Autoacceleration of an Intense Relativistic Electron Beam

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A novel autoacceleration mechanism was used to double the particle energy in a pulsed relativistic electron beam. This mechanism increases electron kinetic energy at the expense of pulse duration. Acceleration is accomplished by passing the beam through a cavity structure inserted into a conventional drift tube. Experimental results showed that the mean electron kinetic energy was increased from about 0.5 to 1.0 MeV, while the beam duration decreased from about 50 to 25 nsec. The total energy efficiency of the process was approximately 75%.

The technology of producing an intense relativistic electron beam with particle energies of less than 10 MeV is highly developed and has been discussed extensively in the literature.[1-3] However, electron beams with particle energies greater than 10 MeV are technologically difficult to generate and generators are quite expensive.

A potentially simple and inexpensive approach to high-kinetic-energy electron beams is to use autoacceleration processes on lower voltage beams. In this Letter an experiment is described in which an autoacceleration mechanism approximately doubled the mean particle energy of a pulsed relativistic electron beam while halving the pulse duration. The experiment (Fig. 1) consisted of a foilless diode[4] emitting an annular electron beam with a current of ~10 kA and a voltage of ~500 kV for 50 nsec duration. The beam radius 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 long 4.7-cm-i.d. stainless-steel tube into which is inserted a gap feeding a long cavity. As can be seen from Fig. 1, for convenience the cavity is "folded" over the drift tube in the form of a coaxial outer tube 3.75 m long. The initial drift tube section (region 1) is 20 cm long; it is followed by a 15-cm gap (region 2); and that is followed by a 3.75-m drift tube (region 3).

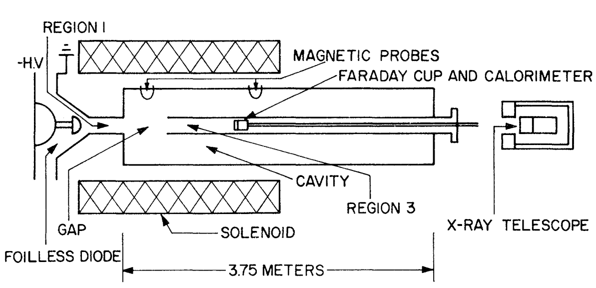

FIG. 1. Schematic of the experiment.

Several diagnostics were used to analyze the electron beam. A calorimeter was employed to determine the total beam energy and a Faraday cup monitored the beam current. Aluminum foils of different thickness were placed in front of the Faraday cup in order to determine particle energy from the reduction of beam current. An x-ray telescope with a set of lead absorbers was used to determine the pulse duration as well as spectral information concerning the bremsstrahlung radiation. This radiation emerged from a tantalum foil serving as a target for the electron beam. Magnetic probes were inserted to measure the current of the electron beam crossing the gap and the wall current flowing in the cavity. These same diagnostics were used in a control experiment in which the properties of a similar beam propagating in an uninterrupted drift tube of 4.7 cm i.d. were measured.

Figure 2 shows beam voltage, x-ray, and Faraday-cup signals. Two Faraday-cup traces are shown for cases where aluminum absorbers were inserted in front of the Faraday cup. The thickness of the absorbers were 6.8×10^{-3} and 0.13 g/cm^2. Note that the duration of the x-ray and the Faraday-cup signals were 25 nsec in comparison with the applied voltage pulse, 50 nsec in duration.

By placing aluminum absorbers in front of the Faraday cup and measuring the transmitted current, the mean particle energy was estimated.[5] Figure 3 shows the percentage of transmission of beam current through different thicknesses of aluminum foil. The mean kinetic energy of the electron beam passing the cavity is seen to be higher than the energy of the electrons in the control experiment. Using Fig. 3 and range-energy relations for relativistic electrons,[5] the particle

