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Authors
Chupp, W.W.
Faltens, A.
Hartwig, E.C.
et al.

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W.W. Chupp, A. Faltens, E.C. Hartwig, D. Keefe, G.R. Lambertson, L.J. Laslett, W. Ott,† J.M. Peterson, J.B. Rechen, A. Salop, and R.W. Schmieder**

Lawrence Berkeley Laboratory
University of California
Berkeley, California

Introduction

The Electron Ring Program[1-3] at Lawrence Berkeley Laboratory has been recently concerned principally with the study of collective instabilities and their control and has led to the injection, trapping, and compression of rings intense enough and compact enough for studies of acceleration and ionization processes.

Experimental Arrangement

The injector accelerator and compressor have been described previously.[4-6] For orientation, we review the principal features of the apparatus and the goals of the program.

Electrons originate at a field-emission cathode in a pulse 40 nanoseconds long, 1100 amperes in intensity, and of 1.2 MeV energy produced by a unit made up of five stages of the induction accelerator. The pulse is then accelerated to 3.6 MeV by twelve additional induction acceleration stages. A beam transport system further modifies the pulse to approximately 25 nanoseconds full duration, 400 amperes maximum intensity. Portions of the pulse of shorter duration, and fractions of the full intensity may be selected. A time-varying and an instantaneous energy spread may be imposed on the pulse also.

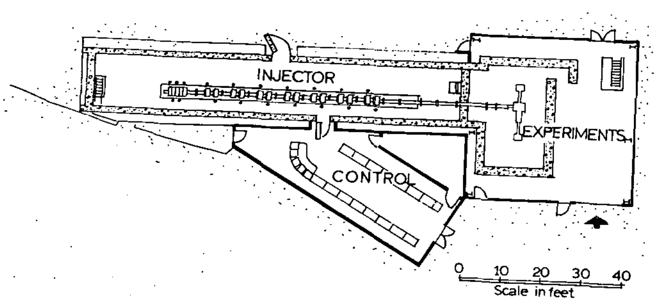

Figure 1 - Electron Ring Facility-Plan View

This tailored electron pulse is then injected into the rising transverse magnetic field of the compressor through a compensated input snout. This field and the inflector form and trap the electrons into a ring at a radius typically of 17.5 centimeters major radius, 2 cm axial width and 4 cm radial extent. It is then further compressed by 3 sets of pulsed coil pairs to the final radius of 3.9 cm and energy of 18 MeV in approximately 700 microseconds.

The compressor vacuum chamber contains a conducting liner, which establishes the electromagnetic environment of the ring, and diagnostic devices in the form of obstacle probes, single-turn loops both movable and fixed, current measuring coils, and a pulsed gas-input valve. A window for viewing synchrotron light is provided on the periphery.

Most of the injection, trapping, and collective instability problems have been studied in the limited apparatus called Compressor 4. It was not designed for full compression, ion loading, or rollout for magnetic expansion acceleration. This compressor was no longer used after August 1973, and Compressor 5A, which could accommodate additional experimental advances, was brought into operation in October, 1973. The details of its design relied heavily on the results of the prior experiments with Compressor 4.

The vacuum capability of Compressor 5A, while better than that of Compressor 4, is not in the pressure range desired for controlled ion loading and acceleration. An improved vacuum chamber of polyimide-glass laminate material was designed and pursued actively, but fabrication methods have not yet been developed to produce a bakeable high-vacuum structure from this material.

The principal goal of the experimental program remains to form intense, stable electron rings of high holding power which may then be accelerated very strongly while loaded with a useful number of the desired ions. A secondary goal is to form intense rings which may be retained for times approaching one second, in a suitably designed compressor, for the production and study of very high ionization states in heavy ions.

Experimental Observations

The principal problem that had to be analyzed and attacked was the intensity-dependent radial broadening of the ring shortly after injection. The effects were increasingly more severe at high beam intensities, and initially the number of electrons that could be formed into a compact ring was small (about 10^{12}) because the broadening led to large losses of beam particles on surrounding structures. Most of the effects occurred within 20 to 100 nanoseconds of injection.

One useful technique adopted was to use a low-intensity, short input pulse which could be easily identified and pursued through the inflection process, which allowed the inflector to be adjusted properly.

