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RING IN A RIPPLED MAGNETIC FIELD

G. Bekefi and R.E. Shefer

Plasma Fusion Center and  
Research Laboratory of Electronics  
Massachusetts Institute of Technology  
Cambridge, MA. 02139

W.W. Destler

Department of Electrical Engineering  
University of Maryland  
College Park, Maryland 20742

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G. Bekefi and R.E. Shefer

Department of Physics and Research Laboratory of Electronics  
Massachusetts Institute of Technology  
Cambridge, Massachusetts 02139

and

W.W. Destler

Department of Electrical Engineering  
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ABSTRACT

We report measurements of millimeter wave emission from a rotating relativistic electron ring (2MV, 1kA) in which electrons move in quasi-circular orbits under the combined action of a uniform axial magnetic field and an azimuthally periodic wiggler magnetic field. We observe radiation at frequencies between 91 and 170GHz, at power levels in excess of 200kW.

There have been many theoretical<sup>1</sup> and experimental<sup>2</sup> studies of free electron lasers (FEL's) in linear geometry with spatially periodic transverse<sup>1,2</sup> or longitudinal<sup>3-6</sup> magnetic wiggler fields. Such configurations have gain limitations imposed by the finite length of the interaction region. Recently, a novel circular version of the free electron laser has been explored both theoretically<sup>7,8,9</sup> and experimentally<sup>10</sup> in which a rotating, relativistic electron stream is subjected to an azimuthally periodic wiggler field. The potential advantages of circular FEL's as compared with the conventional linear form are several. First, the beam circulates continuously through the wiggler field resulting in a long effective interaction region. Secondly, because of the recirculation of the growing electromagnetic wave, the device provides its own internal feedback, and is in essence an oscillator rather than an amplifier, as is the case in linear FEL's. Thus, external mirrors are not required. And thirdly, because the electron motion is primarily circular the system<sup>10</sup> tends to be very compact.

There are several ways of producing a rotating relativistic electron stream. One is to subject the electrons to orthogonal DC electric and magnetic fields as is typical in magnetron-like devices. Here, the electrons undergo a  $\vec{v}(r) = \vec{E}_0(r) \times \vec{B}_0 / |B_0|^2$  drift in a radial electric field  $\hat{r}E_0(r)$  and a uniform axial magnetic field  $\hat{z}B_0$ . Addition of an azimuthally periodic magnetic field  $\vec{B}_w(\theta, r)$  then results in the sought-after circular FEL. This scheme has been explored previously,<sup>7,8,10</sup> and though the experimental results<sup>10</sup> are encouraging, it may have a potential drawback in that the electron velocity  $v(r)$  varies with radial distance  $r$ . This velocity shear may lead to some degradation of the spectral purity of the emitted electromagnetic radiation, and a reduction in gain and efficiency of the device.

In this letter we describe initial experiments on a circular FEL which uses a monoenergetic rotating electron ring and thereby circumvents the problem

of velocity shear mentioned above. Moreover, in the device discussed below one has better control over the circulating current than in a magnetron-like scheme where the anode-cathode gap is part<sup>10</sup> of the magnetic wiggler interaction region.

A high quality (energy spread  $\leq 1\%$ ) rotating electron ring is produced by injecting a hollow nonrotating beam into a narrow magnetic cusp.<sup>11,12</sup> The hollow beam is generated by field emission from an annular graphite cathode energized by a pulsed, high voltage, high current accelerator (2MV, 20kA, 30ns). The resulting rotating electron ring is guided downstream from the cusp by a uniform axial magnetic field of  $\sim 1.4$ kG. The ring is 6cm in radius, has a duration of  $\sim 5$ ns, and carries an axial current of  $\sim 1.5$ kA. The electron rotation velocity  $v_\theta \approx 0.96c$ , and the electron axial velocity  $v_z \approx 0.2c$ . Thus, in the absence of the wiggler magnetic field, the electron orbits form fairly tight helices.