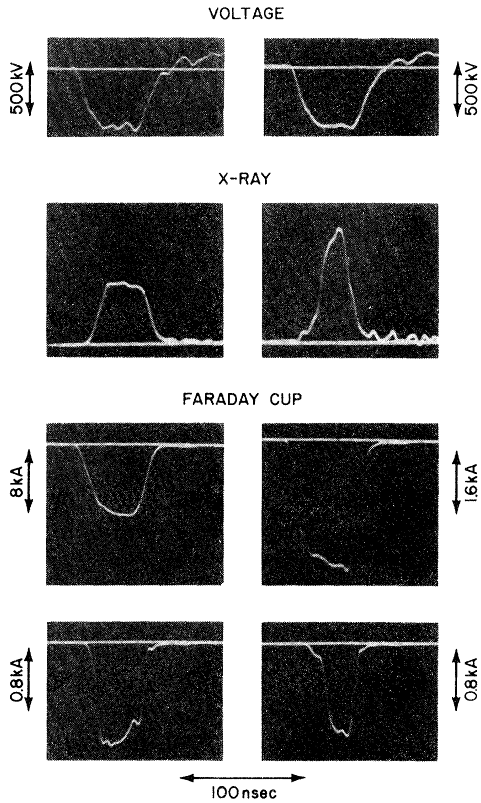

FIG. 2. Typical oscillographs. Diode voltage, x-ray, and Faraday-cup signals obtained for (left) the control experiment and for (right) the experiment (with the cavity). The Faraday-cup signals were taken with different thicknesses of aluminum absorber (6.8×10^{-3} and 0.13 g/cm^2).

energy in the experiment is estimated to be 950 ± 50 keV, while the particle energy in the control experiments is 550 ± 50 keV.

On the basis of the spectrum of the bremsstrahlung radiation one can also deduce the particle energy. Figure 4 shows relative intensity of x-ray radiation produced by the beam passed through the cavity region, after attenuation by lead absorbers of different thicknesses. The absorption coefficient μ for an "infinite" thickness of lead absorber was extrapolated to be ≈ 0.07 cm^2 g^{-1}, while for the control experiment $\mu \approx 0.14$ cm^2 g^{-1}. The first value corresponds to x-ray photons with energy of 1 MeV, and the second number corresponds to 0.5-MeV photons, thereby confirming the Faraday-cup measurements.

A third method used to estimate the mean electron kinetic energy utilized independent measurements from an electron beam calorimeter, a Faraday cup, and the x-ray detector. The following relation was used:

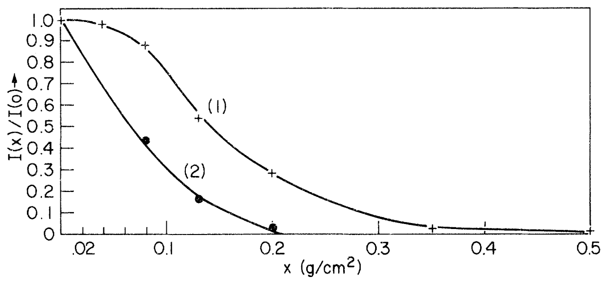

FIG. 3. Relative transmission of beam current through different thicknesses of aluminum foil obtained for (1) the experiment (with the cavity), and (2) the control experiment.

$$\frac{I_1}{I_2}\frac{V_1}{V_2}\frac{\Delta t_1}{\Delta t_2} = \frac{E_1}{E_2}, \tag{1}$$

where I, V, Δt, and E are the current, voltage, time duration, and total energy of the electron beam, respectively. The indices 1 and 2 stand for the experiment (i.e., with the cavity and gap) and control experiment, respectively. It was found that $I_1/I_2 \approx 0.5$ from the Faraday-cup measurements, $\Delta t_1/\Delta t_2 \approx 0.5$ from x-ray pulse durations, and $E_1/E_2 \approx 0.5$ based on calorimeter measurements. Substituting these results in Eq. (1), one finds $V_1/V_2 \approx 2$, or $V_1 \approx 1$ MeV, again consistent with other measurements.