Several effects were observed.[3] One effect was a coherent, transverse, intensity-dependent oscillation of the ring as a whole at a frequency $(1-\nu_R)f_0$, where ν_R is the radial betatron tune and f_0 is the electron gyro-frequency. Another observation was that the ring developed a momentum spread, larger at high beam intensities, shortly after injection, accompanied by radio-frequency emission at harmonics of the electron gyro-frequency. The analysis of this phenomenon is the subject of another paper in this session.[7] Under some circumstances an axial oscillation at a frequency $(1-\nu_Z)f_0$ was observed.

An additional complication was the effect of the single-particle resonance at a field index value of n = 0.5. We chose, at first, to inject at a radial tune of 2/3, (n = 0.55) in order to achieve high inflection efficiency. However, this entailed crossing the n = 0.5 resonance very shortly thereafter, which broadened the ring and caused additional growth and beam loss at other resonances.

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†On leave from MPI für Plasmaphysik, Garching, Germany.
**Sandia Laboratory, Livermore, Calif.

These problems were attacked in several ways. One of the conclusions drawn in Reference 1 was that the compressor liner should have low resistivity to suppress the resistive wall transverse instability and aid in the suppression of the longitudinal instability and yet be resistive enough to allow the fast inflector field to operate through it. Various attempts were made to optimize separately the radial and azimuthal conductivities of liners, but none had the desired effect, as combinations of instabilities still dominated ring behavior, leading to enlarged ring dimensions and losses on surrounding structures.

A drastic change was then made to a thin stainless steel liner of less than 0.1 ohm per square resistivity, with a hole in both side-walls, whose edges formed the current conductors for the inflector pulse. Thus the environment for the electron ring could be varied by means of wall spacing and conductivity, while the inflection process was essentially decoupled from such adjustments. This arrangement was aimed at improving the early growth and loss situation. It was hoped that the inflector holes were a small perturbation, and in a friendly direction, to the impedance presented by the liner to low harmonics of the electron gyro-frequency.

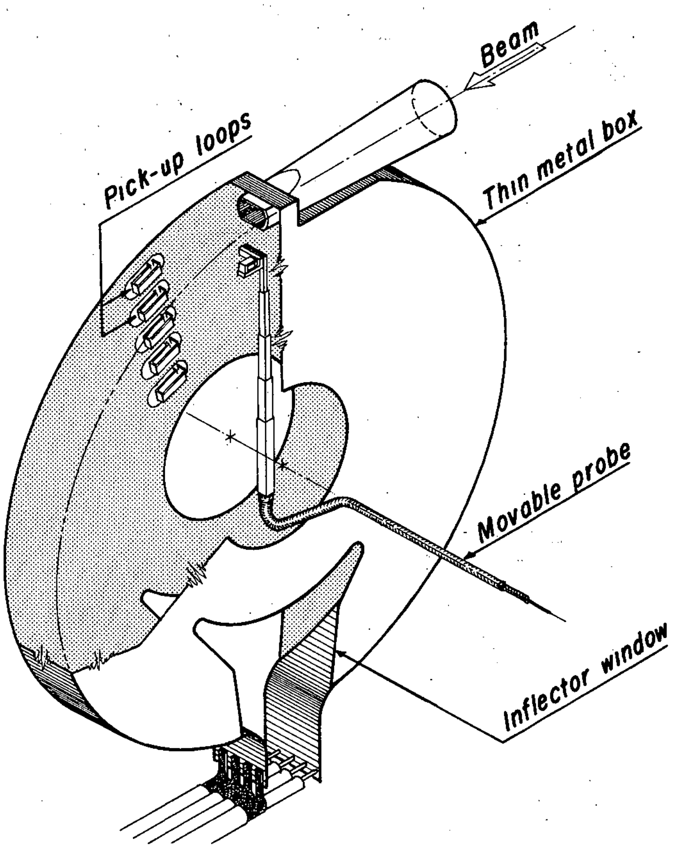

Figure 2 - Compressor metal liner

The opacity of the metal liner to R.F. signals necessitated the introduction of internal loops for high-frequency observations.

In a series of experiments in which we varied wall spacing and conductivity and the low-frequency behavior of the inflector holes and peripheral band, it was found possible to suppress the coherent transverse instabilities, reduce R-F radiation from the ring at high and low harmonics separately, and improve trapping.

One coherent transverse instability was traced to cancellation of terms in the Landau damping coefficients due to eddy currents induced in the windings of the second compression coil pair. A change, first to stranded conductors and then to stainless steel has eliminated this problem.[8]

Another coherent transverse instability was found to be due to full neutralization of the electron ring by ions[9] either from background gas or from gas evolved from arcs or electron impact on unstable materials. The removal of organic materials, careful attention to electrical connections, and improvement of the vacuum have minimized this contribution.

