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RADIAL IMPLOSION ACCELERATION

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ABSTRACT

In this paper we propose a scheme to generate high accelerating gradients [approximately ($\sim$) a few gigaelectronvolts per meter]. The acceleration is nonresonant so that staging may be fairly easy, and the energy source is relativistic e-beams so that a relatively high overall efficiency may be achievable.

I. INTRODUCTION

A magnetic field of 100 kG is equivalent to an electric field of 3 GeV/m. The only way such a magnetic field can be made available for acceleration is through the equation

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \quad ; \tag{1}$$

that is, we must move magnetic fields around or destroy them to generate electric fields. Letting $\nabla \sim 1/L$ (where L is a typical dimension) and $\partial/\partial t \sim 1/T$ (where T is a typical time) Eq. (1) is roughly

$$|E| \sim \frac{1}{c}\left(\frac{L}{T}\right) |B| \equiv \frac{V}{c} |B| \quad . \tag{2}$$

Thus, to get $|E| \sim |B|$, we must have $V/c \sim 1$; that is, we must move B-fields at nearly the velocity of light. An obvious technique for doing this is to push on the B-field with relativistic e-beams. The geometry we have in mind is shown in Figs. 1a and 1b.

Imploding the B-field requires a certain minimum e-beam pressure. We estimate the magnetic pressure as

$$P_B = \frac{B^2}{8\pi} \quad . \tag{3}$$

The e-beam pressure is approximately

$$P_e \simeq J\gamma m v \quad , \tag{4}$$

where J is the particle current/area ($J \sim cm^{-2} sec^{-1}$), γ is the relativistic mass factor, m is the mass, and v is the particles' velocity.

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If we use electrons at 10 MeV and assume B = 100 kG, then we find

$$J \gtrsim 165\ \mathrm{kA/cm^2} \quad . \tag{5}$$

Such current densities have been achieved in a number of machines. The length of the e-beam pulse can be estimated to be the electron gyromagnetic radius divided by the implosion velocity. For the above example, this becomes

$$T_{pulse} \sim 10\ \mathrm{ps} \quad . \tag{6}$$

Thus, the geometry and current density are typical of the Sandia proton beam fusion accelerator (PBFA) running with electrons; however, the pulse length is about 1000 times shorter, and the stored energy required is about 1000 times less.

Because the generated electric field is almost purely longitudinal, the coupling efficiency to accelerated particles can be quite high. In addition, relativistic e-beams can be generated with high efficiency, so that the overall efficiency can potentially be very good. How much of this potential can be realized depends on the details of the implosion process.

In the next section we present a one-dimensional snowplow model for the implosion process to elucidate the details and to show that the implosion velocity is approximately the speed of light. In Sec. III we discuss the validity of the one-dimensional assumption and point out the influence higher dimensional instabilities may have on tailoring the current and energy profile in the e-beams. In Sec. IV we present two schemes for setting up the initial B-field configuration. In the final section we discuss the advantages of our scheme and point out areas for future investigation.

II. SNOWPLOW MODEL

The implosion process not only allows us to move B-fields at the velocity of light, but also to begin with a modest B-field over a relatively large volume and to compress it to a large value. To investigate the implosion process let us use a Cartesian one-dimensional model.

Note from Fig. 1b that the field on axis (r=0) is zero. Letting the Cartesian variable x correspond to r, we use the magnetic field model shown in Fig. 2. This is a snowplow model in which we assume that the e-beams push all of the magnetic flux ahead of them and that the front is sharp. Analytically the magnetic field is

$$B_z = B(t)\,\frac{x}{L(t)}\,[H(x + L) - H(x - L)] \quad , \tag{7}$$

where $\pm L(t)$ are the positions of the fronts and where H is the Heaviside function. Using Eqs. (1) and (7) and recalling that $B(t)L(t) = B(0)L(0)$ = constant, we find that the induced electric field is

$$E_y = B(t)\left(\frac{\dot{L}(t)}{c}\right)\left(\frac{x}{L(t)}\right)^2 [H(x + L) - H(x - L)] \quad , \tag{8}$$

as shown in Fig. 3. Note that for $x = \pm L$, $E_y = B(\dot{L}/c)$; that is, the magnitude depends on the front velocity $\dot{L}$ as we expected.