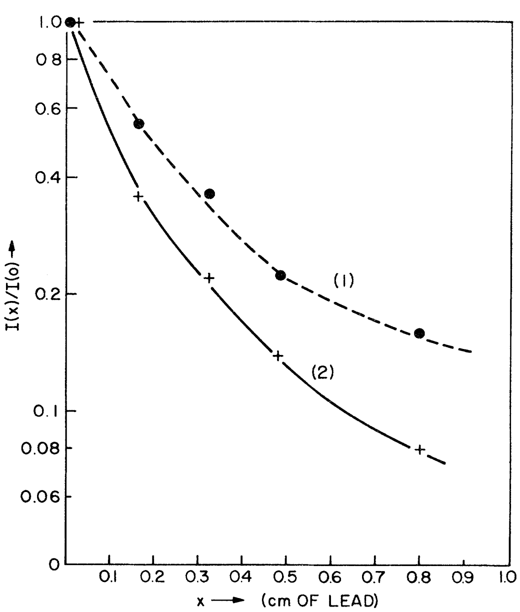

FIG. 4. Relative intensity of x-ray radiation after attenuation by lead absorbers obtained for (1) the experiment (with the cavity), and (2) the control experiment.

The beam shape after passing through the cavity remained annular, but its radius and thickness increased. Only 60% of the electron beam was intercepted by the Faraday cup and the calorimeter. (Under the control-experiment conditions all of the electron beam was intercepted by the calorimeter and the Faraday cup.) This means that the real values for the current and energy of the accelerator beam are ~1.5 times greater than the measured values. In that case the corrected current ratio is $I_1/I_2 \approx 0.75$ and the corrected energy ratio is $E_1/E_2 \approx 0.75$. This last result means that the total efficiency is ≈75%.

The experimental conclusion is thus that the cavity appears to cause an "autoacceleration" of the electron beam fron 0.5 to 1.0 MeV, with the required energy coming from a shortening of the pulse duration. The autoacceleration process can be explained in terms of transmission-line concepts. The electron beam, while flowing in the first drift tube, sees a discontinuity in the drift-tube wall. This discontinuity catastrophically disrupts the electron beam[6] and a virtual cathode is formed at the entrance to the cavity.[7] The potential difference between the virtual cathode and the walls is of the order of 500 kV, the same voltage that was applied on the foilless diode. Electrons are emitted from the virtual cathode and are accelerated across the gap in the cavity. Figure 5 shows the electron current across the gap, as measured by a magnetic probe. Note that the rise time of the current is decreased to 5 nsec, as is characteristic of virtual cathode emission,[7] compared with the applied voltage rise time of 20 nsec. When the electron beam is flowing through region 3 (see Fig. 1), the return current is forced to flow through the walls of the cavity, thereby developing a voltage

$$V_1 = L\,dI/dt$$

across the gap where L is the inductance associated with the cavity (≈4×10^{-7} H) and dI/dt is the rate of change of the current. This voltage decelerates the electrons and reduces their kinetic energy. Hence the cavity may be viewed as being energized at the expense of the electron beam energy; but the cavity can also be seen as a transmission line with a short-circuited end, and when a current pulse of value I flowing in the cavity walls reaches the short-circuited end, the current doubles its value to $2I$ and propagates backwards. When this pulse reaches the open end, it sees a constant current source (i.e., the electron beam) which produces only a current of a value I. In order to match the boundary conditions, a voltage pulse of the same magnitude as in Eq. (2) will be produced but with an opposite sign. Thus, an accelerating energy of eV_1 will be added to the particle energies in the remaining beam passing through the gap.

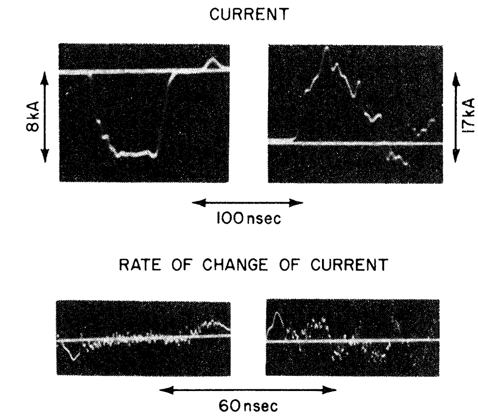

FIG. 5. Typical current and rate of change of current oscillographs that were taken (left) at the gap and (right) at 1.25 m away from the gap.