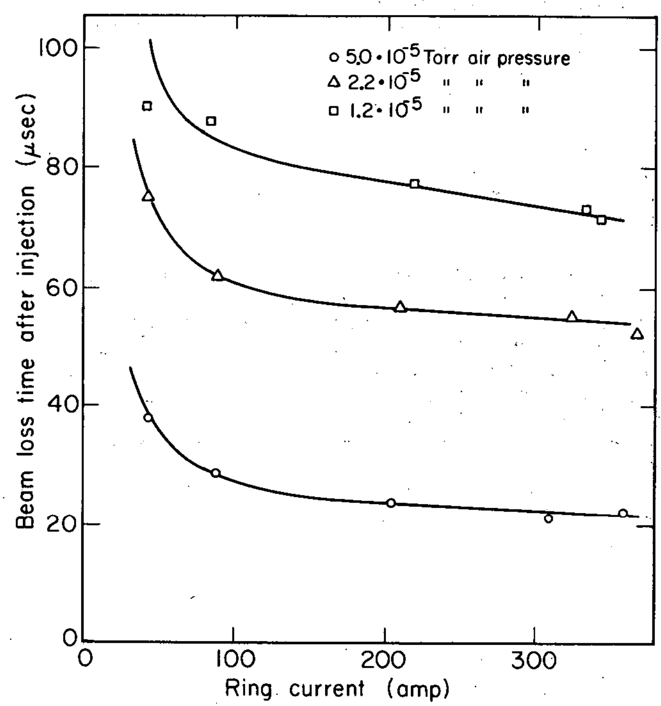

Figure 3 - Beam loss due to neutralization

Another coherent transverse instability is influenced by the spacing and resistivity of the wall material close to the ring.[3] Lowering the resistivity of the wall material below about 0.1 ohm per square raised the intensity threshold for this instability beyond the current levels we inject, and caused a dramatic increase in the maximum current we could trap into a stable ring from 80 Amperes to 300 Amperes (about 7×10^{12} electrons).[2]

The prompt energy spread increase observed[1] was assumed to be caused by the "negative mass", or coherent longitudinal instability, and was approached on that basis. Existing theories[3] predict the onset of the instability at a number of particles N

$$N = |n| \frac{\gamma R}{2\beta^3 r_e} \frac{Z_0}{|Z_M|/M} \left(\frac{\Delta E}{E}\right)^2 ,$$

where $|n| = \left|\left(\frac{1}{1-n}\right) - \gamma^{-2}\right|, \cong \frac{1}{(1-n)}$ for the electron ring, n = magnetic field index, R = major ring radius, r_e = classical electron radius, Z_0 = impedance of free space, $\Delta E/E$ = full-width at half maximum energy spread in the beam and Z_M is the longitudinal coupling impedance of the mode or harmonic number, M. In this threshold formula the only parameters available for effective variation were the energy spread and the coupling impedance. As noted above, the side-wall impedance is a factor also in a transverse instability, and in earlier experiments was limited by the inflector pulse requirements. It has been found that low impedance metallic side-walls, relatively close to the ring can reduce the R.F. activity observed at high electron gyro-frequency harmonics and also the energy spread produced in the electron ring. Careful bridging of the inflector holes with resistive material reduces some of the lower harmonic activity. However, threshold currents do not appear to follow the linear theory, and the R.F. activity seen, in terms of the inferred degree of modulation of the beam current, is never large relative to the observed increase in energy spread. Growth rates predicted by simple theories of mode coupling also do not agree with observations in a qualitative sense. Another paper, No. 4-4,[7] presented at this conference, discusses these observations more fully.

As soon as experiments had progressed to the stage of reliably trapping intense, compact rings, Compressor 5A, incorporating this accumulated knowledge and additional experimental possibilities as outlined above was installed and began operation in October 1973. It was found that the inflector holes and other structures were perturbing the main magnetic field to a significant degree. Inductors were bridged across the inflector holes to carry induced eddy currents more symmetrically in the compressor liner, and perturbations due to other causes also were reduced as much as possible.