To find an equation for $L(t)$, we use momentum conservation. The momentum in the fields is

$$\vec{p}_{field} = \frac{1}{4\pi c} \vec{E} \times \vec{B} \quad . \tag{9}$$

Note that $\vec{p}_{field}(x=0) = 0$, so that the momentum of the particle beam coming from the right (Fig. 2) is absorbed by the fields in $x > 0$. Using Eqs. (7) and (8) in the region $0 \leq x \leq L$, we find

$$\vec{p}_{field} = \frac{\hat{x}B^2}{4\pi c} \left(\frac{\dot{L}}{c}\right)\left(\frac{x}{L}\right)^3 \quad . \tag{10}$$

Integrating the momentum conservation equation

$$\frac{d\,\vec{p}_{field}}{dt} = -\frac{d\,\vec{p}_{particles}}{dt} \tag{11}$$

over the region $x > 0$, we find

$$\frac{B^2}{16\pi c^2} (L\ddot{L} - \dot{L}^2) = -J\gamma mv\left(1 - \frac{|\dot{L}|}{c}\right) \quad , \tag{12}$$

where the particle momentum transfer rate has been reduced to account for the electrons catching up to the front and where Eq. (4) has been used for the change in particle momentum.

Ideally, the particle beam pressure will be tailored to match, approximately, the magnetic field pressure so that excess energy use and instabilities can be minimized. We thus let

$$J\gamma mv \equiv \frac{\alpha(t)B^2}{8\pi} \quad , \tag{13}$$

where α is a, possibly time-dependent, factor of order 1. With this assumption, and noting that we want $\dot{L} < 0$, Eq. (12) becomes

$$L\ddot{L} - \dot{L}^2 = -2\alpha c^2\left(1 + \frac{\dot{L}}{c}\right) \quad . \tag{14}$$

A numerical solution of Eq. (14) for α = constant = 1 is shown in Fig. 4 where $\dot{L}$, the implosion velocity, is plotted as a function of time. It can be seen that fairly quickly the front starts moving at a uniform velocity. In this regime, we let $\ddot{L}$ = 0, and find that Eq. (14) becomes

$$\dot{L} = \alpha c\left(1 - \sqrt{1 + \frac{2}{\alpha}}\right) \quad . \tag{15}$$

The quantity $|\dot{L}|$ achieves its maximum value when $\alpha = \infty$, where $\dot{L} = -c$. For $\alpha = 1$ we find

$$\dot{L} = -0.732\ c \quad . \tag{16}$$

We observe from Fig. 3 that the accelerating field is nonuniform transversely, and thus that one will want to accelerate hollow beams. The transverse nonuniformity will not be so dramatic as shown in Fig. 3 for two reasons: (1) the front will not be as sharp as we assumed in our simple model; (2) the front will move transversely while the accelerated particles traverse the accelerating region longitudinally, causing the accelerated particles to feel a transverse average of the accelerating gradient.

Although we have, for simplicity, assumed α = constant, it is clear that $\alpha(t)$ should be tailored in such a way as to minimize instabilities and may also be chosen so as to produce more uniform accelerating fields. The actual $\alpha(t)$ will depend on a number of factors, including the extent to which J_Y can be controlled in practical e-beam machines. The detailed choice of the optimum $\alpha(t)$ probably will require extensive numerical computation.

III. RAYLEIGH-TAYLOR INSTABILITIES

In the previous section we assumed that the implosion was effectively one-dimensional. Higher dimensional effects will appear mainly through the onset of instabilities, principally the Rayleigh-Taylor instability. The implosion front is Rayleigh-Taylor unstable during the acceleration of the front and becomes neutrally stable during the uniform velocity and deceleration (maximum field) phases of the front.

