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AUTOACCELERATION VIA VIRTUAL CATHODE OSCILLATION

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Abstract

Injection of monoenergetic electron beams with uniform number density into an evacuated, straight-walled, equipotential cylindrical drift tubes has been modeled. An oscillating virtual cathode is produced by having the injected current exceed the space-charge limiting current of the drift tube. If the oscillation frequency of the virtual cathode exceeds the local beam plasma frequency a coherent traveling EM wave is launched with electric fields on the order of MeV/cm for an injected beam density of 10^{12} cm^{-3}. Furthermore, in the absence of a strong axial magnetic field transmitted particles are autoaccelerated up to 3 times their initial kinetic energy.

Introduction

The concept of autoacceleration of electrons by utilizing the enormous self-fields of intense relativistic beams has been around for several years. Many different approaches have been proposed and experiments performed. (See, for example, References 1 and 2 and their bibliographies.) Basically, a portion of the beam pulse is retarded by constructing large self-fields. The energy in the fields is stored in passive elements along the drift tube, such as, resonators, transmission lines, or gaps. At some point the passive elements are made to switch this energy back into the beam. The end result is acceleration of some particles at the expense of others.

The purpose of this paper is to report on a new method of autoacceleration developed during numerical studies into the nature of virtual cathode dynamics. The simulations were carried out using a two-dimensional, fully relativistic, and electromagnetic particle-in-cell code, CCUBE. The code was made to model the injection of cold, uniform density electron beams into evacuated, straight-walled, equipotential drift tubes. The injected beam current in units of mc^3/e, ν_0, exceeded the space-charge limiting current, ν_ℓ, in order to create an oscillating virtual cathode. The code uses dimensionless units, therefore, length is in terms of c/ω_b^0; time is measured in units of $\omega_b^{0^{-1}}$; and particle velocity is given by $v_i = \beta_i\gamma$, where ω_b^0 is the beam plasma frequency at injection, $\gamma = (1-\beta^2)^{-\frac{1}{2}}$, $\beta = v/c$ and c is the speed of light.

The unique feature of this method of autoacceleration is that no passive elements are present inside or in conjunction with the drift tube. The oscillating virtual cathode is the means of redistribution of particle energy. The autoacceleration is evident in Fig. 1, which is a plot of v_z vs Z. Note that in this case where the external magnetic field, B_z, equals zero the acceleration is over by $Z \approx 50$ c/ω_b^0. This agrees with the observed acceleration length of at least one series of experiments.[1] Also, note that all particles, which have not been ejected radially to the drift tube wall, have been autoaccelerated to energies greater than their initial value.

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The remainder of this article will be in two parts. A brief description of virtual cathode oscillation will be given next. The second section will discuss some salient features of the acceleration process.

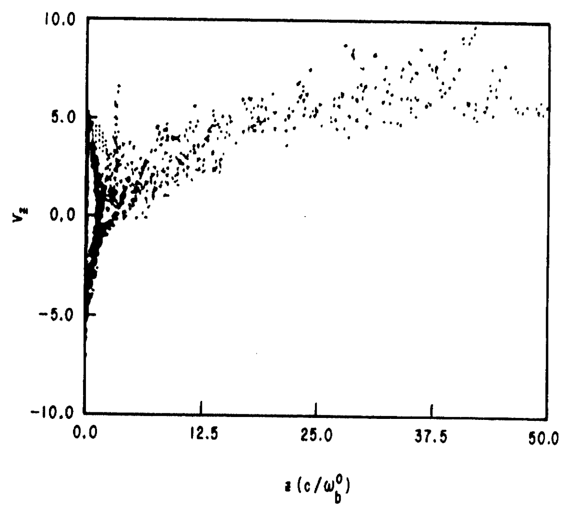

Fig 1. Plot of v_z vs Z showing the autoacceleration of particles in the axial direction. The initial value of $v_z = 5.0$; $B_z = 0$.

Virtual Cathode Oscillation

The virtual cathode is the nonlinear state which developes when ν_0 of the beam exceeds ν_ℓ of the drift tube. Several important features of the oscillation including potential well depth, position, and the oscillation frequency dependence on ν and γ have been covered elsewhere.[3] It is still not clear, however, what initiates virtual cathode formation. Even when $\nu_0 = \nu_\ell$ there is some residual kinetic energy associated with the minimum radial position of the beam. One candidate for the job of triggering initial formation is accumulation of noise at the point of minimum potential, since the phase and group velocities of the noise associated waves tend to zero there.[4]

Once the virtual cathode is formed and reflection of particles commences, large amplitude oscillation is not assured. Small oscillations ($\nu_0 \gtrsim \nu_\ell$) are being treated by linear analysis in order to obtain insights into virtual cathode dynamics. There are several possibilities for the instability that drives the nonlinear state. They include but are not limited to the oscillating two stream, the ponderomotive force, and a model which treats the virtual cathode as being analogous to a collisionless shock front. All of these alternatives require a great deal of analysis, which will be left to a future paper.

