Submitted to Particle Accelerators

LBL-1315
Preprint c.2

# EXPERIMENTS ON ELECTRON RINGS AT BERKELEY

Glen R. Lambertson, Warren W. Chupp, Andris Faltens,
Edward C. Hartwig, Winfried J. Herrmann, Denis Keefe,
L. Jackson Laslett, Jack M. Peterson, Joseph B. Rechen, Arthur Salop

January 8, 1973

Prepared for the U.S. Atomic Energy Commission
under Contract W-7405-ENG-48

RECEIVED
LAWRENCE
RADIATION LABORATORY

MAR 1 1973

LIBRARY AND
DOCUMENTS SECTION

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545*

LBL-1315 c.2

28

## DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

# EXPERIMENTS ON ELECTRON RINGS AT BERKELEY*

Glen R. Lambertson, Warren W. Chupp, Andris Faltens,
Edward C. Hartwig, Winfried J. Herrmann†, Denis Keefe,
L. Jackson Laslett, Jack M. Peterson, Joseph B. Rechen,
Arthur Salop

Lawrence Berkeley Laboratory
University of California
Berkeley, California

January 8, 1973

During the past year or so experimental and theoretical work at Berkeley has been mainly concerned with trying to achieve, in a controlled and understandable way, compact high-intensity rings with high holding power. Enough problems with instabilities and other collective effects that cause degradation in ring quality have been observed in a variety of compressor configurations that we have been reluctant to attempt ion-acceleration experiments before having a good grasp of the phenomena limiting the attainment of high-quality rings. In what follows we describe first the present status of the equipment and experimental results and later return to discuss the theoretical and experimental observa-

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

† Visiting scientist from Max Planck Institute fur Plasmaphysik, Garching bei Munchen.

tions that are relevant to the formation of high-quality rings and that led to the evolution of the present equipment.

## A. Experimental Arrangement

1) Injector: Except for minor changes in detail the 4 MeV electron linear (induction) accelerator is as described in previous reports.[1] In typical operation the cathode current at the 1 MeV gun stage is 1100 A with a duration of 40 nsec. After acceleration and transport through various beam selection devices, the current arriving at the compressor is about 400 A. This current is more than adequate for the present experiments. It could be increased but it is desirable to keep to a minimum the excess transported current in order to minimize energy fluctuations arising, because of beam-loading, from current fluctuations.

For experiments to study the dependence of certain effects on intensity, attenuators can be introduced into the beam upstream of the compressor. These decrease the current by known factors without altering the emittance.

Emittance measurements give a value 0.25 $\pi$ cm-rad for 90% of the current and 0.06 $\pi$ cm-rad for 50% of the current. The instantaneous energy spread appears to be less than 0.5%. For experiments to study the effects of momentum spread, multi-wedged foils can be introduced to give values of $\Delta p/p$ = 1%, 2%, or 4% (FWHM). A new feature currently being exploited is injection with an "energy-ramp" in which the momentum of successive portions of the pulse rises at a rate typically about 1/2% per nsec. This is achieved by delaying the firing-time of one of the accelerating cavities so that its voltage is still rising at a time when the voltages on the other cavities have reached their plateau values.

Also upstream of the compressor is a chopper,[2] which is used to select the length of the current pulse for delivery to the compressor. We have most frequently used pulse lengths of 2 nsec, 8 nsec, and 12 nsec corresponding, respectively, to 1/2 turn, 2 turns, and 3 turns of beam in the compressor. Associated with a time-dependent transverse deflection of the beam is an unavoidable production of a transverse gradient in the energy of the beam particles.[3,4] The question of the magnitude of this energy modulation across the beam arises not only in the chopper system, but also in the inflector and the Radial Sweeper (to be described later). Theoretical estimates and experimental observations both put upper limits of a few tenths of a percent on this transverse energy variation for our system.

The injector has now run for some 2.6 million pulses, and its operation has been relatively trouble-free. Normally, the cathode holder is polished and the tantalum-spiral, field-emission cathode replaced after 100,000 pulses.

2) Compressor: The gross features of the present compressor are the same as those of Compressor 4 as reported before.[5,6] Both the inflection system and the electrical nature of the interior presented to the beam have, however, undergone successive modifications. It may be recalled that in previous attempts to use conducting side-walls a serious constraint was that the rapidly-varying inflector field (about 10 nsec characteristic time) should be able to penetrate these walls without serious degradation; this requirement set a lower limit of resistance of about 4 ohms per square. The present design, shown in Fig. 1, arose from a realization that much lower resistance was necessary, and consequently a radically changed inflector was devised. The beam is surrounded by a cylindrical box of stainless steel, 12 microns in thickness, which has a resistance of 0.06 ohm/square. To allow penetration of the fast inflector pulse a window in the pill-box is located almost (diametrically) opposite the injection snout. Because the walls are highly conducting, the use of separate conductors for the inflector can be avoided and the current pulse applied directly to the wall-material surrounding the window, as illustrated in Fig. 1.

The high conductivity of the walls prevents the use of monitor loops exterior to the compressor for signals with frequencies greater that about 10 MHz. Accordingly a set of high-frequency monitoring loops is mounted on the inner side of the side-wall (see Fig. 1) and their signals brought out on coaxial cables through small holes in the walls.

We shall describe later a method for separating the contributions of momentum spread and betatron amplitudes to the radial width of the electron ring. Crucial to these measurements is the use of a fast, pulsed field (Radial Sweeper) that is triggered shortly after inflection. This sweeper drives the closed orbit outward at the snout azimuth, thus forcing the beam to strike the snout and be lost. The rate of motion of the closed orbit is about 2.5 cm per microsecond. This field is supplied by an auxiliary set of coils, and its action can be considered fast on the time-scale of compression although slow on the time-scale of inflection.

The presence of the conducting pill-box and its lack of azimuthal symmetry cause modifications to the main guide-field provided by the compression coils and to the field derivatives; these small distortions have caused no significant difficulty in our present operation.