A schematic of the device is illustrated in Fig. 1. It comprises two smooth coaxial stainless steel cylinders of radii  $r_o = 6.58$  and  $r_i = 5.25$ cm, respectively. The electron ring propagates within the gap formed by the two cylinders. Superimposed on the axial guiding magnetic field (produced by a solenoid) is an azimuthally periodic magnetic wiggler field  $\vec{B}_w$ . Subject to the requirement that  $\nabla \cdot \vec{B}_w = \nabla \times \vec{B}_w = 0$ , the field in the vacuum gap is calculated to be,

$$\begin{aligned} \vec{B}_w = \hat{r} \frac{B_{0w}}{2} \cos(N\theta) & \left[ \left( \frac{r}{r_o} \right)^{N-1} + \left( \frac{r_i}{r} \right)^{N+1} \right] \left[ \frac{r_o}{r_i} \right]^{(N^2-1)/2N} \\ & - \hat{\theta} \frac{B_{0w}}{2} \sin(N\theta) \left[ \left( \frac{r}{r_o} \right)^{N-1} - \left( \frac{r_i}{r} \right)^{N+1} \right] \left[ \frac{r_o}{r_i} \right]^{(N^2-1)/2N} \end{aligned} \quad (1)$$

where  $\hat{r}$  and  $\hat{\theta}$  are unit vectors in the radial and azimuthal directions, respectively.  $N = \pi(r_o + r_i)/\ell$  is the number of spatial periods and  $\ell$  is the linear

periodicity defined midway in the gap.  $B_{0w}$  is the amplitude of the radial component of the field at a distance  $r=R\equiv(r_0^{N-1} r_i^{N+1})^{1/(2N)}$  where the azimuthal field component vanishes (which is roughly midway between the two cylinders). We see that near the center of the gap the wiggler field is primarily radial and is thus transverse to the electron flow velocity, as is the case in conventional linear free electron lasers. The undulatory force  $-e\vec{v}\times\vec{B}_w$  is along the  $\pm z$  axis. A single particle computer simulation program has been generated for the purpose of studying the electron motion in the combined axial and wiggler magnetic fields. Figure 2a shows the projection of the electron trajectory in the absence of the wiggler, and Fig. 2b shows the trajectory in the presence of a wiggler field of 1.3kG strength (see below). We see that the trajectory is not perturbed too strongly: it remains quasi-helical, the radial displacements are small, and the electron does not strike the cylinder walls.

In our device, the wiggler magnetic field is produced by an assembly of 384 samarium-cobalt bar magnets,<sup>10,13</sup> each of 0.40cm  $\times$  0.40cm cross section and 4.8cm long. Each magnet has a residual induction of  $\sim 9.0$ kG. The magnets are positioned behind the grounded stainless steel cylinders and held in place in grooved aluminum holders. Therefore, the electrons see only smooth metallic boundaries.

To achieve a given periodicity  $\lambda$ , the dipole axes of the magnets are arranged as illustrated in Fig. 3. Because the magnets are discrete, harmonics of the fundamental period  $\cos(N\theta)$  are present. However, use of four or eight magnets per period as shown in the second and third diagrams greatly reduces the harmonic content:<sup>13</sup> all even harmonics are absent and the third harmonic also vanishes. As a result, the magnetic field closely resembles that given by Eq. (1). The lower part of Fig. 3 shows a Hall-probe measurement of the radial component of the wiggler field at the center of the vacuum gap for the case of the longest period  $\lambda=6.28$ cm. The measured wiggler field amplitude,

$B_{0w}$  of Eq. (1), equals 1.31kG. The axial length of the wiggler is 20cm. This length is achieved by stacking end-to-end four rows of bar magnets. At the present time, all of the radiation measurements described below were made with a wiggler having 6 spatial periods (N) and a periodicity  $\lambda=6.28$ cm. Shorter periodicities are expected to give radiation at frequencies which lie above the range of our detection equipment.

The electromagnetic radiation generated in the interaction region is allowed to leak out from the gap formed by the two coaxial metal cylinders. It is then received by means of a small horn antenna, and is guided through various waveguide cut-off filters to a crystal detector where it is rectified and displayed on a fast oscilloscope. Figure 4c illustrates the time history of a typical radiation burst as measured in the 91-170GHz frequency range (T-band). The accompanying beam voltage and axial beam current are shown in Figs. 4a and 4b, respectively. When the magnetic wiggler field is turned off (by removing the samarium-cobalt magnets from their grooved aluminum cylinders) the emitted power falls to a level too small to be distinguished from background noise. This is illustrated in Fig. 4d. We thus conclude that the observed radiation is produced only in the presence of the wiggler field.