Regardless of the mechanism responsible for the oscillation, the end result is that the virtual cathode launches a large amplitude, coherent EM wave in the longitudinal direction. The frequency of the wave is equal to the frequency of oscillation of the virtual cathode. The wave propagates down the drift tube in a TM_{0n} waveguide mode, which determines the wavelength and phase velocity of the wave in the guide. The restrictions of the wave to 0n modes is an obvious result of the code's assumption of azimuthal symmetry. However, the restriction may be real, since one major result of virtual cathode oscillation is the longitudinal bunching of the transmitted beam. The TM_{0n} modes may be just a manifestation of that bunching. The fact that one is dealing with a TM rather than a TE mode is most evident in simulations where there is no externally imposed axial magnetic field. Because of azimuthal symmetry and cold beam injection, the only nonzero fields are E_z, E_r, and B_θ. These three fields define a TM wave traveling in the Z direction. Time histories of these fields at a specific point, namely $Z = 100\ c/\omega_b^0$ and r equal to one-half the drift tube radius, are presented in Fig. 2. At this position almost all beam electrons have been ejected radially to the walls. Note that the harmonics of the oscillation frequency are present in the time histories, especially that of the E_z field. Note also the constancy of phase among the three fields.

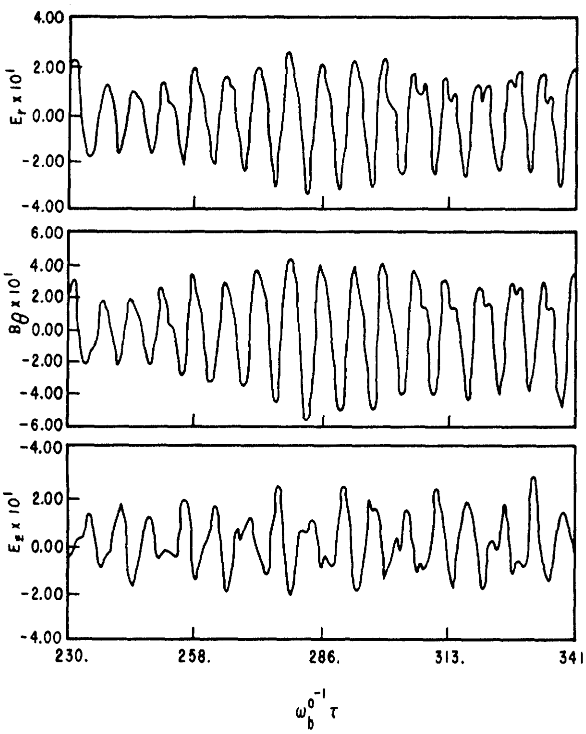

Fig. 2. Time histories of E_z, E_r and B_θ fields far from the injection plane. For a beam density of 10^{12} cm^{-3} the fields are in units of MeV/cm; $B_z = 0$.

Optimum microwave generation has been obtained when a strong axial magnetic field is imposed. For a 2 MeV, 65 kA beam peak electric fields on axis are in excess of 2 MeV/cm for a beam density of 10^{12} cm^{-3}. Very little attenuation is noted when a strong B_z is present. With a phase velocity above the speed of light wave-particle interactions are minimized. Simulations have produced microwave conversion efficiencies of 35%. Apparently, laboratory experiments have already shown this mechanism to be an excellent source of high power microwaves.[5-7] Powers up to 1 GW have been observed.[7] There are many problems such as extraction from a large B_z field, anode foil ionization, and RF vacuum breakdown which still must be addressed. This will be left, however, to a lengthier forthcoming paper.

Autoacceleration

Kolomensky et al.,[1] astutely observed that microwave generation and autoacceleration are interdependent in high ν/γ beams. However, whereas microwave generation is optimized for a strong B_z field, autoacceleration per unit length maximizes when $B_z = 0$. Indeed, autoacceleration occurs, except for the stochastic acceleration of a few particles, only when B_z is weak. If $\omega_c/\omega_b^0 > 5$, where ω_c is the electron cyclotron frequency due to B_z, there is no effective autoacceleration. It is reasonable to expect the two processes to oppose each other, since autoacceleration must attenuate fields, and self-fields are created due to the loss of particle energy. It is also evident that the two must coexist. For microwaves to be extracted from the drift tube the B_z field must be withdrawn, which will result in some autoacceleration. Likewise, if the portion of the beam which is autoaccelerated is to be kept from hitting the walls, some B_z field must be imposed. In fact, even if $B_z = 0$, high energy microwaves are still generated.