## B. Present Performance and Results

### 1) The Electron Ring Intensity

At present we are concentrating mainly on injecting a current pulse of at least two turns ( $\geqslant 8$ nsec) duration with a rising energy-ramp of about 4% from head to tail of the pulse. The motivation for this is to stack a circulating beam with substantial energy spread (to provide Landau damping) and with a radial dimension having approximately equal contributions from betatron amplitude and from momentum spread. The

shape of the inflector pulse is tailored to stack successive parts of the incoming beam on their appropriate closed orbits with minimum betatron amplitude. In addition, however, we have made measurements without the energy ramp, in which case the energy variation from head to tail is less than 1% and the radial width of the stacked beam should be determined mainly by the betatron amplitude distribution, if we ignore changes produced by collective effects.

A typical example of the non-linear behavior of the observed circulating current as a function of injected current is shown in Fig. 2. By integrating the signals from the pick-up loops inside the pill-box we have determined that the major loss at the highest injected intensity takes place during the first five turns of beam in the compressor. Thereafter the circulating intensity, measured within the pill-box and also at later times by outside pick-up loops, remains constant for very long times (hundreds of microseconds). In brief, the efficiency of stacking the beam by the inflection process is a constant up to half of the injected beam and decreases by 40% at full beam. This is interpreted as due to collective effects which cause either transverse deflections or radial spreading of the beam in a matter of just a few turns.

Of relevance to the question of whether an instability may set in at early times are the observations, with the pick-up loops, of radio-frequency activity. The radio-frequency signals in the range below about 1 GHz have not shown much growth after the injection period, and the degree of beam modulation inferred from such signals appears to decrease slightly with increased beam intensity. The duration of the signals, typically some tens or hundreds of turns, also decreases at larger beam levels. These observations in the low harmonics part of the radio-frequency spectrum have not suggested a longitudinal instability.*

* Note added in proof: Later observations at higher harmonics do show rapidly growing signals, suggestive of the negative-mass effect.

In summary, the choice of the present electrical environment and simultaneous stacking in momentum and transverse phase-space have led to routine production of rings that are without loss after the first few turns. Typical values of $N_e = 7 \times 10^{12}$ are quite reproducible. It should be noted that rings with almost twice this number of electrons have easily been formed simply by adjusting the closed orbit at injection to a smaller value. Such a mismatching with the inflection system leads, of course, to a beam with large betatron amplitudes and no small amplitudes, which is undesirable. This procedure does, however, aid particles to miss the injection septum, and one would expect it to manifest an efficiency greater than when stacking a compact beam.

2) The Electron Ring Minor Dimension

To achieve high holding-power it is not enough to have a large number of electrons; one has also to keep the minor dimensions small. The radial width is governed by the distribution of electrons in the two variables of betatron amplitude and closed-orbit radius, the latter variable being related to momentum. Knowledge of these distributions is highly desirable. The momentum width is expected to depend on intensity for many reasons and is important in determining Landau damping, whereas the presence or absence of small betatron amplitudes indicates how well radial disturbances have been controlled in forming the ring.

We have developed a measurement method for determining these two distributions. After a beam has been injected and stacked, the Radial Sweeper can be switched on to drive the beam radially outward at a known rate. As successive portions strike the outer obstacle (in our case, the injection snout), the x-rays produced give a profile in time of the beam arrival. If the beam is also clipped by a probe at the inner side,

a changed x-ray pulse is recorded when that beam is swept outward. The set of x-ray records for various degrees of inner-radius clipping can be analyzed to yield the distribution of particles in amplitude and momentum. This method is to be described by J.M. Peterson[7] in an internal note. An example of the result is shown in Fig. 3. The diagonal lines lie on the loci of the edges of inner- and of outer-radius clippers.

We have used this technique extensively in recent weeks to study how to stack a beam containing small betatron amplitudes and also to observe how intensity affects momentum spread. Results of our first measurements at different intensities are shown in Fig. 4. The points plotted should be viewed as a record of observed stable rings, but the spreads may be corrected downward as we obtain more data and reduce systematic errors. Also in Fig. 4 are shown the theoretical threshold intensities predicted for azimuthal (negative-mass) instabilities for two values of the coupling impedance,[8] $Z_n/n$. We estimate $Z_n/n$ for our pillbox for the lowest mode (n=1) to be about 10 ohms and for high, weakly-resonant modes (n about 15) to be about 100 ohms. As we shall note later, in Section C1, we have reason to believe that the apparent rise in momentum spread in our experiments may be produced by a collective effect other than the conventional longitudinal instability. Since we have observed stable ring behavior under conditions that are not consistent with a coupling impedance as high as 100 ohms, we must investigate whether our estimate of the coupling impedance is too high or whether some other effect is interfering with the classical longitudinal instability.

## C. Interpretation of Results

### 1) Azimuthal Bunching

In pursuit of stability with respect to possible azimuthal bunching, we

have tried a variety of inner-wall arrangements aimed at producing a low coupling impedance, $Z_n$, the ratio between current modulation and the azimuthal electric fields produced. An electrical method[9] of measuring the impedance in an actual compressor structure has been developed and was described at the conference in Geneva last year. We have used the method in conjunction with calculations to evaluate the properties of some wall configurations. An example of the results of the technique is shown in Figure 5. The measured impedance to first-harmonic modulation of a ring of current inside a closed circular box is shown as a function of the axial separation of the end walls. (For a standard of reference, note that the impedance for a ring in free space is about 300 ohms.) With highly conducting walls, this impedance is determined only by the geometry of the space inside the box, and smallest separation gives lowest impedance. Resistive walls, on the other hand, give a contribution at low spacing, as shown in the figure. These results of measurement are reasonable when compared with calculations of simpler cases, such as infinite parallel walls.[10] The method of measurement is not applicable to very imperfectly conducting walls that do not substantially terminate the electromagnetic waves in the TEM mode. Also, at very high frequencies, problems of mode selection interfere with the measurement technique.

The inner walls of stainless steel shown in Figure 1 present an impedance $\frac{Z_n}{n}$ at low mode numbers of about 8 ohms. At high modes, a closed box of this shape will have resonant responses that result in high impedance.[11] We expect the openings in the box that we use to reduce the resonant impedances, but we do not know precisely the extent of this favorable action.

In operation, we have looked for radiofrequency signals that

would indicate an instability from negative-mass action. The signals we have measured appear too small to indicate a substantial azimuthal instability. Hence, we cannot yet attribute to typical negative-mass effects the increased momentum spread at higher intensity.