Because we anticipate using the uniform velocity and deceleration phases of the front for particle acceleration, the principal concern arising from the Rayleigh-Taylor instability has to do with the amount of field flux actually captured by the front. The less flux captured, the higher will be the e-beam energy required for a given accelerating gradient and, thus, the lower the efficiency. By tailoring $\alpha(t)$ initially, it should be possible to minimize the effect of the Rayleigh-Taylor instability, because $\alpha(t)$ controls the acceleration rate. Finding the optimum $\alpha(t)$ probably will require numerical simulations.

IV. INITIAL CONFIGURATION

There are at least two ways that the initial B-field configuration can be obtained: exciting it with a high-current, low-energy e-beam along the accelerator axis, and running the gap as an rf cavity.

By exciting the gap with a preceding e-beam, the desired B-field can be set up. In this mode of operation, our scheme resembles a wake-field accelerator in which the wake function is dramatically increased by the imploding e-beams.

If we excite the gap with pulsed rf power in the TM_{010} mode, the B-field configuration will have the desired form for a half cycle of the rf. However, the vanishing of the azimuthal B-field at the walls seriously violates the 1-D geometry assumption. By adding a static axial B-field, we can prevent all the electrons from flowing along the wall. It is possible that such a configuration might develop into a roughly 1-D implosion, although probably this can only be investigated in numerical simulations.

It is, of course, also possible that other schemes can be devised to set up the initial B-field.

V. DISCUSSION

The scheme we have proposed may have several advantages to recommend it. First, the accelerating gradient can be quite high and might be pushed even higher than we have estimated if higher current-density e-beam machines become available. Next, the overall efficiency might be quite good because e-beams can be produced with high efficiency and the E-fields generated are almost purely longitudinal. Finally, the acceleration is nonresonant, which implies both easy staging of accelerating sections and the possibility of accelerating slower particles, such as heavy ions.

A number of issues clearly remain to be resolved. The best initiation scheme must be decided on. The influence on the Rayleigh-Taylor instability should be investigated in more sophisticated models, probably including numerical simulations. The acceleration process should also be studied in better models to determine both the best beam to accelerate and the energy spread induced by the transverse variation of field.

Once the theoretical tools have been devised to design and interpret an experiment, it will be appropriate to build such a machine. Note that such an experiment could be rather modest in scope because the implosion and acceleration processes can be tested in a single gap. The simultaneous promise of high accelerating gradient and high efficiency would certainly justify such an effort.

Fig. 1a. View from side of initial configuration.

Fig. 1b. View along accelerated beam axis of initial configuration.

Fig. 2. Plot of magnetic field as a function of x at a fixed t.

Fig. 3. Plot of electric field as a function of x at fixed t.

Fig. 4. Plot at $\dot{L}(t)/c$ as a functio of t.

