[13]D. A. Leonard, Appl. Phys. Lett. 7, 4 (1965).
[14]E. T. Gerry, Appl. Phys. Lett. 7, 6 (1965); A. W. Ali, A. C. Kolb, and A. D. Anderson, Appl. Opt. 6, 2115 (1967), Eqs. (18) and (19).
[15]C. B. Opal, W. K. Peterson, and E. C. Beaty, J. Chem. Phys. 55, 4100 (1971).

Automodulation of an Intense Relativistic Electron Beam

M. Friedman
Naval Research Laboratory, Washington, D.C. 20375
(Received 23 October 1973)

A novel method of automodulating an intense relativistic electron beam has been demonstrated. The modulation is accomplished by passing the electron beam through a series of cavities that are inserted into a conventional drift tube. Experimental results indicate that the current is modulated at a frequency of 500 MHz at a relative modulation amplitude exceeding 80%.

Modulated electron beams have been the subject of many theoretical and experimental investigations. Their utility has been suggested or demonstrated for collective ion acceleration,[1,2] the production of hot plasmas,[3,4] and the generation of electromagnetic radiation.[5,6] Techniques for modulating low-power electron beams are relatively straightforward and are discussed in the literature.[7,8] In these techniques, external oscillating electric or magnetic fields are used to modulate the electron beam. The power in these oscillating fields must be of the same order of magnitude as the power in the electron beam. Thus, it is obvious that these techniques will be difficult to apply to a high-power relativistic electron beam.

A simple passive technique to modulate an intense relativistic electron beam of power greater than 10^{10} W is reported in this Letter. Beam-current modulation at a frequency of 500 MHz was achieved. The relative amplitude of the modulation apparently exceeded 80%. The experimental arrangement (Fig. 1) consisted of a foilless diode[9] emitting an annular electron beam with a current of ~15 kA and a voltage of ~500 kV for 50 nsec duration. The beam radius (at the diode) was 1.9 cm and its thickness was 0.2 cm. An 8-kG magnetic field confined the electron beam. The drift chamber consisted of a 1.2-m-long, 4.7-cm-i.d. stainless-steel tube. Four gaps feeding four coaxial cavities were inserted in the drift tube at various axial positions, as shown in Fig. 1. The length of each cavity was 15 cm and its outer diameter was 18 cm. The base pressure in the drift chamber and cavities was $\leqslant 10^{-5}$ Torr of air.

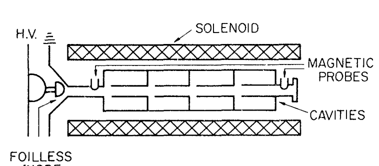

FIG. 1. Schematic of the experiment.

Several diagnostics were used to analyze the electron beam. Two magnetic probes, which measured the azimuthal component of the self magnetic field of the beam, were used to determine the rate of change of the beam current. These probes were located on either end of the multiple cavity structure. In addition, a Faraday cup was used to monitor beam current. Aluminum foils of different thickness were placed in front of the Faraday cup in order to estimate the mean electron kinetic energy from the attenuation of the measured beam current. Stray inductance in the Faraday cup (of the order of 10^{-10} H) limited the frequency response of the probe to ~100 MHz. In order to observe the current modulation directly, a small fast Faraday cup was used in which only a small portion of the beam was detected. The frequency response of this probe was greater than 1 GHz.

Figure 2 shows the beam voltage and Faraday-cup and fast-Faraday-cup signals. From the fast Faraday-cup signal one can see the current modulation of the electron beam. This probe samples parts of the beam passing through four holes located at different azimuthal and radial positions. The fast Faraday cup was connected through an ~20-m-long RGU-58 cable to a traveling-wave

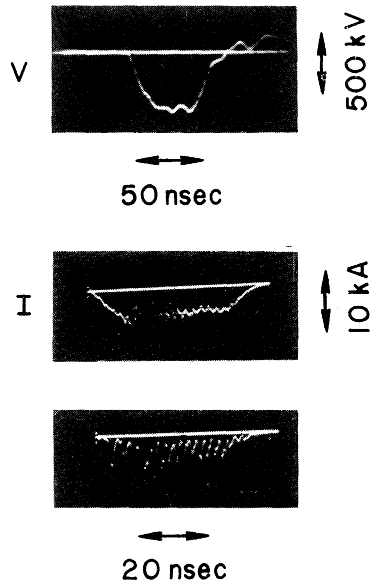

FIG. 2. Typical oscillographs. From top to bottom, beam voltage, Faraday-cup signal, and fast—Faraday-cup signal. Note that the frequency response of the Faraday cup is ~100 MHz. Any current signal with frequency components greater than 100 MHz was integrated by the probe and effectively eliminated from the oscillograph trace. Hence, the signal from this Faraday cup indicated in "dc" component of the current.