2) Transverse (Radial) Effects From Decay of Image Currents in the Walls.

In the course of studying the control of longitudinal instabilities we had occasion to study both experimentally and theoretically, the effects of side-walls with various surface resistivities. An especial effort was made to achieve successful ring-formation with side-walls of resistance greater than or equal to a few ohms per square because these would allow penetration of the rapidly varying inflector field. It will be clear from the earlier discussion of our present experiments that these efforts were unsuccessful, and much more highly conducting walls were needed with a special window for the inflector field.

The presence of partially-conducting side-walls can lead to transverse forces that radially deflect the circulating beam. The well-known theory of the resistive-wall instability treats the problem of whether a perturbation occurring in a quiescent beam will or will not grow under the action of these forces. Of immediate concern in our case was the transient problem of deflections occurring during the early turns that could interfere with the proper working of the inflection process. Substantial radial shifts, indeed, were experimentally observed at high injected intensities with resistive walls ( $> 5\Omega/\square$), and these radial shifts were quite different for different portions of the beam, such as head, middle, or tail.

The magnitude of the transverse deflecting forces depends critically on the time constant for decay (or redistribution) of the image currents.

While the currents persist fully, they reduce the effect of purely electrical images by a factor $1/\gamma^2$. When the currents redistribute and decay, the electrical image forces achieve full potency in acting on the beam. The decay behavior of the current images was studied by Laslett[12] and, while more complicated than exponential, can be characterized by a time to fall by a factor 1/e; for example, with a resistance of 5Ω/square this time is 4 ns, or about one revolution time. Further work on the time-dependence of the surface-current distributions in a pill-box geometry has been carried out by Herrmann.[13]

To study the radial behavior of the injected beam during the inflection process and for some time thereafter, an approximate simulation program was devised by Laslett. The beam was represented by 30 macro-particles with successive momenta adjusted to simulate the energy-ramp that is in use. The progress of a particular "test-particle", whose initial conditions of injection or location in the beam could be prescribed, was follow computationally under the action of the guide field, thethe pulsed inflection field, and the induced wall fields. Azimuthal forces were ignored, thus information on any bunching action could not be obtained. Also, all particles were given a constant angular velocity, so that Landau damping was neglected. Results from this program (see two typical examples in Fig. 6) were valuable in showing the dramatic alteration in transverse excursions that occurred at high intensities, and the difference in behavior of the head and the tail of the beam, when resistive side-walls are used. A significant result of the calculations was that the radial growth was dominated by images in the side-walls and very little by the presence of images in the snout and circumferential band. The computational

results showed that the effects of transverse deflections and head-tail differences would be acceptably small for hundreds of turns if the decay time were adjusted to about 100 ns or longer. For beams that survive without serious modification for this number of turns it is anticipated that rather modest Landau damping by momentum spread, present in reality but not in the program, would inhibit growth of significant transverse excursions.

When the resistance of the sidewalls was reduced to 0.06 Ω/square (decay time of about 300 ns) an experimental search for transverse deflections showed they had decreased markedly, in agreement with the calculations. There did seem, however, at high intensity to be a radial broadening of the beam developing in a few turns, for reasons not yet understood. A dramatic consequence of changing from resistive to conductive walls was an increase in the stable circulating current for relatively compact rings by a factor of about four (80 amps to 300 amps).

3) Transient Intensity Effects

Consideration of the process of injecting an intense beam of electrons onto a circular path in a small chamber has made us aware of a number of transient disturbances that result from collective effects. The existence of such effects is most dramatically demonstrated by the phenomenon of self-inflection, wherein a substantial portion of beam injected with no pulsed inflector field is captured in stable closed orbits. . In one experiment, the beam was injected into a stainless-steel cylindrical box similar to that described and shown in the first figure but lacking any inflector window. In these very simple surroundings, we could capture up to 100 amperes of self-inflected beam, which was about one fourth of the charge injected during a 2 or 3 turn burst. The

amount of beam self-inflected was non-linearly dependent on the intnesity of the injected beam.

The effects that cause self-inflection must necessarily act during the first few turns, and they must alter the trajectories of an appreciable fraction of the beam. The trajectory and the width of the beam were observed during the first three turns. At highest injected intensity, the beam was seen to grow radially wider in the third turn. It was not possible to determine whether these effects were the result of radial deflections or of energy changes.

It is not a purpose of this report to discuss all possible transient effects, but a few examples will be illustrative. When the beam emerges from the entrance snout into the compressor, it must start to build up the electro-magnetic fields in the more open volume of the compressor. As turns merge and cross, adjustments in the self-fields must occur. The energy to establish these fields comes from the particle kinetic energy, is intensity-dependent, and is not distributed equally among all particles. Transverse deflections may also arise as beam streams merge or pass near surrounding conductors. If the walls of the compressor are not infinitely-conducting, a further decrease of particle energy is required to supply the resistive losses in the walls and to establish magnetic fields that penetrate the walls. With simple thin walls, these two losses are equal in size, and the resistivity only affects the rate of approach to steady state. Modulations of energy or intensity in the injected stream of particles will result in bunching and energy changes before the Landau damping becomes effective.

We estimate that singly, each of these effects will typically result in trajectory changes of a few millimeters. Is it possible

these small items can combine to produce the self-inflection? When using the inflector, the observed early loss of current at high intensity apparently occurs during the inflection process. We also observe a damping of initial circulating beam fluctuations that indicates a prompt energy spreading at high intensity. These observations of intensity-dependent disturbances in the first turns make us speculate that transient effects must be more seriously considered in our electron ring experiments and calculations.

D. Other Theoretical Topics

Finally, we mention briefly some other important topics under active study. Two papers will be presented later in this Symposium which bear on the limitations in performance of an electron ring accelerator on the basis of current theory. The paper by Faltens and Laslett[14] considers the possible reduction of longitudinal coupling impedance by arranging for the ring, at the time of release from the magnetic well, to be close to one of a pair of co-axial conducting tubes. The radial dispersion due to momentum spread needed for Landau damping limits the proximity of the ring to the tube; the balance between these factors and other phenomena is considered in the paper by Möhl *et al.*[15]

A further paper by Möhl *et al.*[16] submitted to the forthcoming Soviet National Accelerator Conference in Moscow extends this subject with special reference to the ion-electron resonances studied by Koshkarev and Zenkevich[17] and the role of Landau damping, intra-species forces, and image focussing in modifying their effects.