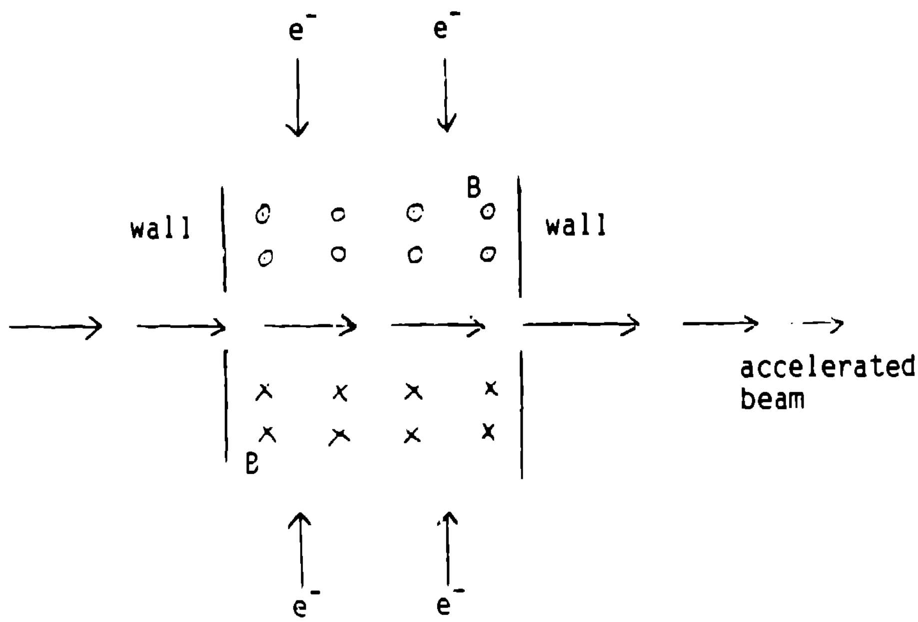

Fig. 1a. View from side of initial configuration.

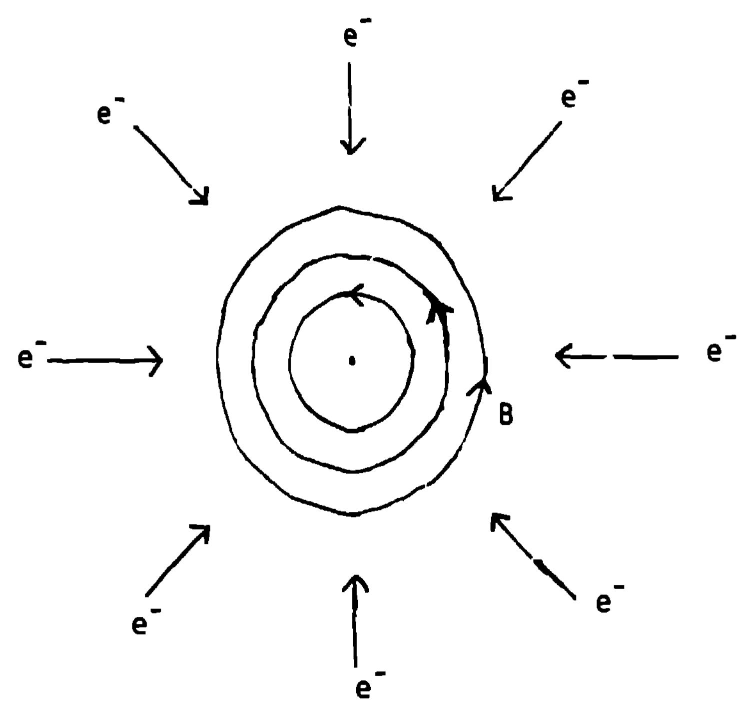

Fig. 1b. View along accelerated beam axis of initial configuration.

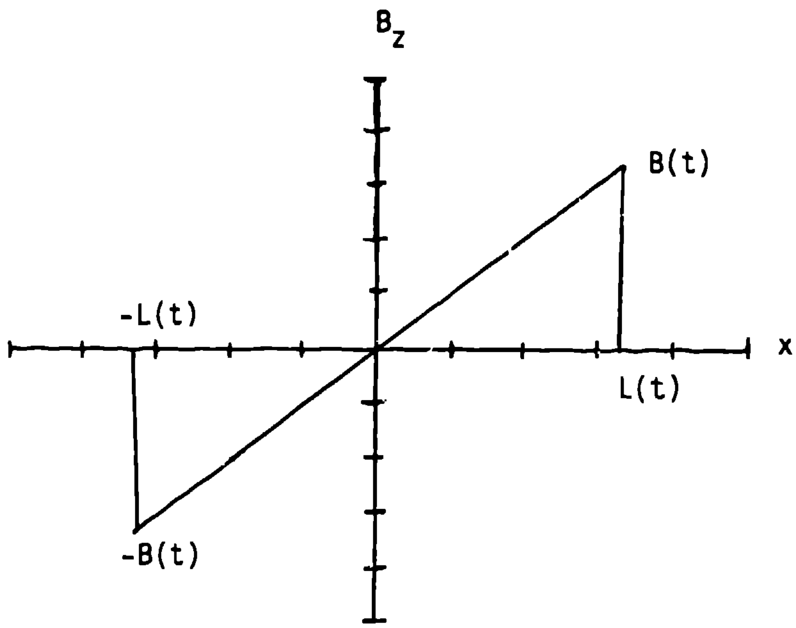

Fig. 2. Plot of magnetic field as a function of x at a fixed t.

