same $(1-\nu_r)f_o$ instability can be driven by any mechanism whereby the electrons in the ring can lose energy -- image currents in resistive walls and electromagnetic radiation being the usual mechanisms. Such unstable oscillations can be countered either by reducing the "gain" of the feedback loop involved or by smearing the oscillation frequencies (Landau damping) by means of an energy spread in the beam. We have used both approaches and have moved the threshold for the onset of this instability to an intensity higher than our current operating level.[5]

The third and most serious beam instability that we have encountered is a longitudinal coherent bunching effect known as the negative-mass instability. Because of the intense fields in the rings and the beam dynamics of a weak-focusing system, the rings tend to be unstable against an azimuthal clumping process. As a result, the energy within the beam spreads out and the radial width of the ring increases, causing both loss of electrons and loss of beam quality. This negative-mass phenomenon is at present our limiting effect. With injection at high beam levels, it develops within a few turns, and within 100 nanoseconds much of the beam is lost, and the part that remains has spread out several centimeters in radius. We are trying to suppress this negative-mass effect through control of the electrical environment seen by the electron rings. The general idea is to encourage image charges and currents in the side walls such as to produce electric fields at the ring that counteract those due to the ring itself. Theoretically, this method looks feasible, and experimentally we have made progress with this approach and can see where more is possible.

We are preparing another experiment for accelerating ions by means of electron rings. The apparatus is the compressor shown in Figure 5, in which the third coil on the right side is developed into a solenoid 1 meter long for magnetic acceleration of the ring. Once the electron ring is released from the compressor there is no axial focusing due to the external magnetic field. The ring is held together by a combination of focusing due partly to the positive ion payload and partly to electric image forces in a nearby image cylinder. The strength of each of these focusing forces is proportional to ring intensity, so that one can see that there is a threshold ring intensity below which these focusing forces are insufficient. When we tried to accelerate ions in a previous experiment, we failed because the rings were of such low intensity (because of the negative-mass effect) that the rings simply spread out axially when released from the compressor. We will operate this experiment after we have learned to suppress the instabilities we are currently observing.

We in Berkeley have been both encouraged and discouraged by the success of the Russian group[6] under Sarantsev in Dubna in accelerating alpha particles to 29 MeV by means of electron rings having a holding power of 60 MV m^{-1}. Just why their compressor system is less prone than ours to the negative-mass instability is not clear, but it may be that the main distinction is that electromagnetic radiation by the electron ring is at present better controlled in their system. In any case, the Russian results are good evidence that the electron-ring type of accelerator is indeed feasible and that a practical accelerator design is not far away.

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* Work supported by the U.S. Atomic Energy Commission.

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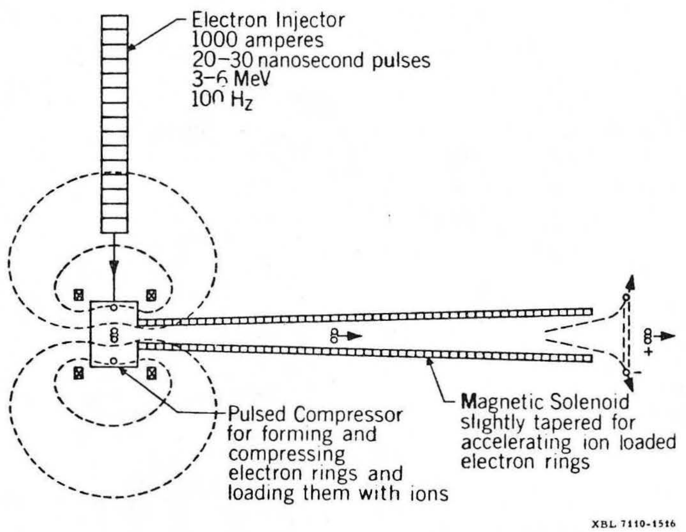

Figure 1 - Schematic layout of a heavy-ion ERA.

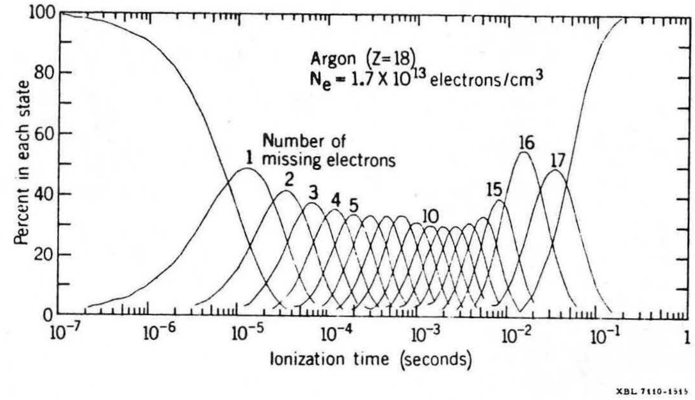

Figure 2 - Graph of ionization states versus time for argon in an electron ring of density 1.7×10^{13} cm^{-3}.