The electron ring, during compression, must cross several single-particle resonances. To minimize the growth of ring dimensions and loss of beam particles caused by these resonances, each has been examined to ascertain the driving terms and the factors involved in growth rates.[10] The resonances involved and the corresponding integral tune relationships are:

n = .50	$\nu_R - \nu_z = 0$
n = .44	$3\nu_z = 2$
n = .36	$\nu_R + 2\nu_z = 2,\ 2\nu_R - \nu_z = 1$
n = .25	$2\nu_z = 1$
n = .20	$\nu_R - 2\nu_z = 0$

Our inflection system was designed for 3-turn injection with a closed orbit radial tune just above $\nu_R = 2/3$ (n = .556). While the inflection process performs best here, the ring must cross n = .5 immediately thereafter. Attempts to delay this crossing and then perform it rapidly involved extra coils and did not show much promise.

This problem could be avoided completely if the inflection were performed at n less than 0.5. Trapping efficiencies with the inflector optimized here were not as high as previously, but the lack of beam damage due to the resonance was considered as acceptable compensation.

Presently, small beam losses accompanied by broadening of the ring are seen at approximately 20 and 40 μsec after injection. These have been tentatively associated with the resonances at n = .44 and n = .36. They may be minimized by careful adjustment of injection parameters and by the use of harmonic correction coils designed to counteract the known first and second harmonic distortions of the compressor magnetic fields due to eddy currents, injection snout and inflector holes.

The resonance at n = .25 is crossed immediately after the second coil-pair is turned on, giving a maximum crossing rate for this resonance. If the ring is allowed to reach this resonance slowly, as at the end of the first coil's cycle, the entire beam may be lost. This

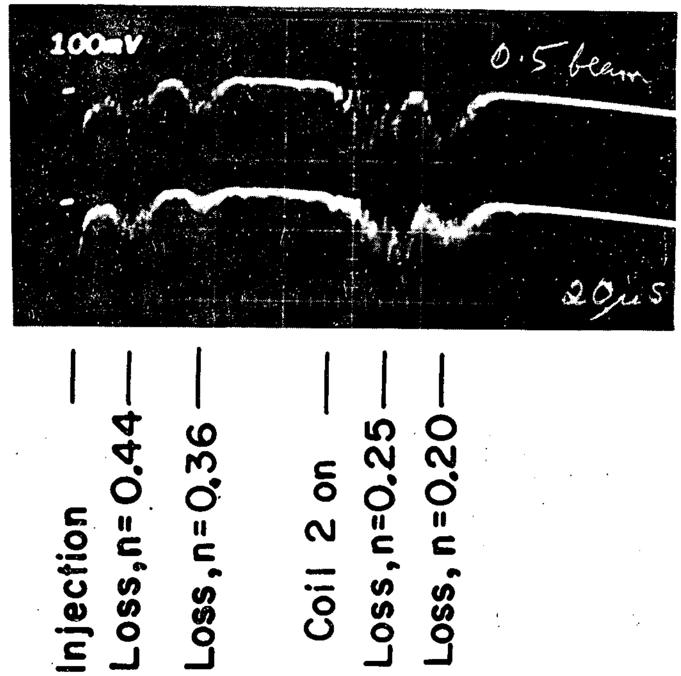

Figure 4 - X-ray loss pattern

resonance also responds to the use of the harmonic correction coils.

The n = .20 resonance is observed to cause X-ray losses also. These may also be minimized by use of the field harmonic correction coils, as growth on this resonance has a field second-harmonic term.