In anticipation of the use of electron rings for heavy ion acceleration, computations have been made of the distribution of charge state versus time for ions trapped in a ring. We are now trying to

improve these calculations by including Auger processes, which can significantly enhance the multiple-ionization rate.

There is also a continuing effort on understanding the complexities of the inflection process, including non-linearities, using computer calculations.

## References


1. R. Avery, G. Behrsing, W. Chupp, A. Faltens, E. Hartwig, H. Hernandez, C. Macdonald, J. Meneghetti, R. Nemetz, W. Popenuck, W. Salsig, and D. Vanecek, "The ERA Injector", Lawrence Berkeley Laboratory Report UCRL-20174, February 1971; and Proceedings of the 1971 Particle Accelerator Conference, IEEE Trans. Nucl. Sci. NS-18 #3, June 1971, p. 479.

2. The general layout and basic parameters of the chopper system, which consists of a d.c. bias magnet plus a pair of deflection plates to which is applied a sharp electromagnetic pulse were established by G.R. Lambertson; the pulsing systems were developed by A. Faltens; the mechanical design was due to H.P. Hernandez and D.L. Vanecek (unpublished).

3. L. Jackson Laslett, "On the Passage of a Beam Through a Cavity", Lawrence Berkeley Laboratory Report ERAN-72-B, April 1970.

4. T.K. Fowler and W.M. Good, Nucl. Instr. & Meth. 7, 245-252 (1960).

5. E.J. Lofgren, "The Berkeley ERA Program:, Proceedings of the 1971 Particle Accelerator Conference, IEEE Trans. Nucl. Sci. NS-18 #3, June, 1971, p. 456; also Lawrence Berkeley Report UCRL-20116.

6. G.R. Lambertson, D. Keefe, L.J. Laslett, W.A. Perkins, J.M. Peterson, and J.B. Rechen, "Recent Experiments on Forming Electron Rings at Berkeley", ibid, p. 50; also Lawrence Berkeley Report UCRL-20183.

7. J.M. Peterson, "A Method of Analyzing the Momentum and Betatron Amplitude Distributions in a Circulating Beam", Lawrence Berkeley Laboratory Report ERAN-198; and Proceedings of the 1973 Particle Accelerator Conference (to be published in IEEE Trans. Nucl. Sci.).

8. A.M. Sessler, Proceedings of the 1971 Particle Accelerator Conference, IEEE Trans. Nucl. Sci. NS-18 #3, June 1971, p. 1039.

9. A. Faltens, E.C. Hartwig, D. Möhl, and A.M. Sessler, "An Analog Method for Measuring the Longitudinal Coupling Impedance of a Relativistic Particle Beam with its Environment", Lawrence Berkeley Laboratory Report LBL-43, Aug. 1971; and Proceedings of the VIII International Conference on High Energy Accelerators, 1971.

10. A. Garren, D. Möhl, and A. Entis, "The Longitudinal Coupling Impedance of a Circular Beam Between Infinite Plane-Parallel Laminated Plates of Arbitrary Electrical Properties", Lawrence Berkeley Laboratory Report ERAN-174, June 1972 (unpublished).

11. A. Entis, A. Garren, and L. Smith, "Negative Mass Instabilities in an Electron-Ring Compressor", Lawrence Berkeley Laboratory Report UCRL-20208, February 1971; and Proceedings of the 1971 Particle Accelerator Conference, IEEE Trans. Nucl. Sci. NS-18 #3, June 1971, p. 1092.

12. L. Jackson Laslett, "The Resistive Decay of Magnetic Image Fields", unpublished ERA manuscript (Lawrence Berkeley Laboratory 1972).

13. W. Herrmann, "Time Behavior of Eddy Currents in Resistive Axisymmetric Systems", Lawrence Berkeley Laboratory Report ERAN-197, Sept. 1972, (unpublished).

14. A. Faltens and L.J. Laslett, "Longitudinal Coupling Impedance of a Stationary Electron Ring in a Cylindrical Geometry", Lawrence Berkeley Laboratory Report LBL-1070, Sept. 1972; to be published in Particle Accelerators.

15. D. Möhl, L.J. Laslett, and A.M. Sessler, "On the Performance Characteristics of Electron Ring Accelerators", Lawrence Berkeley Laboratory Report LBL-1062, Sept. 1972; to be published in Particle Accelerators.

16. L.J. Laslett, A.M. Sessler, and D. Möhl, "Transverse Two-Stream Instability in the Presence of Strong Species-Species and Image Forces", Lawrence Berkeley Laboratory Report LBL-1072, Sept. 1972; to be published in the Proc. of the 1972 All-Union Conference on Particle Accelerators (Moscow, U.S.S.R.).

17. P.R. Zenkevich and D.G. Koshkarev, Particle Accelerators 3, 1 (1972).

## Figure Captions

Figure 1 - Sketch of the cylindrical, stainless-steel box, in which the electron ring is formed and compressed.