Since it takes 25 nsec for an electromagnetic wave to propagate in the cavity, for 25 nsec the beam will supply energy to the cavity while, for the next 25 nsec, the beam will gain energy from the cavity. Figure 5 shows the current flowing on the walls of the cavity as measured by a magnetic probe which was located at a distance $d = 1.25$ m from the gap. Figure 5 also shows the rate of change of this current. Here it is easy to see the current and the reflected current pulses. In comparison, the rate of change of the electron beam current flowing across the gap (i.e., $d=0$) is also shown. The traces of Fig. 5 can be reproduced using standard transmission-line calculations. Using Eq. (2) and Fig. 5 one finds that $V_1 \approx 500$ kV. Hence the total particle energy after the acceleration phase is expected to be of the order of 1 MeV.

There is no reason why this simple autoacceleration process could not be repeated, and even higher particle energies and shorter pulse durations might be obtained.

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[1]J. C. Martin, U. S. Patent No. 3 344 298, "Flash X-Ray Tube with Gas Focussing of Beam" (26 September 1967).

[2]S. E. Graybill and S. V. Nablo, Appl. Phys. Lett. 8, 18 (1968).
[3]J. J. Clark, M. Ury, M. L. Andrews, D. Hammer, and S. Linke, in *Record of the Tenth Symposium on Electron, Ion, and Laser Beam Technology*, edited by L. Marton (San Francisco Press, San Francisco, Calif., 1969), p. 117.
[4]M. Friedman and M. Ury, Rev. Sci. Instrum. 41, 1334 (1970).
[5]See, for example, R. D. Evans, *The Atomic Nucleus* (McGraw-Hill, New York, 1970), Chapt. 21.
[6]M. Friedman and D. A. Hammer, Appl. Phys. Lett. 21, 174 (1972).
[7]M. Friedman, to be published.

Nonlinear Absorption of Radiation by Optical Mixing in a Plasma

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Parametric excitation of longitudinal plasma oscillations can occur when a plasma is simultaneously irradiated by two laser beams whose frequencies differ by $(2/n)\omega_{pe}$, $n=1, 2, 3, \ldots$, where ω_{pe} is the electron plasma frequency. We examine (i) the effect of a frequency mismatch on the excitation of the principal mode, (ii) the mode coupling in an inhomogeneous plasma, and (iii) the radiation absorption efficiencies.

Recent experimental[1] and theoretical results[2-4] indicate that enhanced absorption of radiation by a plasma can occur through the excitation of a large-amplitude longitudinal wave at the beat frequency of two laser beams. We investigate this excitation for a homogeneous, cold plasma, showing, in a weak-field approximation, that the parametric resonances fall into the regions of instability of the solutions of a nonhomogeneous Mathieu equation. The time dependence of the solutions is a function of the mismatch, $\delta\omega$, between the beat frequency, $\Delta\omega$, and the natural plasma frequency ω_{pe}. By considering $\delta\omega$ to be spatially dependent, we generalize our solution to the case of an inhomogeneous plasma. This treatment is presented as an alternative to that of Rosenbluth and Liu,[3] who solve the longitudinal wave equation directly, and to that of Kaufman and Cohen,[4] who formulate the interaction in terms of the local longitudinal dielectric constant with vanishingly small damping. The present method enables us to calculate the steady-state spatial distribution of power transfer as a function of the dissipation rate. In particular, in the presence of collisions, transfer occurs over a region defined by $\delta\omega(x) \simeq \pm \nu/2$, while when convection predominates, the zone of transfer is $\delta\omega(x) \simeq \pm \Delta\omega v_e^2/2v_p^2$; ν is the collision frequency, v_e the electron thermal velocity, and v_p the plasma-wave phase velocity. We then calculate the transfer efficiencies for parallel and antiparallel laser beam.