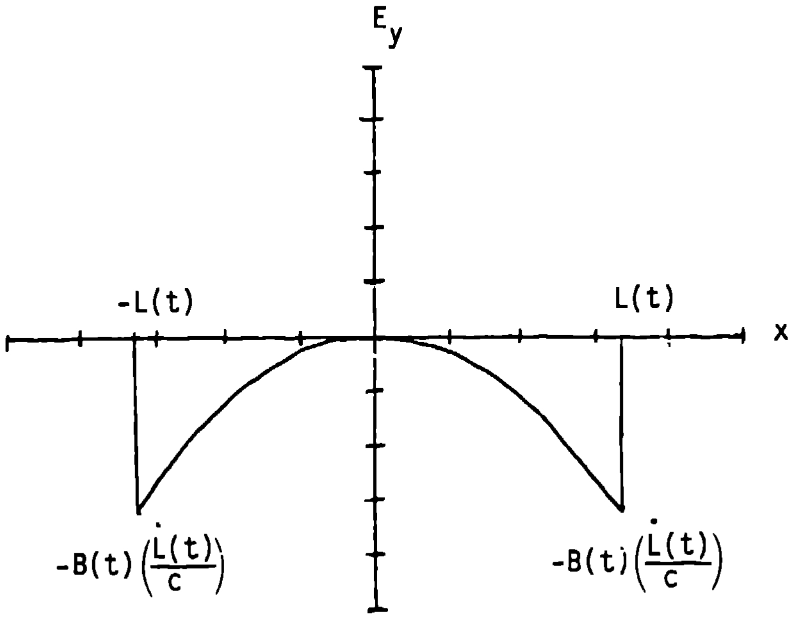

Fig. 3. Plot of electric field as a function of x at fixed t.

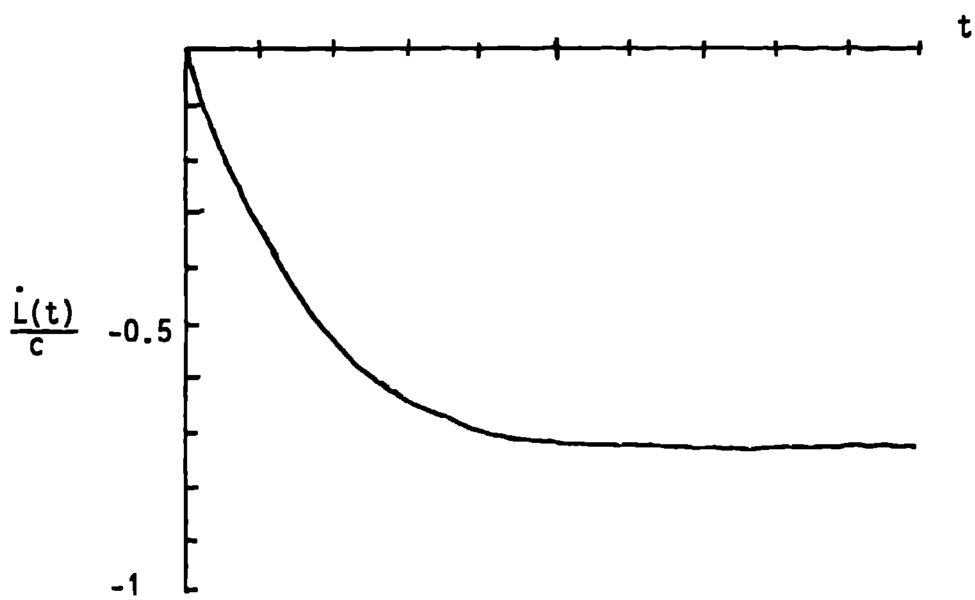

Fig. 4. Plot of $\dot{L}(t)/c$ as a function of t.