7

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EXPERIMENTS ON THE AUTOACCELERATION OF A
RELATIVISTIC HIGH CURRENT ELECTRON BEAM

T. J. Fessenden and R. J. Briggs

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EXPERIMENTS ON THE AUTOACCELERATION OF A
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Introduction

Results of a brief experimental test of an electron autoaccelerator structure (carried out for two weeks in Sept. 1973) are described in this report. These preliminary experiments studied the interaction of an intense relativistic beam with a simple multicavity structure. The main goal of the experiment was to determine the characteristics of the r.f. fields excited by the beam, and to see if the longitudinal r.f. electric fields would result in autoacceleration of some beam particles. Control of the r.f. modes is a central issue in any of the autoacceleration schemes that have been proposed,^{1,2,3} since one may wish to enhance their excitation in a self-excited r.f. acceleration mode, or suppress them to allow "adiabatic" ($E_z \sim -\dot{I}$) inductive acceleration of particles at the pulse tail to dominate.

In the experiment, the transverse beam breakup mode was observed and suppressed by alterations in the cavity walls. The longitudinal modes were then dominant and strong modifications in the particle energy distributions were observed. Many important aspects of this experiment have been modeled by the theoretical computations of Neil and Mirin.⁴

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Experimental Configuration and Beam Characteristics

The pulsed diode device (Physics International 422) we used injects a beam of up to 50 kAmp at 2.5-3 MeV with a 30 nsec half width into a 30 cm inside diameter aluminum drift tube that is 130 cm long. The total beam energy measured with a calorimeter at the anode was approximately 2.6 kJ. All experiments were performed at the best obtainable vacuum in the system ($p \approx 10^{-4}$ torr).

The autoaccelerating structure consisted of a series of 30 cm diameter aluminum disks separated by 2.54 cm placed inside the drift tube. A 5 cm diameter hole was punched on axis through the disks to form an iris loaded waveguide structure. The electron beam was fired through these holes and guided by an axial magnetic field of up to 8 kG. We should also emphasize that the electrical behavior of this structure is basically the same as a chain of uncoupled cavities because of the small ratio of hole diameter to tube diameter. That is, the group velocity of propagating modes in this periodic structure is very much less than the beam velocity.

A diagram of the experimental apparatus is presented in Fig. 1. The net beam current flowing in the structure was measured by placing resistive shunts (RS) in the wall of the drift tube and measuring the return current at each side of the anode plane and at the drift tube-end plate junction. In this way the current emitted by the cathode, the current injected into the drift tube and the current leaving the drift tube were monitored. The level and frequency of the r.f. oscillations induced in the autoaccelerating structure were monitored at two axial points with the aid of a Tektronix 7904 direct access oscilloscope and an r.f. coupling loop.

This oscilloscope has a 3 db cutoff frequency of 1 GHz. The loop was calibrated with a known signal and it was determined that over the frequency band from 0.5 to 1.0 GHz, the loop calibration varied from .6 to 1 Volt/Gauss.

Beam Drifting Experiments

Initial experiments were performed in which the beam was propagated the length of the drift tube in the presence of a strong ($B_z \approx 8$ kGauss) axial magnetic field, with no accelerating structure within the tube. These experiments initialized the beam parameters for the autoacceleration experiment, and essentially repeated the experiment of Mkheidze et al.⁵ It was found that only 10-12 kAmps could be propagated as measured with resistor shunt 3. For these experiments the peak diode voltage was 3.0 MeV and approximately 600 joules were transferred to a calorimeter on the end plate of the drift tube. According to Eq. (4) of Appendix I, the space charge limited current at these voltages should be 10.7 kAmps, in good agreement with the experimental result. An approximate energy distribution function of the beam at the end plate was measured using the procedure described in Appendix II. This data is presented as a dashed curve in Fig. 2. Note the sharp cutoff of the energy distribution at an energy corresponding to the peak diode voltage.

Autoacceleration Experiments

Initial autoacceleration experiments with 24 disks placed in the drift tube revealed that an intense oscillation at 1.2 GHz was being strongly excited by the beam. Figure 3 shows reproductions of oscillograms obtained

with the aid of the r.f. loops. It was verified by both calculations of the eigenfrequency for our cavity dimensions and bench tests of the structure that this oscillation resulted from excitation of the TM_{110} mode. Bench testing showed that typical "Q's" of the TM_{110} mode at 1.2 GHz and the TM_{010} mode at 0.8 GHz were 300 to 500. As seen in the oscillograms this oscillation strongly disrupted the beam and limited the transmitted beam current. In order to suppress the excitation of the TM_{110} mode, the disks were sliced along six radii approximately 60° apart from the center hole to within approximately 3 cm of the outer radius. As a result of these slices the TM_{110} mode could no longer be detected even in bench tests, whereas the TM_{010} mode "Q" was reduced by less than a factor of two. With the sliced disks, the disruption of beam propagation and intense 1.2 GHz oscillations were eliminated.

