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Electrons were injected from a 3.3-MeV 300-A accelerator into a circular orbit in a pulsed magnetic field. Trapped ring currents of 150 A (4×10^{12} electrons) were magnetically compressed from 19 cm to 3.5 cm radii and simultaneously accelerated from 3.3 MeV to 18 MeV in energy. The rms dimensions of the cross section of the ring after compression were $a = 2.3 \pm 0.2$ mm radially and $b = 1.6 \pm 0.2$ mm axially. The lifetime of the ring was typically 5.5 msec, and was determined by the decay of the magnetic field after compression. This lifetime could be decreased by the addition of hydrogen gas, indicating the focusing effect of the trapped positive ions.

In contrast to our present-day "single-particle" accelerators, in which the self-fields of the circulating particles can be treated as a negligible or minor perturbation, the basic concept of "collective-effect" accelerators involves use of self-fields larger than fields applied externally. Use of self-fields of intense clusters of electrons to accelerate protons and ions, with advantages over other methods, has been speculated on in the last two decades.[1-4]

One form of collective-effect accelerator creates an intense electron cluster, containing trapped ions, that can be accelerated electrically (or magnetically). Existing linear accelerating columns have typically achieved 3 MeV/m for protons; if sufficiently high electric holding fields in the cluster can be maintained, this limit can be advanced by the factor (proton mass/electron mass). Using an electron ring as a possible vehicle is suggested in a sentence by Harvie,[1] and final stabilization of the ring by ion-focusing is suggested by Veksler et al.[5] The latter work is especially significant in reporting experimental efforts to form electron rings with suitable holding power.

Problems of forming very intense rings have been studied intensively at this Laboratory, possible instability problems uncovered, and a variety of solutions proposed.[6] Encouraged by earlier experimental results[5] and by calculations,[6] we undertook an experimental program to form rings, load them with ions, and study self-stabilization and acceleration. This note reports on an experiment on the first two of these four objectives, with a ring-forming "compressor" that was used at the 300-A, 3.3-MeV Astron facility.[7]

The equipment is described in Ref. 8. The ring-forming apparatus, or compressor, is illustrated in Fig. 1. Alumina was chosen for the vacuum envelope because it is structurally strong and has good vacuum characteristics, but mostly because eddy-current effects precluded use of large areas of metal. Pumping by two 500 ℓ/sec ion pumps achieved pressures between 10^{-8} and 10^{-7} torr.

A pulsed magnetic field was generated by three nested coil pairs, pulsed sequentially. The magnetic field cycle, represented in Fig. 2, shows a rise from 660 G at injection to 17 kG after compression, in a time of

500 μsec. Electrons are injected on an orbit radius R of 19 cm. They are simultaneously accelerated azimuthally by betatron action from 3.3 to 18 MeV, and compressed in radius to 3.5 cm. During this process, the minor diameter of the ring damps adiabatically from a few centimeters to a few millimeters.

The beam was introduced into the compressor through a snout made of soft iron (to cancel the field inside) and plated with a graduated coating of copper to minimize (at the moment of injection) field perturbations of the pulsed field outside. The center of this snout was at a radius of $R = 21.4$ cm. The closed orbit at injection was chosen to be 19.0 cm, corresponding to a revolution time of 4 nsec. A fast current pulse is applied to the inflector coils distributed around the compressor (see Fig. 1), which displaces the closed orbit from 19 cm to 21.4 cm and, then, during the 20-nsec pulse of beam, returns it rapidly to 19 cm. The system was designed to inject with a radial betatron tune, ν_R, near 2/3 and so to capture three or four turns.

Several diagnostic devices were installed to study the formation of the ring and its subsequent behavior. A pair of shielded Faraday cups (left-right pair) recorded the beam after about a single turn (330 deg). When the beam struck the chamber walls or any of the movable targets, x rays produced were monitored external to the vacuum chamber by means of a plastic scintillator viewed by a lead-shielded photomultiplier. A microwave horn and heterodyne receiver detected radiation from the ring at K-band frequencies (22 GHz). Typical oscilloscope traces from the microwave and x-ray detectors are shown in Figs. 3a and 3b.

A loop antenna detected the cyclotron frequency (≈ 270 MHz) and its harmonics. A variety of loops was used to pick up the magnetic field due to the ring itself, and provided an absolute calibration of the circulating current. Synchrotron light from the compressed ring emerged from a glass observation port and was recorded with an image-intensifier camera having an exposure time of 500 nsec.