We point out that we have as yet not addressed the problem how best to couple out the available radiation. Our horn antenna shown in Fig. 1 merely probes the radiation field and receives only a small fraction of the available power. Using the crystal calibration of our detector, and assuming that at the high frequencies in question quasi-optical arguments are applicable, (wavelength is small compared with relevant dimensions), the total power radiated from the device at frequencies between 91 and 170GHz is calculated to be no smaller than 200kW. We also note that although we have as yet not determined the radiation spectrum, the observed frequencies are in the range expected from the familiar free electron laser formula<sup>1,2</sup>

$$\omega \approx (1 + \beta_\theta) \beta_\theta \gamma^2 k_0 / K \quad (2)$$

Here  $\beta_\theta = v_\theta/c$ ,  $\gamma = 1 + eV/m_0c^2$  is the total relativistic energy factor with  $V$  as the beam voltage;  $k_0 = 2\pi/\ell$  is the wiggler wave number with  $\ell$  as its period.

$\Omega_W = eB_{0W}/m_0$  is the nonrelativistic cyclotron frequency in the wiggler field of amplitude  $B_{0W}$ , and  $K = 1 + (\Omega_W/k_0c)^2$ . Inserting experimental parameters into Eq. (2) yields a radiation frequency  $\omega/2\pi \approx 143\text{GHz}$ .

In addition to the high frequency T-band (91-170GHz) range of frequencies, we also explored emission at lower frequencies including Ka-band (21-40 GHz), V-band (40-75GHz), E-band (48-90GHz), R-band (59-110GHz) and N-band (73-140GHz). In these lower frequency bands we find that some emission occurs even in the absence of the wiggler magnetic field. The cause of this radiation is the negative mass instability which has been fully documented in earlier studies.<sup>14-17</sup> It is noteworthy that as a result of the proximity of the two grounded, concentric metal cylinders the level of this radiation is greatly reduced compared to that observed in earlier work<sup>14,15</sup> on the negative mass instability, where the conducting boundaries were not in such close proximity to the beam. This points to the fact that considerable stabilization is achieved, as expected,<sup>18</sup> by use of the closely spaced (1.3cm gap width) system of cylinders. When the azimuthal wiggler magnetic field is introduced (by inserting the samarium-cobalt magnets) the level of the low frequency emission remains either unchanged or in some cases, it is in fact diminished. This shows that the presence of the wiggler field does not enhance the negative mass instability, which has been a worrisome possibility.

In conclusion, we have observed radiation in the millimeter wavelength range (1.8-3.3mm) from a novel type of circular FEL which uses a high quality, high current relativistic electron ring rotating in an azimuthally periodic wiggler magnetic field. The emitted power attributed to the FEL instability

is at least 200kW. Detailed spectral measurement using a calibrated microwave grating spectrometer<sup>10,19</sup> will be carried out in the near future. In addition, by rearranging the magnets as illustrated in Fig. 3, we will be able to shorten the wiggler periodicity  $\lambda$  and thereby study emission at wavelengths ranging from 0.05 to 1.0mm.

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FIGURE CAPTIONS

- Fig. 1. General experimental configuration.
- Fig. 2. Calculated particle orbits in the  $r-\theta$  and  $r-z$  planes for an electron injected with  $v_z=0.20c$ ,  $v_\theta=0.96c$  into the interaction space with (a)  $B_{0z}=1.4\text{kG}$ ,  $B_{0w}=0$ , and (b)  $B_{0z}=1.4\text{kG}$ ,  $B_{0w}=1.3\text{kG}$ .
- Fig. 3. Arrangement of bar magnets (top); Hall probe measurement of the radial magnetic field at a radial position  $r=5.92\text{cm}$ , as a function of azimuthal angle (bottom).
- Fig. 4. Oscilloscope waveforms of (a) diode voltage, (b) axial current collected by a  $2.24\text{mm}^2$  collector located in the center of the interaction region, (c) microwave signal in T-band (91-170GHz) with wiggler magnets, and (d) microwave signal without wiggler magnets.