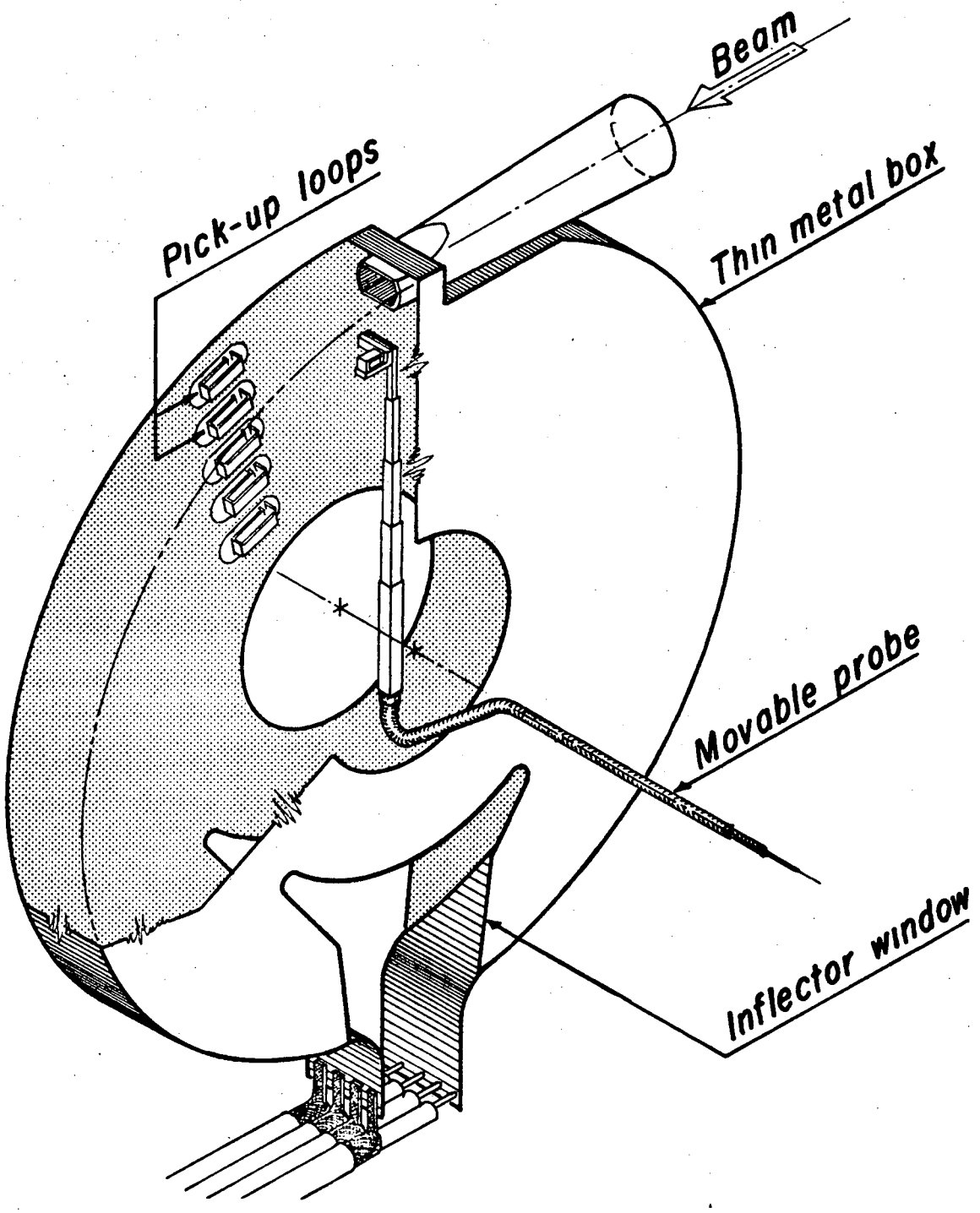
Figure 2 - Plot of the number of electrons trapped in the ring versus intensity of the injected beam current.

Figure 3 - An example of measured distributions in momentum and betatron amplitude for a relatively intense electron ring. The contours are of constant electron density in momentum-betatron-amplitude phase space.

Figure 4 - Measured momentum spread versus number of electrons in the ring, and curves of theoretical, negative-mass threshold intensities for two values of the coupling impedance.

Figure 5 - Measured values of the coupling impedance at the electron revolution frequency versus spacing to the side walls at two values of the sidewall surface resistivity.

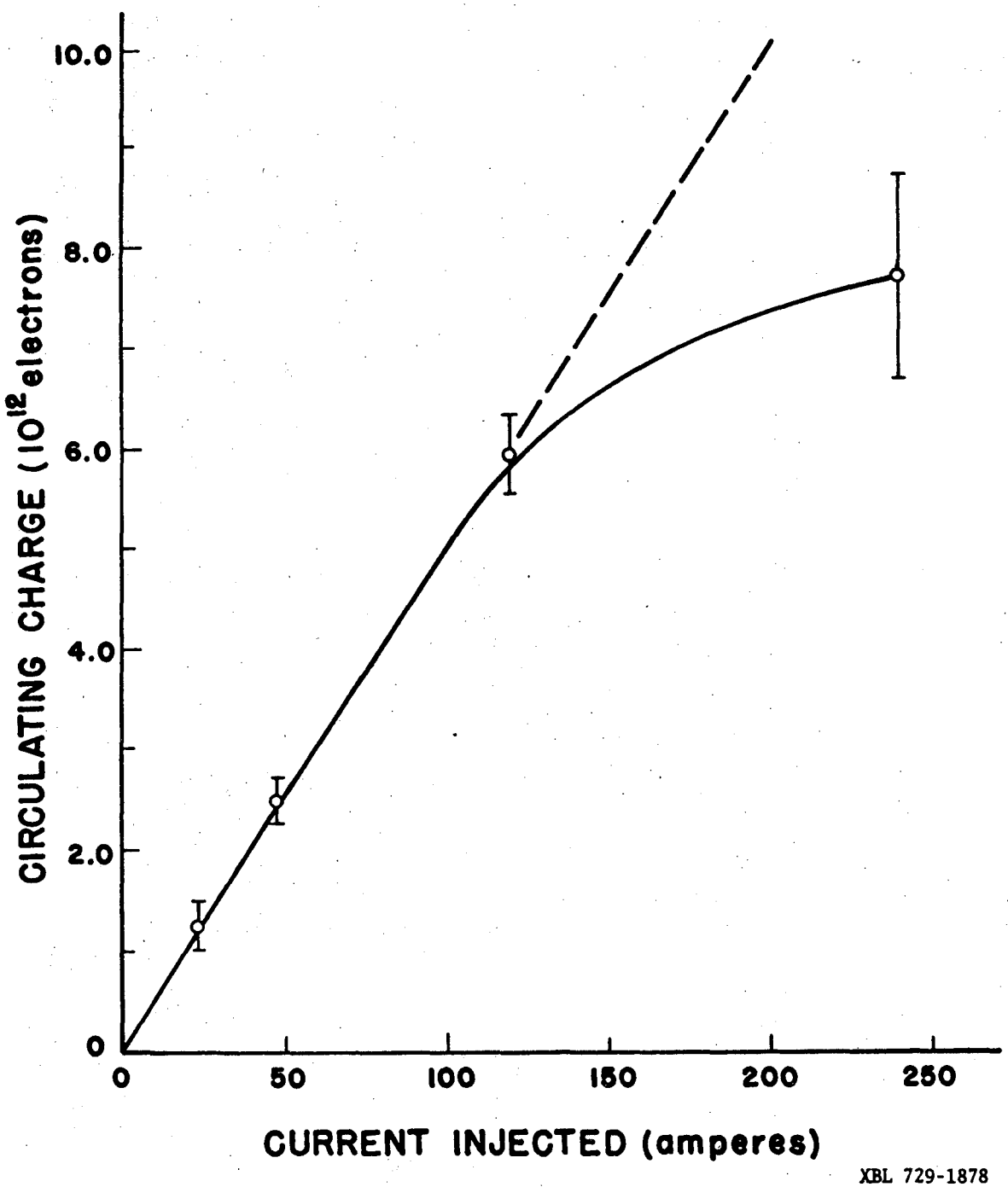
Figure 6 - Examples of computed radial effects caused by time-dependent electric and magnetic images in the metal box surrounding the electron ring. Each plot represents the radial position of a sample "test" electron in the ring when it crosses a certain azimuth on successive turns in the compressor. The solid curves are for an electron ring having $1.2 \times 10^{13}$ electrons and the dotted curves for a ring having such a small number that intensity effects are negligible. The characteristic decay time of the image currents in the sidewalls was 4 nsec in these examples.