A special beam-transport line was set up to transport the beam from the 3.3-MeV 300-A electron linear induction accelerator to the compressor, some 10 m away. As well as transport solenoids and pumping equipment the line included many steering elements and diagnostic tools, including a real-time visual display of emittance[9] that aided tuning of the beam for maximum brightness. A fast electromagnetic chopper was used to select a 20-nsec burst of electrons for delivery to the compressor, which was pulsed every 2.5 sec. The momentum spread in the beam was 0.5% (full width). The phase-area acceptance of the compressor was 0.02 π cm-rad, which was 40% of the incident beam emittance.

Satisfactory multiturn injection was readily achieved. Initially, serious troubles were encountered in trying to make the beam survive more than a few thousand turns ($\approx$ 10 μsec). This loss was eventually traced to beam resonances encountered where the field index, $n = \frac{-R}{B} \frac{dB}{dR}$, swept downward through the value 0.5 soon after injection. By modifying the current programs in the coils to postpone the crossing of betatron resonances close to n = 0.5, the difficulties near injection were cured. Crossing n = 0.25 early in the compression cycle also led to beam loss. This is illustrated in Fig. 3a, where the drop in microwave signal and simultaneous burst of x rays indicate catastrophic beam loss at 40 μsec. Again, by further adjusting the current program in the coils it was possible to postpone the crossing of this resonance until late in the cycle, when it could be negotiated without loss. These resonance difficulties could all be understood in terms of single-particle phenomena and were not due to collective effects.

When a suitable magnetic field cycle had been established, currents of 150 A (at injection) were trapped, corresponding to about 4×10^{12} electrons. The ring was compressed without significant beam loss to a final major radius of 3.5 cm, where it was observed to be centered in the compressor within 1 mm, both axially and radially. After compression, as the magnetic field decayed, the electrons were decelerated and the ring expanded slowly, eventually being lost upon gradual encounter with the radial integral resonance. The lifetime of the ring up to this point was typically 5 msec (see Fig. 3b), but could be increased to 8 msec by a current program that extended the peak current in Coil 3 for an additional 3 msec before its usual exponential decay.

The minor cross section of the ring was approximately elliptical. Several determinations were made of radial dimension a and axial dimension b, by use of both radial and axial probes and--most directly--by photographs of the synchrotron light (see Fig. 3c). All data are well fitted by a Gaussian density in four-dimensional phase space (r, r', z, z'). This leads to a density profile for the cross section of the beam,

$$\frac{d^2N}{dr\,dz} = \frac{N_e}{2\pi\,ab} \exp\left[-(r^2/a^2 + z^2/b^2)/2\right].$$

The values deduced are $a = 2.3 \pm 0.2$ mm, and $b = 1.6 \pm 0.2$ mm. The peak electric field relevant for holding ions is 10 MV/m, when this Gaussian form factor is used, and with $N_e = 4 \times 10^{12}$ and $R = 3.5$ cm.

Metered quantities of hydrogen gas were admitted to study its effect on the ring. Above a threshold value (about 10^{-5} torr H_2 gas) the behavior of the long-time (5 msec) containment changed drastically and the electrons were lost much earlier in the magnetic field decay cycle. If H_2 gas were pulsed into the chamber, after the compression cycle, the transition occurred at the same equivalent gas pressure as with uniform filling. Corresponding synchrotron-light pictures showed radial blowup of the beam.

The degree of neutralization cannot be greater than unity, and in the absence of ions ν_R is 0.84; therefore from the assumption that the observed radial beam blowup occurred at $\nu_R = 1.00$, we can conclude[10] that $N_e/[\pi a(a+b)] \geqslant 1.1 \times 10^{13}\ \mathrm{cm}^{-2}$. This is in good agreement with the value calculated from the N_e, a, and b obtained by independent measurements, which yields $N_e/[\pi a(a+b)] = 1.4 \times 10^{13}\ \mathrm{cm}^{-2}$. The blowup was dependent on ring current, and at low current the 5-msec containment persists to much higher pressures. This result supports the above model in which blowup requires an ion density sufficient to give the $\Delta\nu$ shift of 0.16.

Evidence of high-current effects was observed at injection when the entering current was greater than about 10 A. The time constant for decay of magnetic images in the inflector plates was very short, and beam circulating only a few nsec after the onset of current exhibited a reduced coherent radial betatron frequency as a result of electrostatic images. This, and perhaps other effects such as coherent bunching, interfered with an orderly beam stacking process, and we observed reduced and variable efficiency of injection at higher currents. Satisfactory and stable injection at the highest injected current was achieved by eliminating the inflector pulse; the mechanism for this self-trapping is as yet little understood.