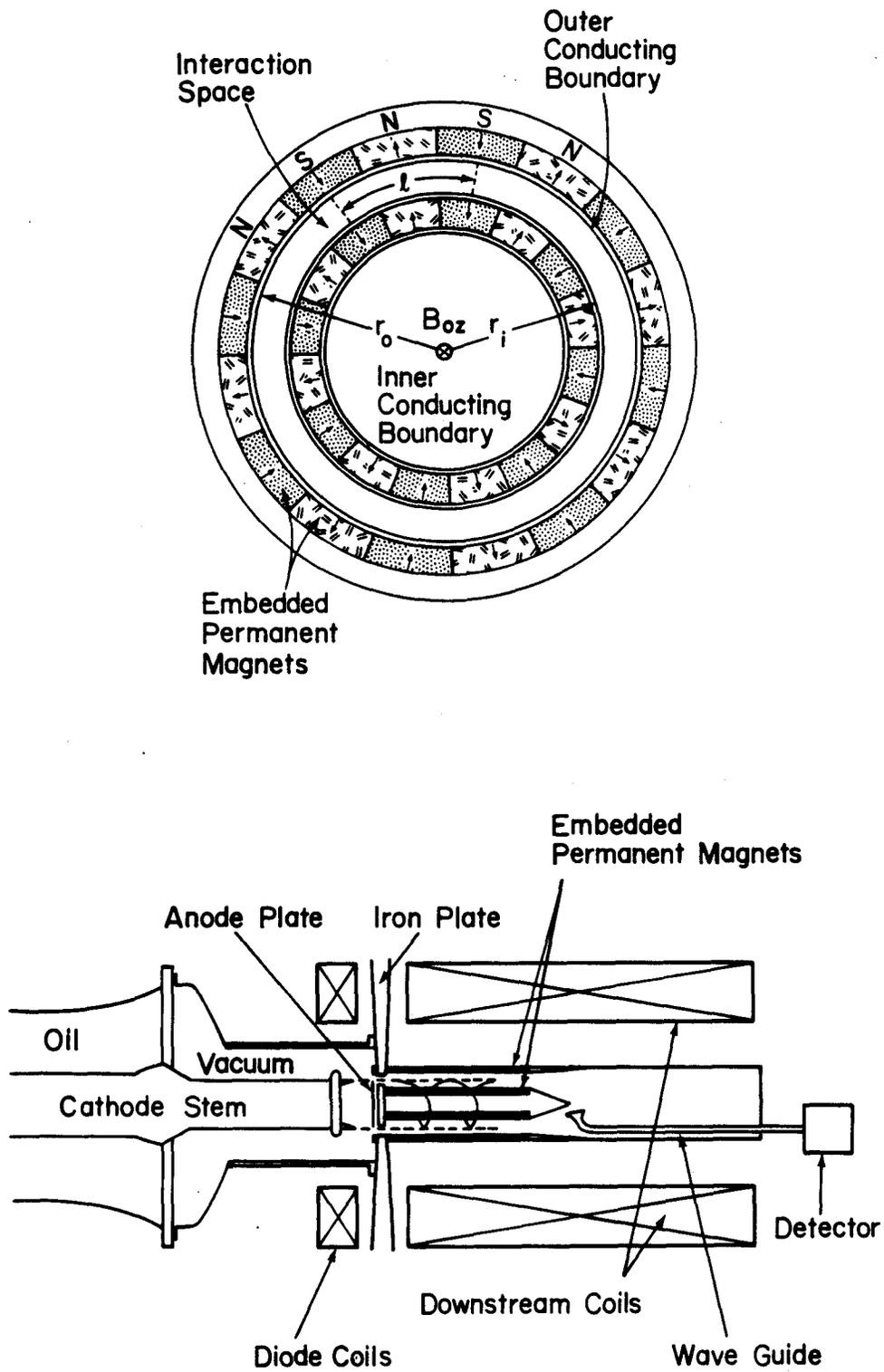
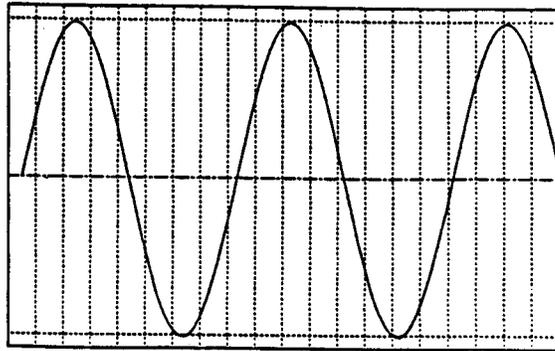
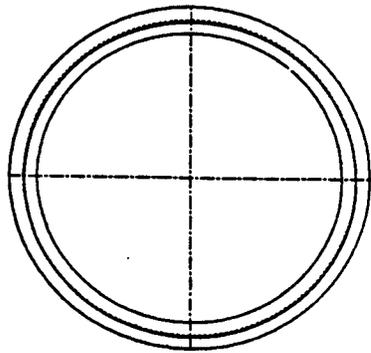
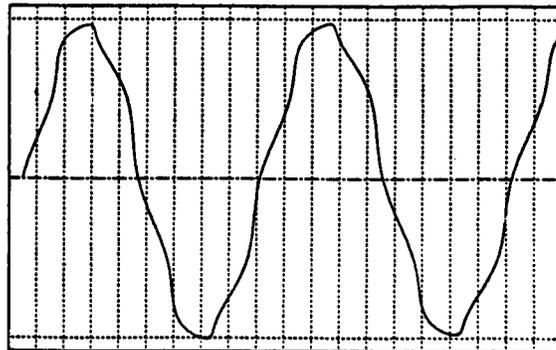
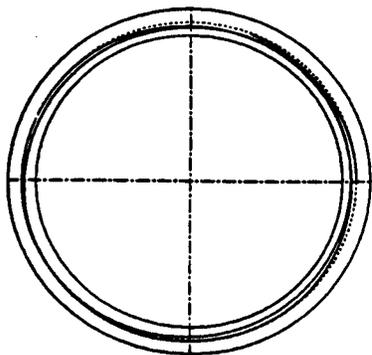