INNER WALLS OF COMPRESSOR

XBL 729-1700

Figure 1




XBL 729-1878

Figure 2

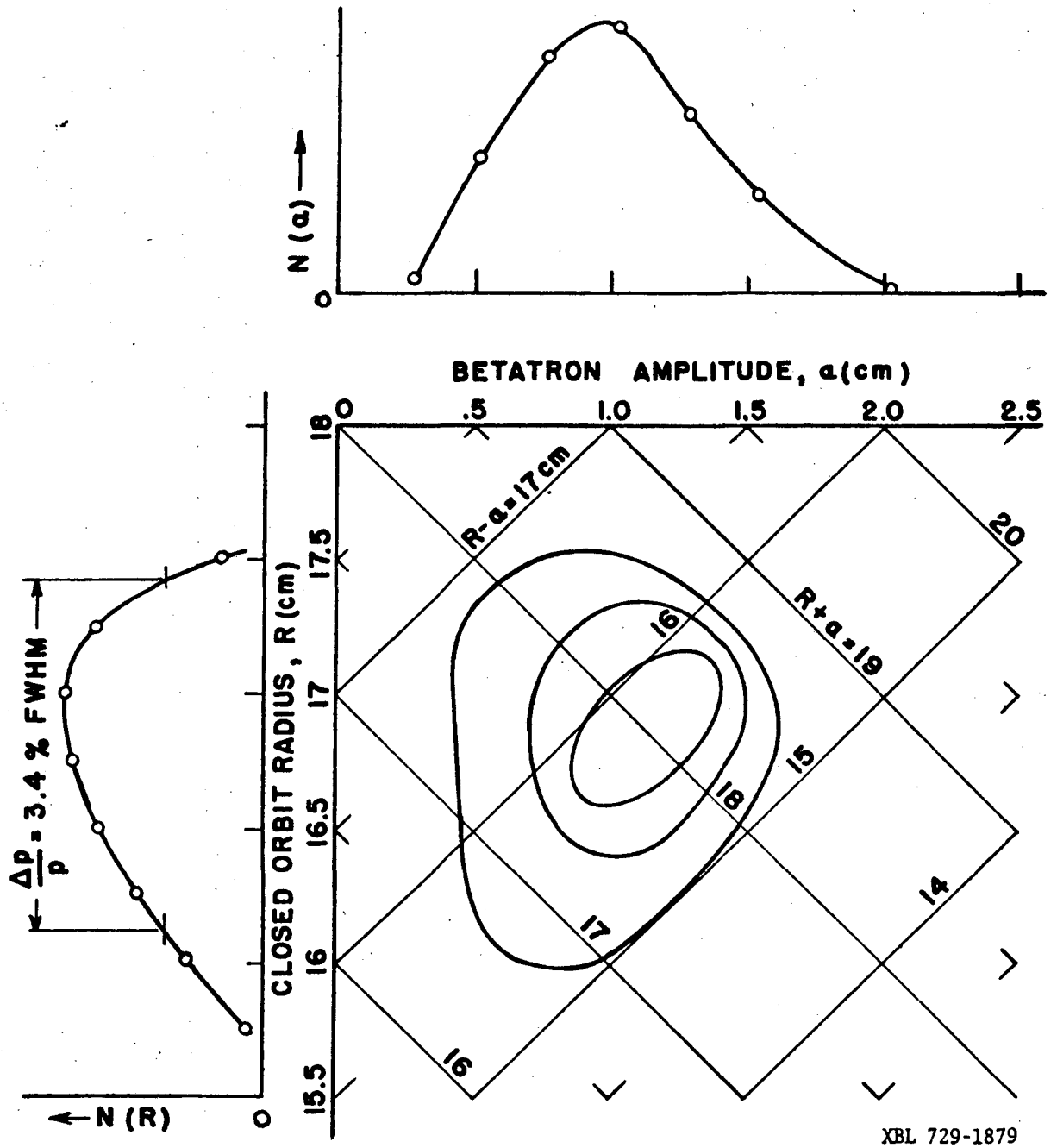