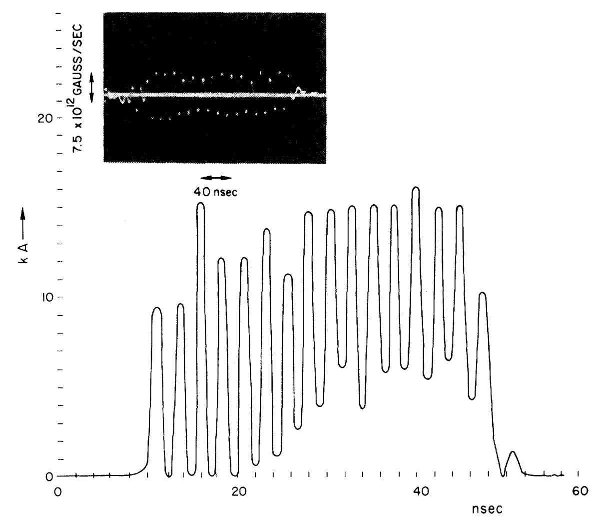

FIG. 3. Net electron beam current derived from a magnetic probe signal. The magnetic probe was located beyond the cavity structure. (Insert, oscillograph of the magnetic probe signal.)

oscilloscope. This cable attenuated the 500-MHz component of the signal by a factor of ~3.[10] Taking this into account, it indicates that the relative amplitude of the current modulation exceeded 80%. By placing aluminum absorbers in front of the Faraday cup and measuring the transmitted current the mean particle energy could be estimated.[11,12] It was found that the particle energy in the bunched beam is ~1.0 MeV although the diode voltage was only 500 kV. This result is similar to the results reported earlier in an auto-acceleration experiment with intense relativistic electron beams, in which a single large cavity was used.[12]

The magnetic probe measuring the rate of change of the azimuthal component of the magnetic field beyond the cavity structure shows the same type of modulation. Figure 3 shows the net electron beam current derived from the magnetic probe signal (a trace of dB_θ/dt is shown in an inset in Fig. 3). As a comparison, Fig. 4 shows the current measured by a magnetic probe located just in front of the cavity structure where no modulation is observed.

The experimental conclusion from all of the above is that the cavity structure appears to cause an automodulation of the electron beam. Although the experiment (Fig. 1) superficially resembles a klystron amplifier, the mechanism of beam bunching is quite different. A simple picture views each of the cavities as a parallel LC resonance circuit.[13] This resonant circuit is shock energized by a voltage impulse

$$V_1 = L\,dI/dt, \tag{1}$$

where L is the inductance associated with each cavity and dI/dt is the rate of change of current flowing at the cavity walls (i.e., the return current). Using the dimensions of the cavities and the measured dI/dt (from Fig. 4) one finds that $V_1 \approx 120$ kV. (A more detailed discussion of this mechanism can be found in an earlier work.[12]) Each cavity thus will oscillate at a characteristic frequency of 500 MHz with an amplitude of the order of 120 kV. In any 2-nsec interval each cavity will first decelerate the beam and absorb energy. Subsequently, in the second nanosecond

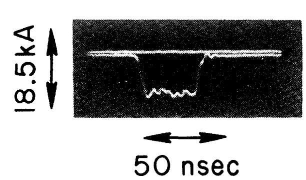

FIG. 4. Electron beam current measured just in front of the cavity structure.

the cavity will give energy to the beam and accelerate the electrons. A similar picture can be obtained by looking at the force $\vec{F}$ exerted on an electron travelling in the gap of the cavity,

$$\vec{F} = \vec{F}_s + R(\vec{E}_c + \vec{V} \times \vec{B}_c), \tag{2}$$

where $\vec{F}_s$ is the self-force generated by the electron beam, $\vec{E}_c$ and $\vec{B}_c$ are the respective electric and magnetic fields stored in the cavity, and $\vec{V}$ is the velocity of the electron. To the first-order approximation $\vec{V} = (0, 0, V_z)$ and $\vec{F} = (F_{rs}, F_{\theta s}, 0)$; in that case

$$d\epsilon/dt = e\vec{E}_c \cdot \vec{V}, \tag{3}$$

where ϵ is the energy of the electron. $\vec{E}_c$ is a periodic function of time (not necessarily sinusoidal). Since the time an electron spends in the gap is short compared to the period of the oscillation of the electric field, the electron will gain or lose energy depending on the sign of the scalar product $\vec{E} \cdot \vec{V}$. Hence, some electrons will gain energy from the cavity during the first half-period while the rest will give energy to the cavity during the second half-period. Since the electrons in the beam are relativistic, a change in their energy will only slightly affect their velocity. This is the reason that all the cavities are energized in the right phase so that the same electrons will always lose energy while the rest will always gain. The total effect will be to establish relativistic electron bunches embedded in a background of slow electrons. The current modulation is presumably observed because the slower electrons are lost from the beam. The frequency of these bunches will be 500 MHz and the mean particle energy within each bunch is ~1 MeV. The total number of high-energy electrons, in the beam, is half the number that was produced by the diode; however, their kinetic energy is twice as high. The total energy in the beam stays, approximately, the same.