Fig. 1  
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(a)



(b)

Fig. 2  
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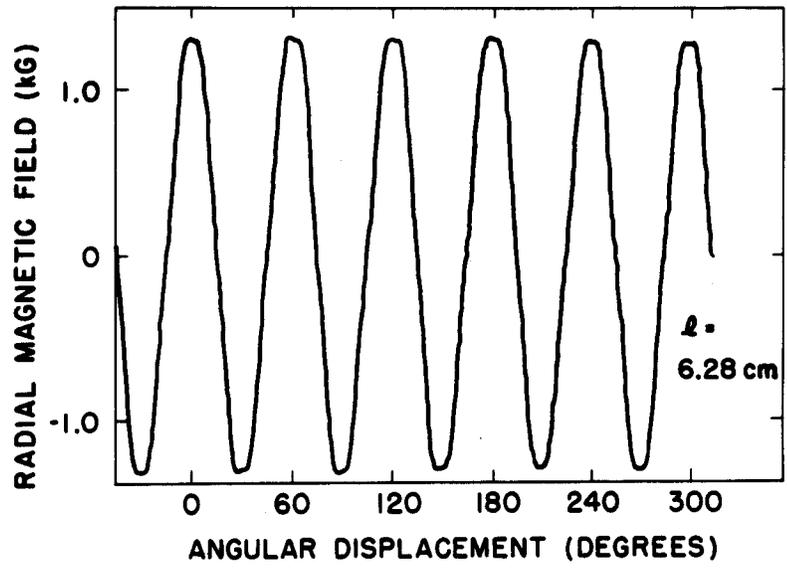
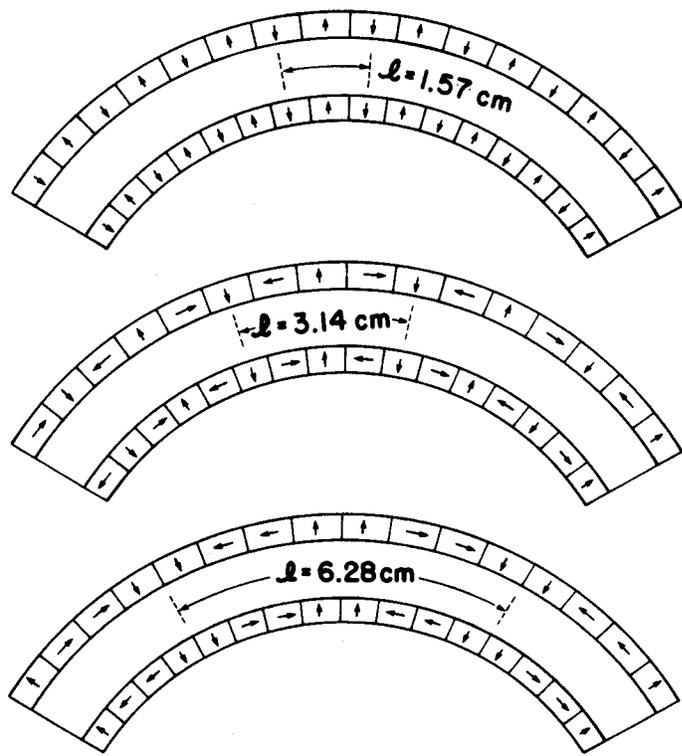