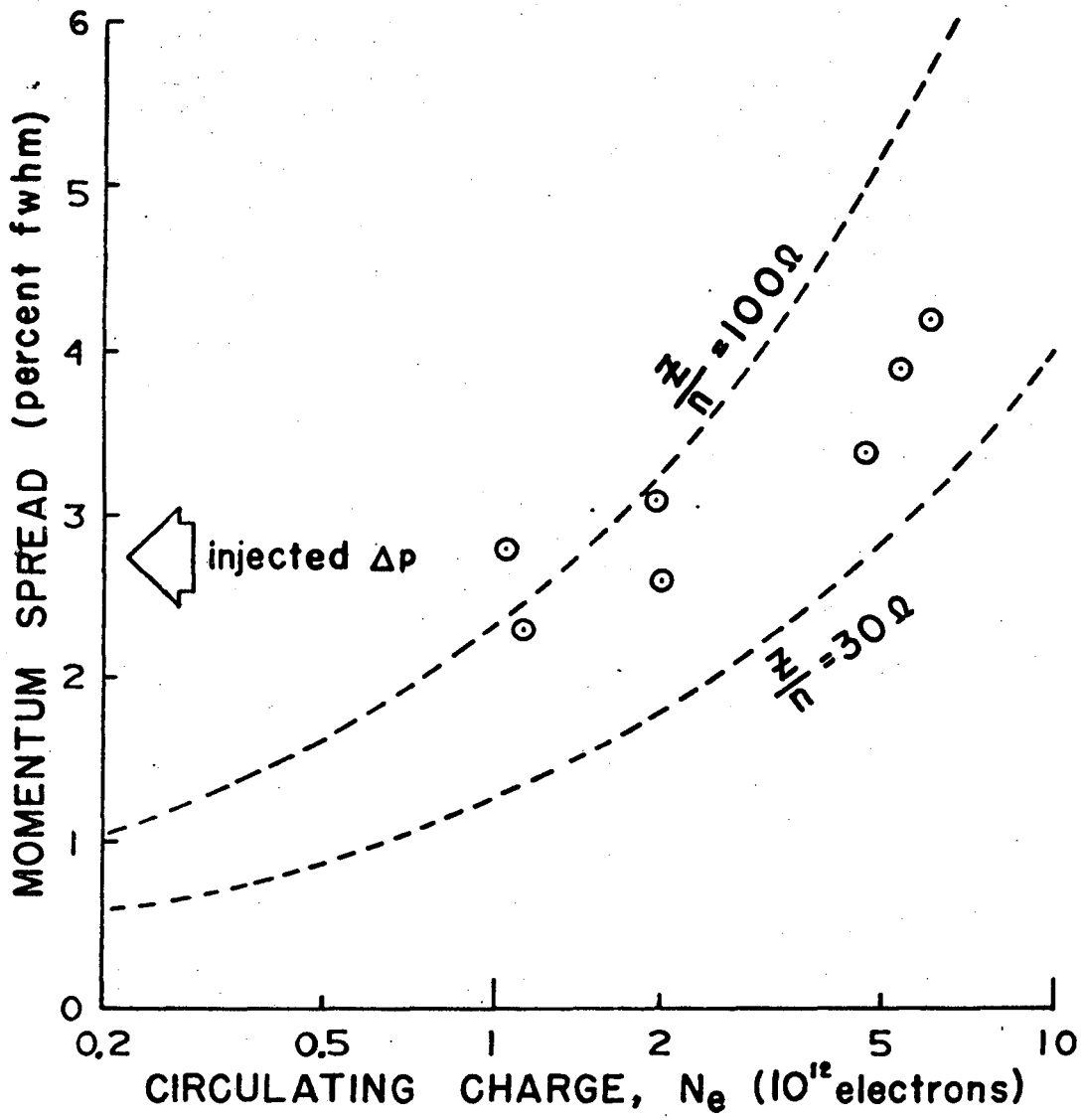
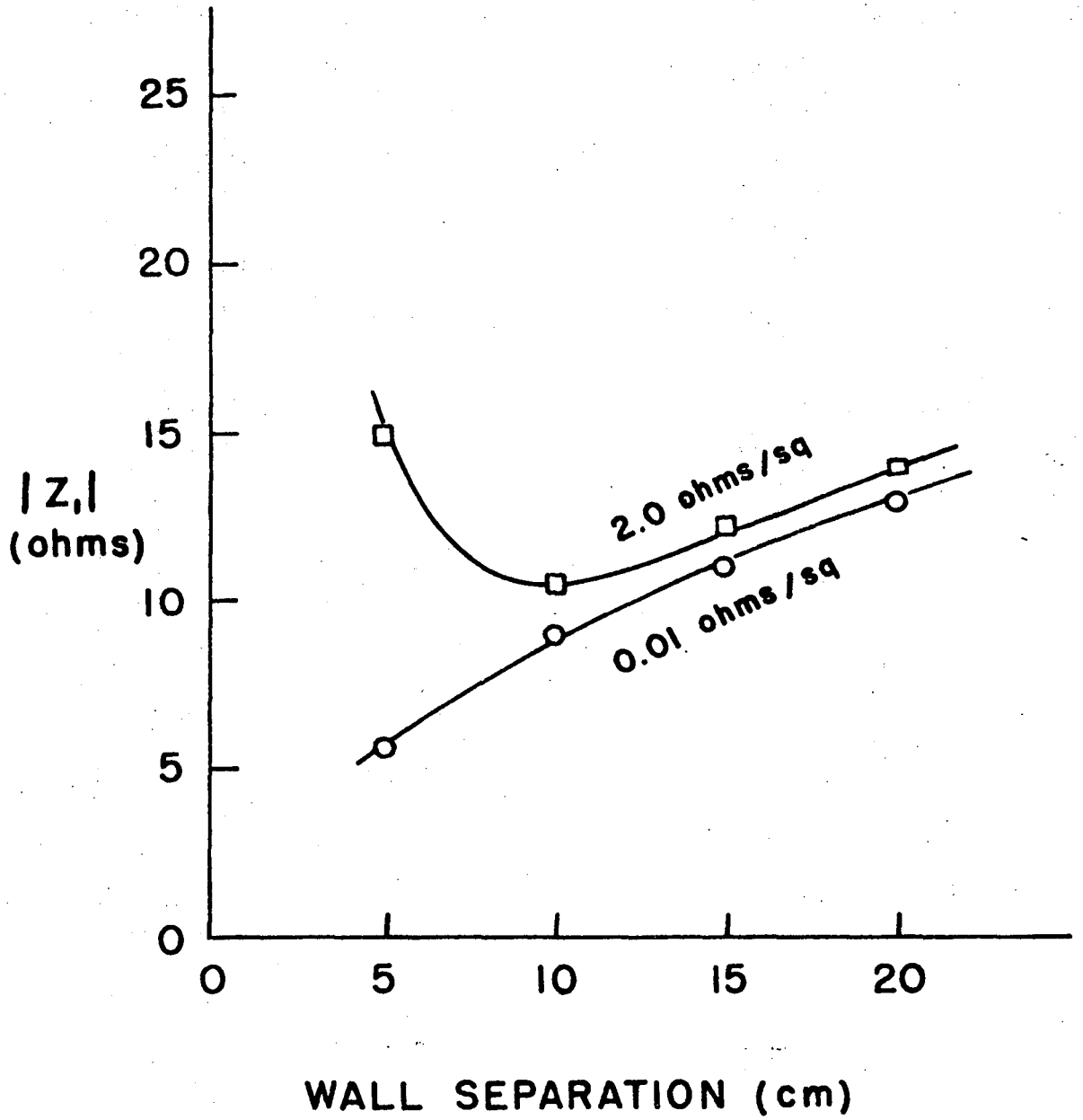