The configuration that produced the most easily detectable auto-acceleration in our experiments consisted of the system shown in Fig. 1. A 1.5 cm diameter collimator was placed just after the anode foil, and the beam was drifted a distance of 29 cm in the empty tank before entering the autoaccelerating structure. Figure 2 shows a measurement of the effect of the structure on the beam distribution function obtained with the technique of Appendix II. Oscillograms of the signal detected by r.f. loop 2 are shown in Fig. 4. This signal results from the excitation of the TM_{010} mode (as identified by its frequency). Note that the scope gain has been increased by a factor of 25 over that used in obtaining the oscillogram of Fig. 3. In Fig. 4 we also show oscillograms of the current detected by resistor shunt 3. Of particular interest is the prolonged decay of the

signal, which suggests that an appreciable number of electrons are being slowed to very low energies by the fields of the structure. Estimates of the r.f. fields in the cavities as obtained from Fig. 4 give an oscillating field of 3×10^4 V/cm on axis. This measurement is consistent with an energy gain or loss of 2-3 MeV over the 90 cm length of the structure.

Comments on the Experimental Observations

In a structure of this type, the TM_{110} mode is easily excited and, if not decoupled from the system, will build up to a sufficient amplitude to destroy the electron beam. Under these conditions we found that little or no autoacceleration occurs.

With the disks located close to the anode, autoacceleration effects are barely detectable. When a 29 cm drift space (30 cm tube diameter) separated the disks from the anode plane, the results described in Fig. 2 were obtained. The most plausible explanation for the difference between these two configurations is the change in the initial kinetic energy (γ) of the beam electrons in the iris structure because of the space charge effects discussed in Appendix I. That is, if the beam current is limited only by the space charge potential in the iris structure itself, the kinetic energy of the particles is $\gamma = \gamma_0^{1/3} \approx 1.8$ and the autoacceleration is barely detectable. Reducing the beam current from this value (by placing a current limiting drift space in front of the disks) reduces the space charge potential depression in the iris section causing γ to increase in this section. With the latter configuration, γ is estimated to be approximately 4.5 in the structure, and the autoacceleration evidenced in

Fig. 2 is observed. (It is also important to note in this connection that when the electrons approach the end plate (ground potential), they recover a kinetic energy equal to the potential depression in the structure.)

The above interpretations suggest a strong dependence of the autoacceleration effect on the initial kinetic energy of the electrons inside the structure. The computational models¹ have also indicated this general trend.

APPENDIX I
SPACE CHARGE LIMITED CURRENT
OF A RELATIVISTIC ELECTRON BEAM

Consider an electron beam of radius a moving in a drift chamber of radius b in the presence of a strong axial guide magnetic field. We shall assume that the beam radius is small compared to the chamber radius b so that the space charge potential seen by all the beam particles is given by

$$\phi_p = \frac{I}{4\pi\epsilon_0\beta c} (1 + 2 \ln b/a). \quad (1)$$

Assume further that we are considering times long compared to the rise time of the beam and that the current is independent of axial position. Thus we need not consider the axial electric fields arising from a time-variation in the self magnetic field of the beam. The kinetic energy (in volts) of each particle is

$$(\gamma-1) \frac{mc^2}{e} = \phi_0 - \phi_p. \quad (2)$$

Here ϕ_0 is the accelerating potential applied to the beam.

Defining $\gamma_0 = 1 + \phi_0 e/mc^2$ we find

$$\sqrt{1 - 1/\gamma^2} (\gamma_0 - \gamma) = \frac{I}{I_c} (1 + 2 \ln b/a) \quad (3)$$

where $I_c = 4\pi\epsilon_0 mc^3/e$ ($= 17,000$ for electrons).