Radiation at the cyclotron frequency, observed with the loop antenna, appeared with an injected beam current of about 1 A, but it was small, with a 10-μsec decay constant. At higher beam currents it increased in amplitude and duration and had a more complicated structure--for example, one large burst of rf in the first few μsec followed by several later bursts occurring out to 100 μsec. The later bursts caused some slight beam loss, as indicated by small, correlated x-ray bursts. Higher harmonics of the cyclotron frequency were present, and the microwave receiver indicated that they extend out to the 100th harmonic. We suspect that the cyclotron radiation is indicative of a coherent radiative (negative mass) instability.[11] This instability is to be expected above ≈8 A because of the small momentum spread, but it did not appear to limit the ring current in these experiments.

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FOOTNOTES AND REFERENCES

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

[†] On leave from University of Milan, Italy.

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11. See, for example, Ref. 6, p. 442.

FIGURE CAPTIONS

Fig. 1. Cross-section view of the compressor.

Fig. 2. 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 for a typical compression cycle.

Fig. 3 a, b. Heterodyne microwave receiver (upper trace), and x-ray (lower trace) signals, showing (a) containment with fast dump at 40 μsec; (b) 5.5-msec containment with resonance loss as the magnetic field decays.

c. Synchrotron light picture taken with an image converter camera showing the cross section of the ring (500 nsec exposure time). The black dot and line are caused by the grid of the camera.