This simple automodulation of an intense relativistic electron beam may open new research possibilities for beams in plasma heating, collective acceleration of ions, and intense rf emissions.

Discussions with Dr. L. S. Levine are gratefully acknowledged.

[1]A. I. Alikhan'yan and S. A. Kheiefts, Usp. Fiz. Nauk 101, 217 (1970) [Sov. Phys. Usp. 13, 353 (1970)].

[2]W. B. Lewis, in Proceedings of the Symposium on Electron Ring Accelerators, Lawrence Radiation Laboratory, Berkeley, California, 1968, UCRL Report No. 18103, 1968 (unpublished).

[3]E. A. Pashitskii, Zh. Tekh. Fiz. 39 209 (1969) [Sov. Phys. Tech. Phys. 14, 149 (1969)].

[4]A. A. Mondelli and P. L. Auer, Cornell University Report No. LPS 101, 1972 (unpublished).

[5]M. Danos, S. Geschwind, H. Lashinsky, and A. Van Trier, Phys. Rev. 92, 828 (1953).

[6]M. D. Sizkis and P. D. Coleman, J. Appl. Phys. 28, 944 (1957).

[7]See, for example, N. G. Kovalskii, B. I. Khripunov, and S. A. Chuvatin, Zh. Tekh. Fiz. 41, 308 (1971) [Sov. Phys. Tech. Phys. 16, 232 (1971)].

[8]See, for example, G. M. Haas and M. Eisner, Phys. Fluids 14, 606 (1971).

[9]M. Friedman and M. Ury, Rev. Sci. Instrum. 41, 1334 (1970).

[10]The characteristics of the signal cable were measured experimentally and were in excellent agreement with the manufacturer's data.

[11]See, for example, R. D. Evans, *The Atomic Nucleus* (McGraw-Hill, New York, 1970), Chap. 21.

[12]M. Friedman, Phys. Rev. Lett. 31, 1107 (1973).

[13]See, for example, R. G. E. Hutter and S. W. Harrison, *Beam and Wave Electronics in Microwave Tubes* (Van Nostrand, Princeton, N. J. 1960), Chap. 6.

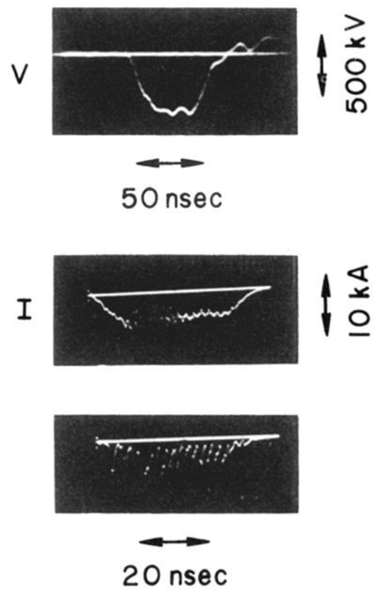

FIG. 2. Typical oscillographs. From top to bottom, beam voltage, Faraday-cup signal, and fast–Faraday-cup signal. Note that the frequency response of the Faraday cup is ~100 MHz. Any current signal with frequency components greater than 100 MHz was integrated by the probe and effectively eliminated from the oscillograph trace. Hence, the signal from this Faraday cup indicated in "dc" component of the current.

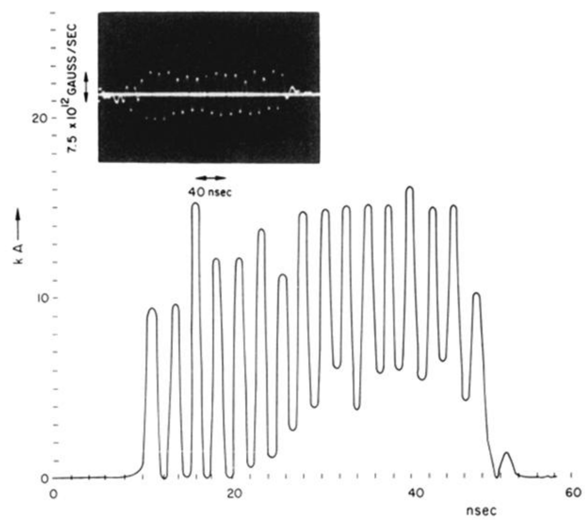

FIG. 3. Net electron beam current derived from a magnetic probe signal. The magnetic probe was located beyond the cavity structure. (Insert, oscillograph of the magnetic probe signal.)

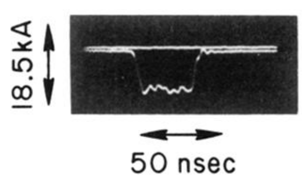

FIG. 4. Electron beam current measured just in front of the cavity structure.