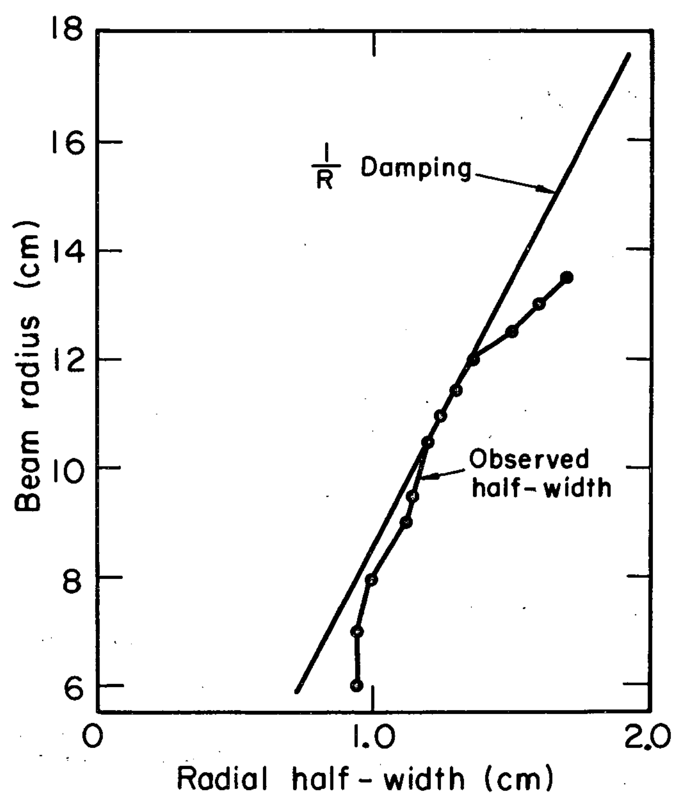

Figure 5 - Radial half-width vs. radius

Taken together, these ring-growth minimizing measures have been successful. The final ring dimensions, as seen by synchrotron light from the fully compressed ring show diffuse rings of low intensity without resonance-crossing assistance. Many of these rings are observed to have an oscillating, multiple-ring appearance also. When the measures outlined above are optimized, it is found that practically all of the trapped electrons survive to form a final compressed ring whose dimensions, at present, are:

Major radius	4.2 cm
Minor radial half-width	0.2-0.3 cm
Minor axial half-width	0.3-0.4 cm

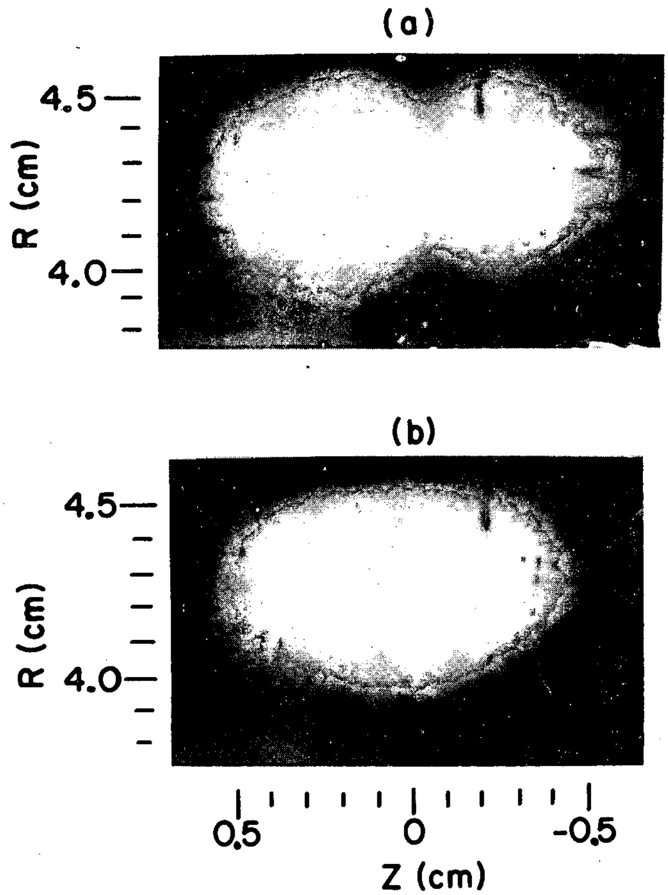

Figure 6 - Synchrotron light
(a) No harmonic compensation
(b) With harmonic compensation

A smaller major radius was planned, but a capacitor bank voltage limitation at present prevents full use of the third coil-pair.

Other Experiments

An experiment on the observation of K and L x-rays from atoms undergoing ionization in the electron ring was performed on the Compressor 4 apparatus.[11] Detection was by means of a cooled lithium-drifted silicon diode, collimated to view a small portion of the fully-compressed ring. The detector was heavily shielded against the copious x-rays and electrical and magnetic disturbances present near the compressor. The characteristic K and L x-rays of Xenon were successfully observed and identified (Fig. 7). It is believed that the ionizing capabilities of an intense electron ring are unique and could enable research on the ionization process and on the spectroscopy of highly-stripped ions.[12] A conceptual design for such a compressor is the subject of another paper to appear in the proceedings of this conference.[13] A typical calculated progression of the ionization of argon in an intense electron ring is shown in Figure 8.