Fig. 3  
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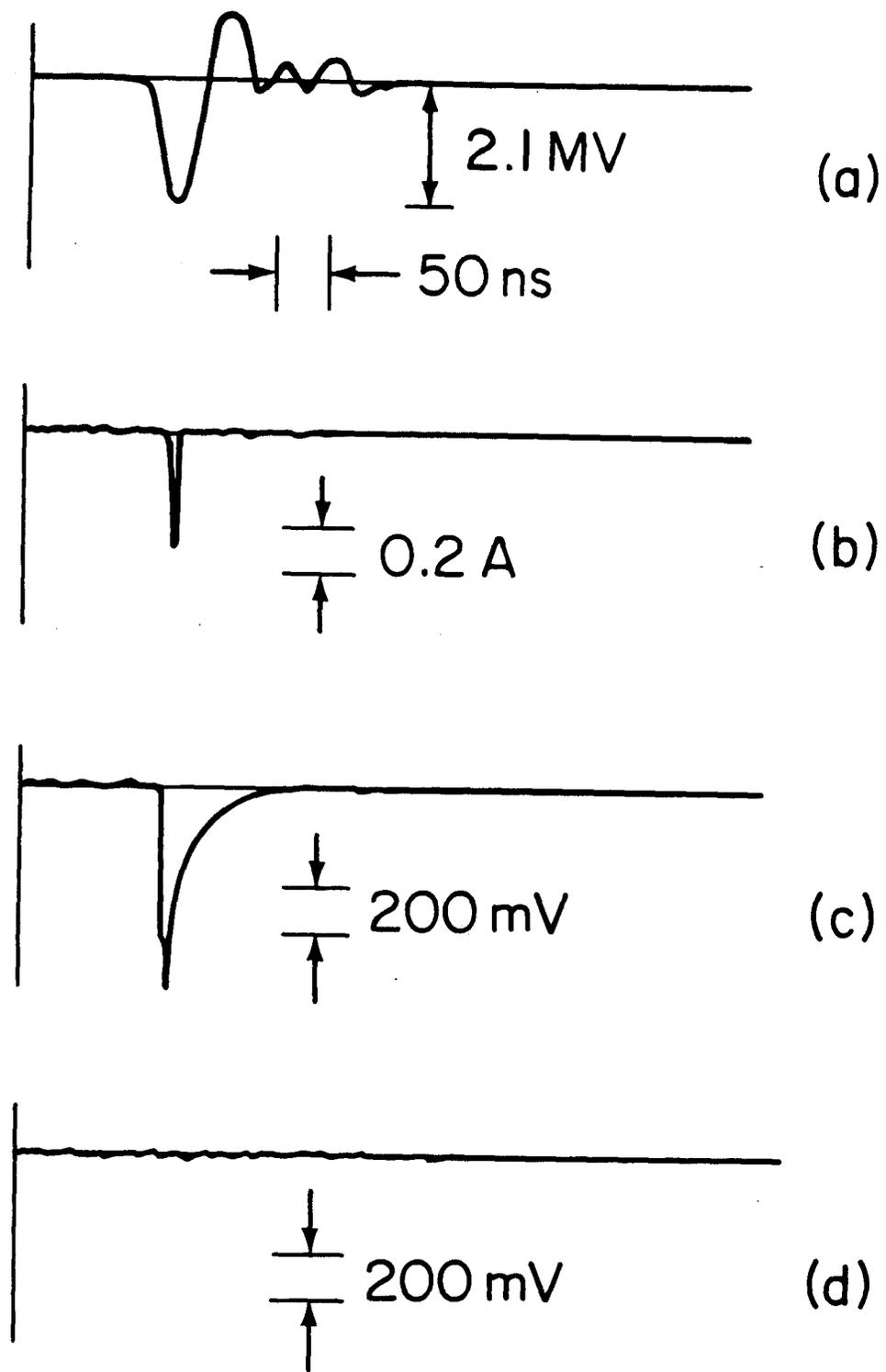


Fig. 4  
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