The specific mechanism which produces the autoacceleration has not been isolated. However, some conclusions can be drawn from simulation results. The first deals with the vector, A, and scalar, ϕ, potential profiles. In the large B_z case there is no net gradient in potential away from the virtual cathode, although large local gradients exist due to the oscillation. When $B_z = 0$, large positive gradients in the Z direction exist in both ϕ and A_z on the downstream side of the virtual cathode. Another salient feature is that when B_z is large $v_r \approx 0$, but when $B_z = 0$, v_r is large and positive. One also knows that the acceleration must be directly linked to the oscillation. If a steady state existed, conservation laws would not allow the redistribution of energy among the particles.

The particle distribution in kinetic energy is given in Fig. 3. It shows that the acceleration is continuous up to 2.5 times the initial kinetic energy. Stochastic processes then push the kinetic energy of a few particles up to three times the initial value. By examining Fig. 1 and Fig. 3 one can establish that the overall efficiency is at most 10%. Two ways of increasing the efficiency and overall energy would be to design a magnetic field configuration which would contain the beam and yet allow acceleration; then the beam could be staged to increase the energy. The accelerated remainder of the first beam would easily pass through a virtual cathode created by a second beam, since its energy would be greater than the second beam's initial kinetic energy. Confinement and recycling of the beam may result in an efficient mechanism of autoacceleration, but the process of initial acceleration must first be understood.

Summary

Simulations into the nature of virtual cathode dynamics have revealed that the oscillation is a source of autoacceleration as well as high energy microwave generation. RF conversion efficiencies of 35% have been attained, but autoacceleration efficiency is not greater than 10%, if one includes the particles reflected by the virtual cathode.

The mechanisms of microwave generation and autoacceleration through virtual cathode oscillation in intense relativistic electron beams are interdependent. Although the two must coexist, they are competing processes which can be optimized by the proper choice of an axial magnetic field. As noted above RF generation maximizes in the presence of a strong B_z field. The efficiency is also affected by choice of radial cross section of the beam and drift tube. By varying the size of the drift tube and/or the virtual cathode oscillation frequency one is in a position to select the wave guide mode which propagates. The 35% RF conversion efficiency was obtained with a TM_{03} mode! Future simulations will attempt to produce a TM_{01} mode with a resultant higher efficiency of microwave production.

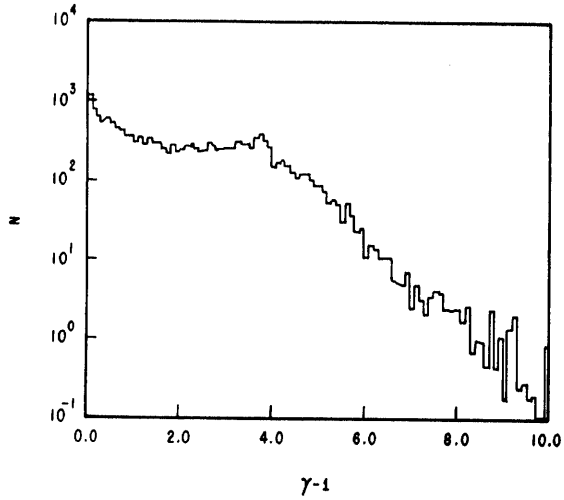

Fig. 3. Beam particle distribution over kinetic energy (γ-1). The initial kinetic energy was 4.0.

While the largest autoacceleration per unit length occurs when no axial magnetic field is imposed, total autoacceleration may be increased when a weak spatially varying field is present. The field would be necessary to contain the beam while not cutting off acceleration completely. The beam could then be staged as noted above. Additional problems would arise due to the development of a zero frequency cyclotron wave. Studies in this area will be conducted shortly.

Finally, the coincidence of certain aspects of autoacceleration experimental results, such as optimum length of the drift tube for autoacceleration[1] and energy spectrum of the accelerated portion of the beam,[8] with the process reported in this paper is noted. It is suggested that experimental results should be reviewed in order to determine what, if any, role virtual cathode oscillation played in the acceleration process.

Acknowledgements

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