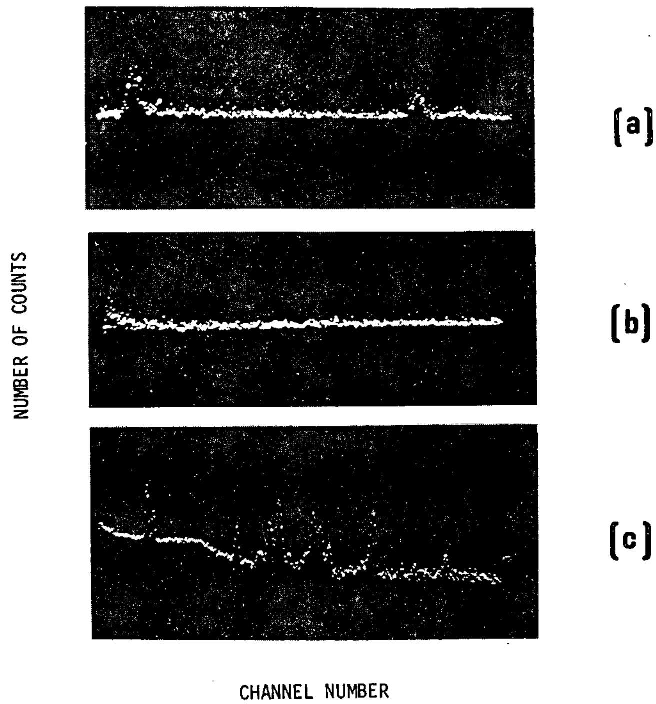

Figure 7 - Xenon x-ray observations
(a) K and L x-rays of Xenon
(b) X-rays, Xenon gas absent
(c) Calibration

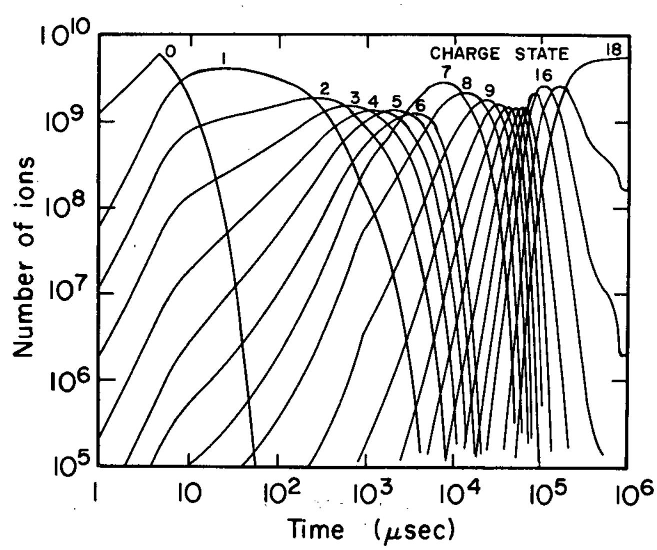

Figure 8 - Progress of ionization, Argon in electron ring

Theoretical and Calculational Work

An extensive calculational program has served and guided the experimental program throughout. Most of the results appear as internal reports (ERAN). Topics which have been treated recently are:

Minimization of field coil eddy currents[4]

The transverse resistive wall instability[15]

The negative-mass instability[16]

The full neutralization instability[9]

Ring stability and behavior during acceleration[17]

An electron ring as a spectroscopic source for ion study[11,12]

Ionization of heavy atoms by electron impact[18,19]

Conclusions

The LBL Electron Ring Program has demonstrated the injection and efficient trapping of rings of 7×10^{12} electrons without significant losses or dimensional broadening due to instabilities. The instabilities have been identified and either eliminated or ameliorated to the extent that their effects are acceptable. Most of the ring initially trapped can be compressed to a radius of 4 cm. The radial width of the rings show the expected adiabatic damping but the axial width shows blow-up caused by resonances. The next stages, ion loading and magnetic expansion, are ready to be undertaken except for the requisite vacuum of less than 10^{-8} torr.

Because of funding limitations, the Berkeley Electron Ring Program will be suspended after June, 1974.

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16. The negative-mass instability has been addressed recently by our group in several LBL internal ERAN reports (unpublished):

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    A. Sessler, ERAN-207, April, 1973

    P. Channell, ERAN-222, Nov. 1973; ERAN-226, Dec. 1973; ERAN-240, April, 1974.
17. Ring stability under acceleration and the performance as an accelerator has been addressed by the Berkeley group in the following LBL internal ERAN reports (unpublished):

    L.J. Laslett - ERAN-206, March 1973; ERAN-208, May, 1973; ERAN-211, July, 1973; ERAN-214, August, 1973; ERAN-228, January, 1974.

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TECHNICAL INFORMATION DIVISION
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UNIVERSITY OF CALIFORNIA
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