The maximum current which can propagate is found by differentiating Eq. (3) with respect to γ and setting the resulting equation to zero. This yields

$$I_{\max} = \frac{I_c (\gamma_o^{2/3} - 1)^{3/2}}{1 + 2 \ln b/a} \quad (4)$$

and

$$\gamma = \gamma_o^{1/3}. \quad (5)$$

This result has previously been obtained by Mkhaidze et al.⁵

It is interesting to consider the nonrelativistic expansion of Eq. (4). If the beam potential ϕ_o is small compared with the rest energy ($\phi_r = mc^2/e$) of the particles we find

$$I_{\max} \approx \frac{I_c}{1 + 2 \ln b/a} \left(\frac{2}{3} \frac{\theta_o}{\theta_N} \right)^{3/2}. \quad (6)$$

Or for electrons

$$I = \frac{k \theta_o^{3/2}}{1 + 2 \ln b/a}$$

where

$$k = 17,000 \left(\frac{2}{3 \times 511,000} \right)^{3/2} = 25.3 \times 10^{-6}. \quad (7)$$

A more exact nonrelativistic calculation which considers the potential variation within the beam gives $k = 44 \times 10^{-6}$ for $b = a$.

As a particle moves in the system its kinetic energy is reduced by the space charge potential. Thus particles traveling in a potential well will have a smaller effective γ than that corresponding to the applied potential. Fig. 5 shows the variation of γ/γ_0 with the normalized beam current for various values of γ_0 .

APPENDIX II

CRUDE MEASUREMENT OF ELECTRON ENERGY DISTRIBUTION FUNCTION

The range of penetration of an energetic electron beam into a metal will depend on its energy. The details of the primary electron flux in the metal are a complicated and not well known function of the beam distribution function. Nonetheless, qualitative information about the energy of the electrons can be obtained by a measurement of the depth dependence of the energetic electron flux in a metal target.

The diagnostic used is a radiochronic sensor material consisting of a .05 mm thick solid solution of hexadroxethylpararosaniline-cyanide in a nylon resin.⁶ The film has an approximate radiation dose range of 1×10^4 to 1×10^7 rads. The radiochronic film is carefully sandwiched between two flat metal blocks and placed with its edge forcing the incident electron beam. Because of the narrow gap between the metal blocks, the electron flux in the film is essentially the same as that in the metal. Thus the darkening of the film is representative of the electron flux in the metal.

After irradiation, the film is scanned at a wave length of 600 nmeters in the direction parallel to the incident electron beam. The transmission of light through the film as a function of distance is then recorded on an x-y recorder.

Theoretical Basis of the Film Measurements

We assume that the transmission of 600 nmeters light through the film is inversely proportional to the exponential of the number of electrons in the metal at that point. That is

$$\frac{T(x)}{T_0} = e^{-n_e(x)} \quad (\text{AII-1})$$

Experiment⁶ has indicated that this relation is good in the radiochromic film over a variation of approximately 3 orders of magnitude.

We further assume that $n_e(x)$ in the metal is given by

$$n_e(x) = \int_{kx}^{\infty} f(u) du \quad (\text{AII-2})$$

where $f(u)$ is the beam electron energy distribution function and k is a constant relating the energy loss in the metal to the distance traveled. This relation assumes that the energy of a primary electron decreases linearly with penetration in the metal and that straggling of electrons can be ignored. Assuming constant dE/dx is reasonable only at energies above 500 keV. The constant k was determined experimentally by Katz and Penfold.⁷ In our experiment magnesium was used as the metal and the value $k = 3.3 \text{ MeV/cm}$ was used. It is these approximations that make this measurement technique crude.

With the above approximations Eqs. (1) and (2) can be solved directly for the normalized distribution function $f(u)/n_{\text{total}}$.

$$\frac{f(u)}{n} = \frac{1}{\ln T_0 \kappa / T_\infty} \frac{1}{T} \frac{\partial T}{\partial x} \quad (3)$$

The scanning device used to scan the radiochronic film plots the film density versus length. The density D is defined as

$$D = -\log_{10}(T/T_\infty). \quad (4)$$

Here T_∞ is the transmission through the undarkened film. In terms of this parameter Eq. (3) is simply

$$f(u) = - \frac{1}{kD_0} \frac{\partial D}{\partial x}$$

where D_0 is the value of the density at the film edge.

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Figure 1: Experimental Apparatus

Fig. 2: Crude measurements of the normalized distribution function of the drifted beam (dotted line) and of the autoaccelerated beam (solid line).

Fig. 3: Oscillograms of the TM₁₁₀ magnetic field detected by RF 2 (a) and of the transmitted current (b) under beam-breakup conditions. Signal levels in (a) imply transverse oscillating magnetic fields on axis greater than one kilogram.

Fig. 4: Oscillograms of the TM_{010} magnetic field detected by RF 2 (a) and of the transmitted current (b) under autoacceleration conditions. Signal levels in (a) correspond to an axial electric field of approximately 30 kV/cm.

Fig. 5: Effects of space charge on the normalized kinetic energy (γ/γ_0) of beam particles as function of the normalized current.

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