N (a)
0
BETATRON AMPLITUDE, a(cm)
0
.5
1.0
1.5
2.0
2.5
CLOSED ORBIT RADIUS, R (cm)
18
17.5
17
16.5
16
15.5
R-a=17cm
R+a=19
20
16
15
18
17
14
16
Δp/p = 3.4 % FWHM
N (R)
0
XBL 729-1879

Figure 3




XBL 729-1880

Figure 4




XBL 732-117

Figure 5

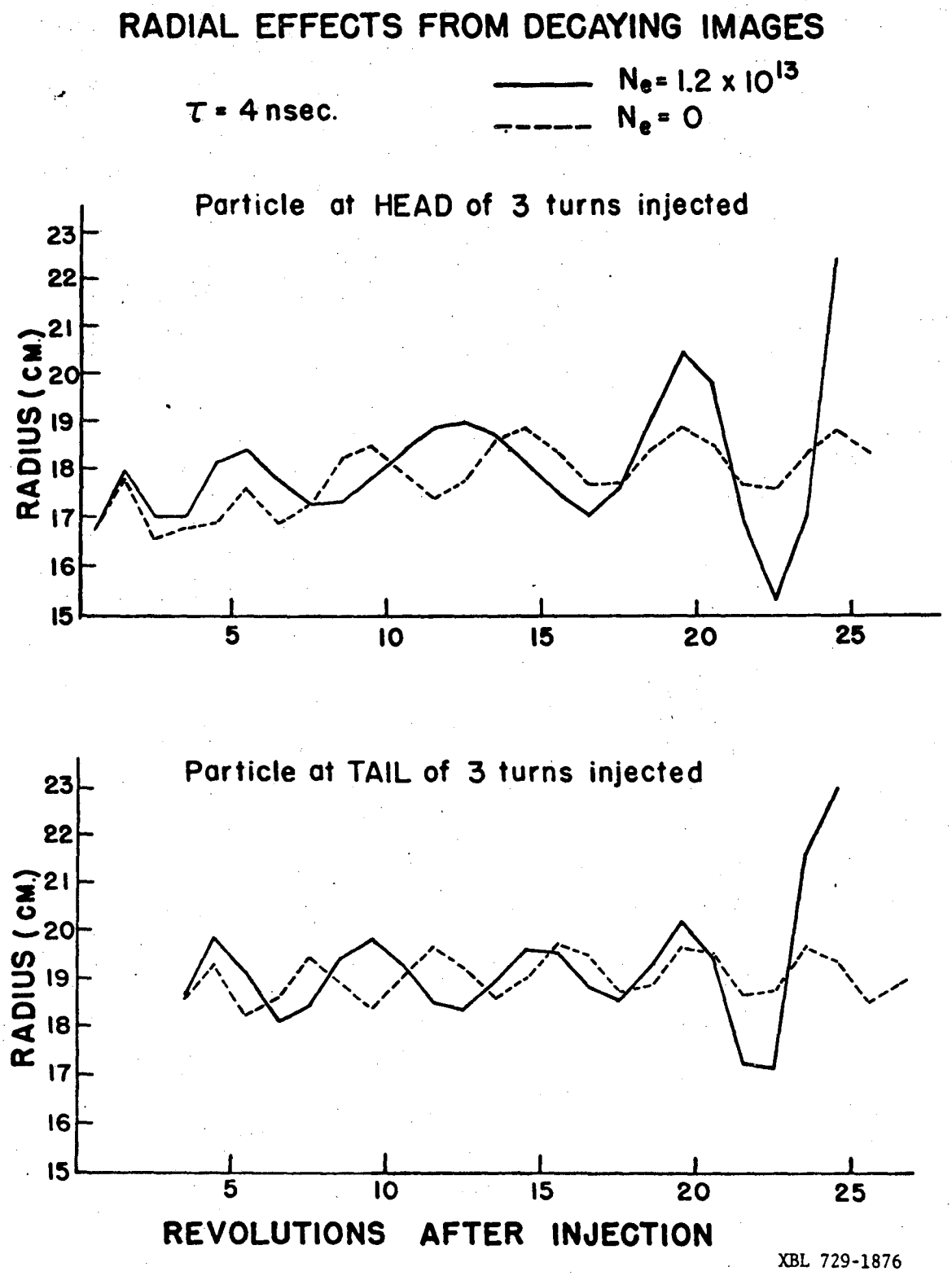

RADIAL EFFECTS FROM DECAYING IMAGES
τ = 4 nsec.
Ne = 1.2 x 10^13
Ne = 0
Particle at HEAD of 3 turns injected
RADIUS (CM.)
23
22
21
20
19
18
17
16
15
5
10
15
20
25
Particle at TAIL of 3 turns injected
RADIUS (CM.)
23
22
21
20
19
18
17
16
15
5
10
15
20
25
REVOLUTIONS AFTER INJECTION
XBL 729-1876

Figure 6

LEGAL NOTICE

*This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.*

*TECHNICAL INFORMATION DIVISION*
*LAWRENCE BERKELEY LABORATORY*
*UNIVERSITY OF CALIFORNIA*
*BERKELEY, CALIFORNIA 94720*