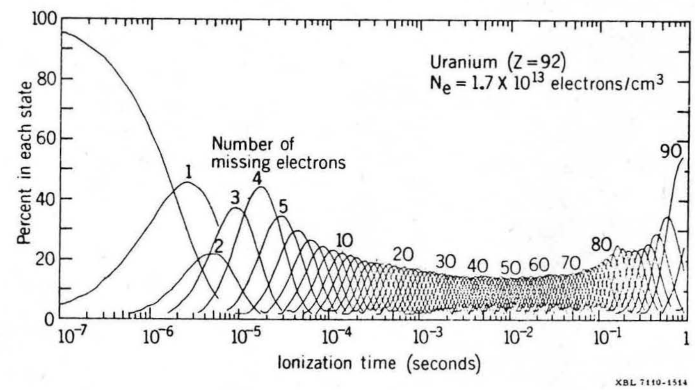

Figure 3 - Graph of ionization state versus time for uranium in an electron ring of density 1.7×10^{13} cm^{-3}.

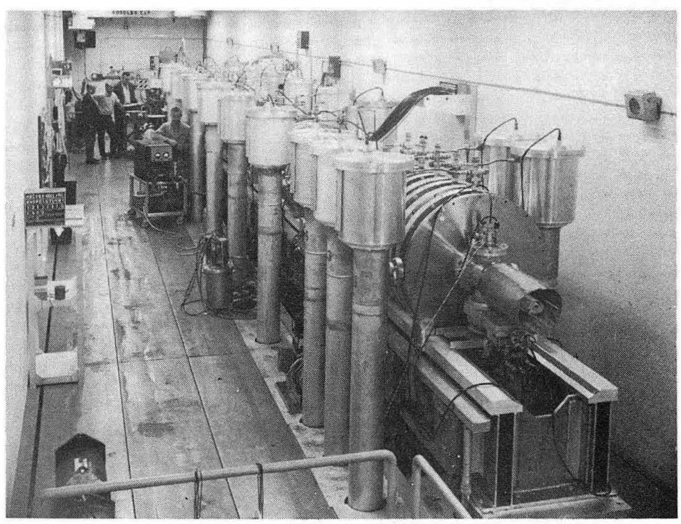

Figure 4 - Photograph of 4 MeV linear induction electron accelerator in Berkeley.

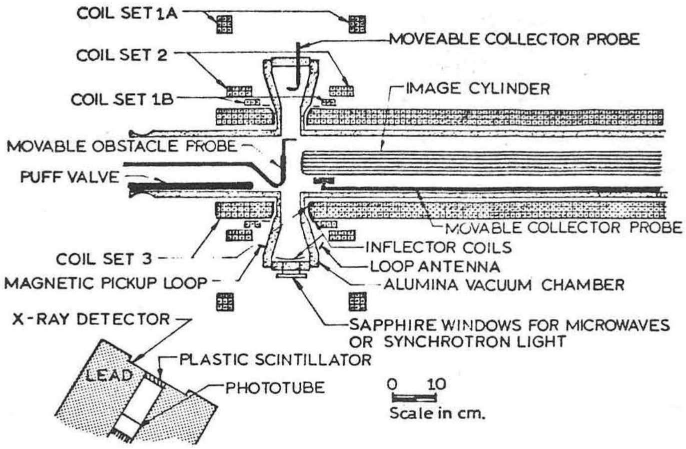

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Figure 5 - Cross section of an experimental electron-ring compressor. The three sets of coils are pulsed sequentially. The innermost set of coils is developed on the right side into a 1 meter long solenoid for magnetic acceleration of the rings.

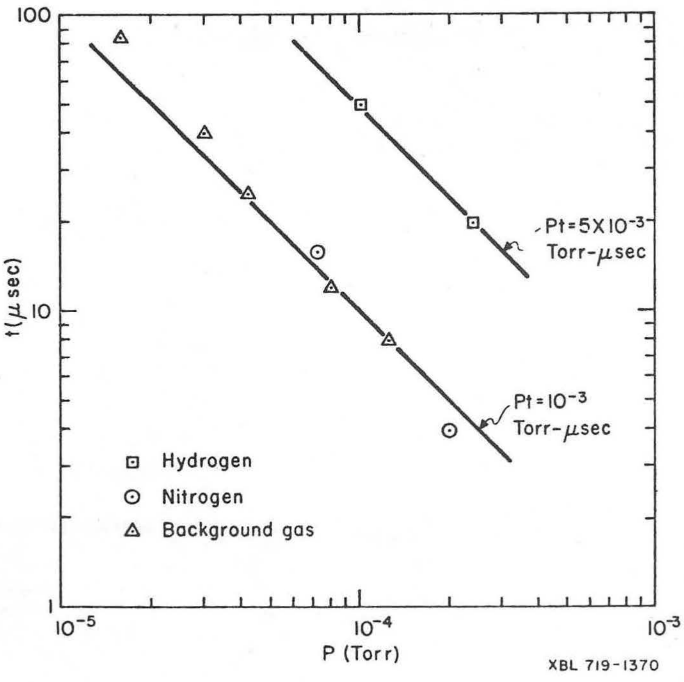

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Figure 6 - Time of onset of gas-induced transverse coherent $(1-\nu_r)f_0$ instability versus gas pressure.

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