Consider two electromagnetic waves:

$$\vec{E}_i'(\vec{r}, t) = \vec{E}_i \sin(\omega_i t - \vec{k}_i \cdot \vec{r}), \quad i = 1, 2, \tag{1}$$

linearly polarized in the positive y direction, propagating through a cold homogeneous plasma along the x direction, at frequencies ω_i much above the plasma frequency ω_{pe}. The equation of motion of an electron fluid element in the composite field $\vec{E}' = \vec{E}_1' + \vec{E}_2'$ is

$$\ddot{\vec{A}} + \nu\dot{\vec{A}} = (e/m)(\vec{E}' + \dot{\vec{A}} \times \vec{B}'/c + \vec{E}_s), \tag{2}$$

where $\vec{A} = \vec{r} - \vec{r}_0$ is the displacement of the fluid element from its equilibrium position $\vec{r}_0$, $\vec{E}_s$ is the self-consistent electrostatic field, and ν is the longitudinal damping rate. Assuming that $\alpha_i = (eE/mc\omega_i) \ll 1$, $A_x|\vec{k}_1 - \vec{k}_2| \ll 1$, and $\nu \ll \omega_i$, and making use of $\omega_{pe} \ll \omega_i$, we find, for the longitudinal displacement A_x at the beat frequency $\Delta\omega$,

$$d^2A_x/d\tau^2 + (\nu/\Delta\omega)dA_x/d\tau + [\delta - \epsilon\cos(\tau - kx_0)]A_x = -(\epsilon/k)\sin(\tau - kx_0). \tag{3}$$

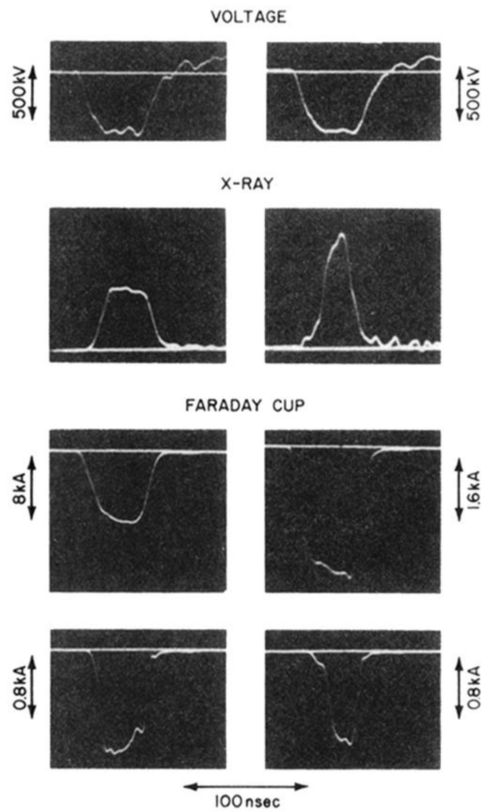
Here, $\tau = \Delta\omega t$ and $\delta = (\omega_{pe}/\Delta\omega)^2$; ϵ and k depend on the mutual orientation of the wave vectors, $\vec{k}_i$. For parallel beams

$$k_p = k_2 - k_1, \quad \epsilon_p = \tfrac{1}{2}\alpha_1\alpha_2, \tag{4}$$

and for antiparallel beams

$$k_a = k_2 + k_1, \quad \epsilon_a = \tfrac{1}{2}\alpha_1\alpha_2(\omega_1 + \omega_2)^2/\Delta\omega^2. \tag{5}$$

For small ϵ the regions of instability of the Mathieu equation (3) lie in the vicinity of the



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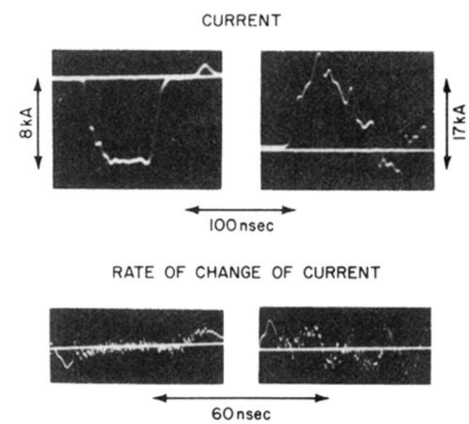

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