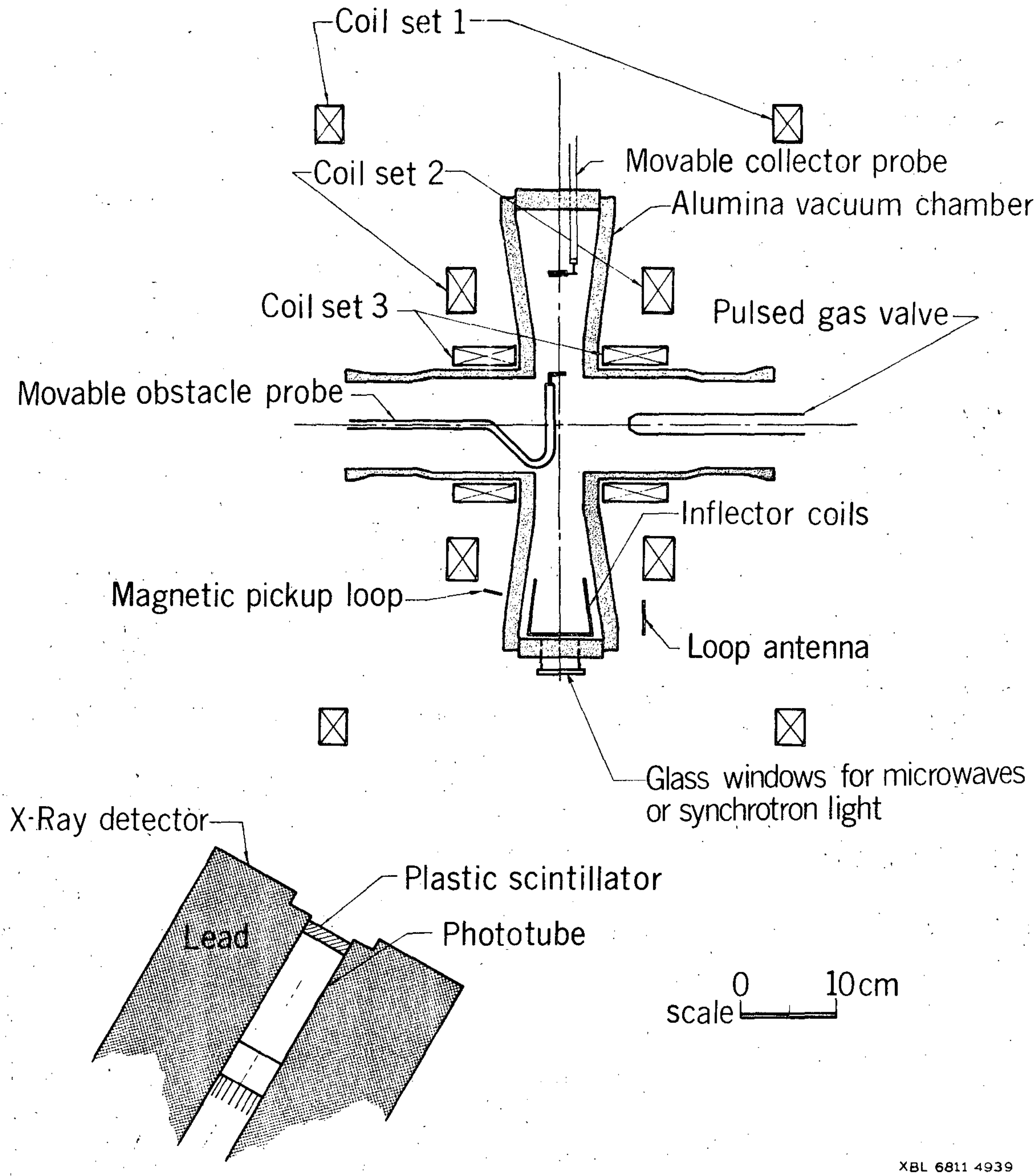
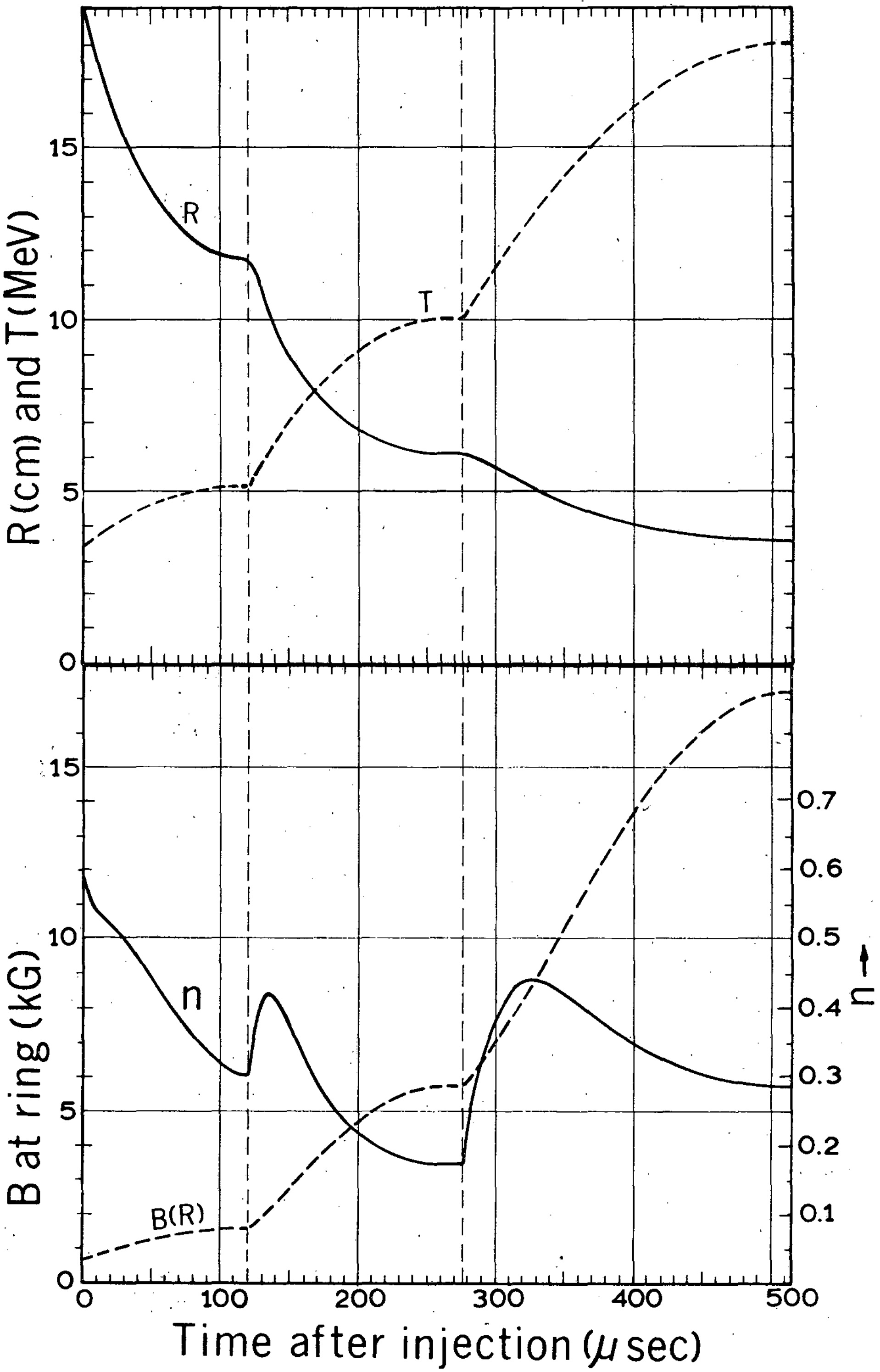
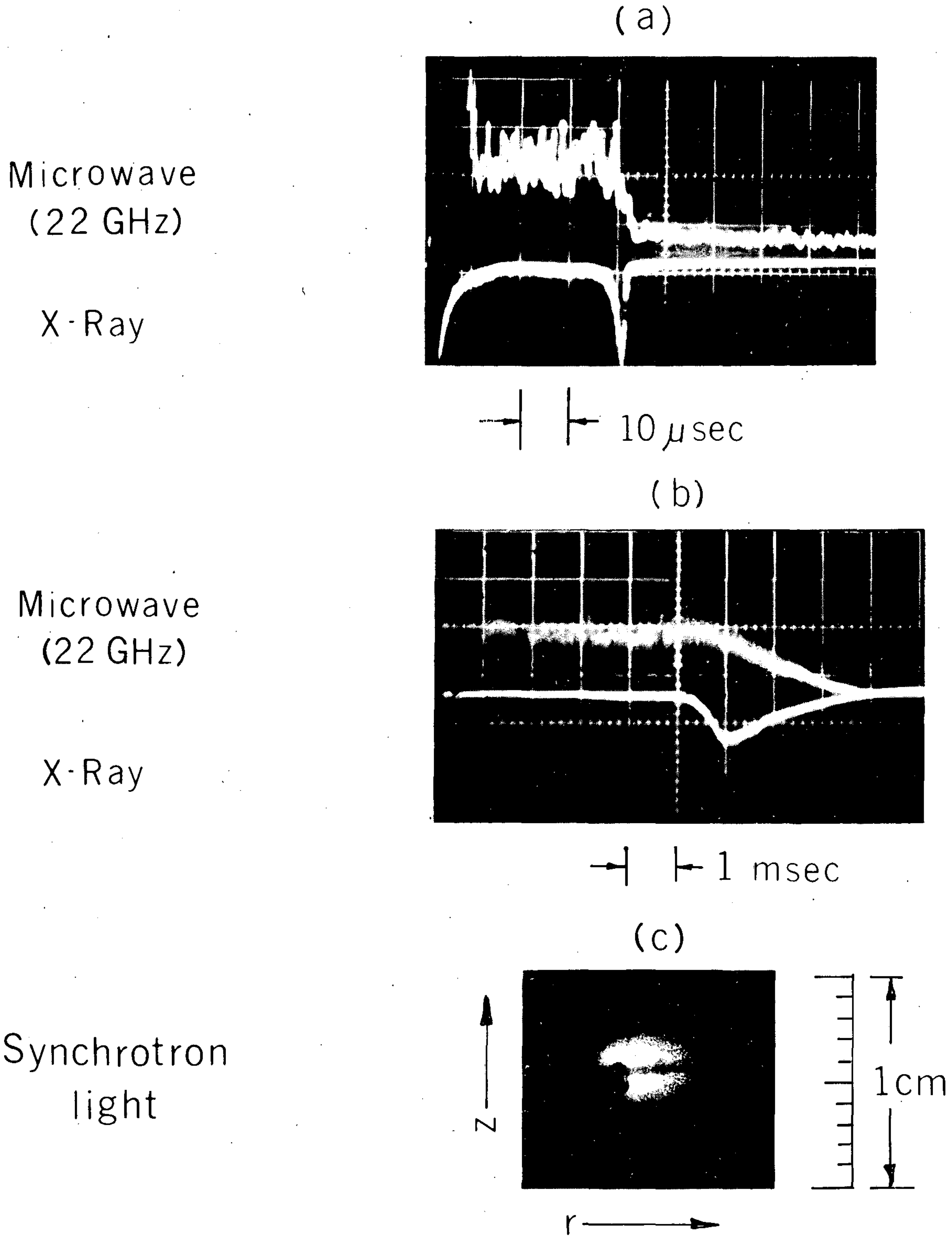

Coil set 1
Movable collector probe
Coil set 2
Alumina vacuum chamber
Coil set 3
Pulsed gas valve
Movable obstacle probe
Inflector coils
Magnetic pickup loop
Loop antenna
Glass windows for microwaves or synchrotron light
X-Ray detector
Plastic scintillator
Lead
Phototube
scale 0 10cm
XBL 6811 4939

Fig. 1



XBL 6812-6462

Fig. 2



XBB 691-8

Fig. 3

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