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SIMULATION STUDIES ON A NOVEL BETATRON INJECTION SCHEME

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Abstract

The feasibility of external transport into a modified betatron by the propagation of a relativistic electron beam into a z-pinch channel is discussed. Results from particle-in-cell simulations do not indicate any deleterious instabilities. Though the plasma collision frequency is shown to be just large enough to suppress the beam-plasma instability, a discharge current tapering scheme for decreasing the beam perpendicular velocity will also be a principal stabilizing mechanism. A new high-frequency microwave source based on this study is also detailed.

Introduction

In this paper we discuss the feasibility of using applied currents in waveguide structures both as a means of transporting high-current relativistic electron beams across magnetic field lines and also as a possible source for the production of high-frequency and highly tunable microwave radiation.

The basic concept is as follows: a relativistic electron beam is injected into a conducting drift tube of radius R and length L. An axial current, I, is produced either by a gas discharge or by inserting a guiding wire along the cylindrical axis. The resulting magnetic field B_0 varies either as the radius r or as 1/r, depending on which current scheme is used. An axial magnetic field B_z is applied by external coils.

Cross-field transport of relativistic electron beams by this method has been discussed with relation to injection into the NRL modified betatron by Mako et al [1]. Analytical and numerical results based on simple single-particle theory seem to suggest that this approach is feasible provided the discharge current is tapered along the cylindrical axis to reduce the increase in beam perpendicular velocity $v_\perp$.

In this report we present preliminary results of particle-in-cell simulations of the full self-consistent and electrodynamic problem of beam dynamics in both the cross-field transport and microwave problems. Our calculations include effects of beam injection through a foil, waveguide modes, and resistive walls. The simulations are done with the fully relativistic and electromagnetic 2½-dimensional particle-in-cell code CCUBE.

Cross-Field Transport into a Betatron

The feasibility of transporting a high-current relativistic electron beam across magnetic field lines via a z-pinch channel was first proposed by Mako et al [1]. In this injection approach, a relativistic electron beam is introduced into a modified betatron through a small diameter tube that is terminated in a thin foil.

The basic scheme is pictured in Fig. 1. A current channel created by the electrical breakdown of a gas (e.g., hydrogen) is used to focus a 10 A electron beam across a transverse betatron field $B_x \cong 0.7$ kG. The beam is guided by a 2 kG longitudinal magnetic field along the tube axis.

External injection has several attractive advantages over direct beam injection into a modified betatron via a protruding high-voltage cathode [1]. First, the high vacuum of the torus can be isolated from the rougher vacuum of the injector. Also, because a smaller porthole is required, electric and magnetic field perturbations are correspondingly

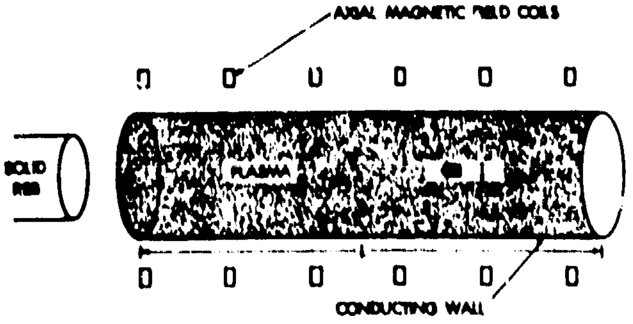

Fig. 1. Current-channel scheme for cross-field transport into a betatron. The plasma channel has a radius r = a, and the wall is at r = R.

smaller. In addition, there can be no applied voltage perturbation that results from the cathode voltage fall time. Finally, because the anode-cathode plasma is removed from the vacuum chamber, one source for the ion resonance instability is removed.

To analyze the effect of the magnetic field B_θ due to the current channel on a beam particle, we consider the single-particle equation of motion

$$\frac{d}{dt}\,(\gamma m\underset{\sim}{v}) = \frac{-|e|}{c}\,(\underset{\sim}{v} \times \underset{\sim}{B}) \quad . \tag{1}$$

In this equation, B_z is the longitudinal guide field and $B_\theta = 2Ir/a^2$ is the field due to the current channel, where I is the magnitude of the current and a is the channel radius. From Eq. (1), an equation for the axial coordinates z(t) can be derived in the form

$$\frac{dz}{dt} = v_o + A\sin^2(\omega t + \phi) \quad , \tag{2}$$

where A and ϕ are numerical constants, and we have assumed $v_z(0) = v_o$, $v_r = v_\theta = 0$. The quantity ω is defined to be $\omega = (v_o\Omega_\theta/a)^{1/2}$ where $\Omega_\theta = |e|B_\theta/\gamma mc$. Solving Eq. (2) for the betatron wavelength $\lambda_b \cong 2\pi v_o/\omega$, we find

$$\lambda_b \cong 2\pi\left[\frac{a^2\gamma m v_o c^2}{2|e|I}\right]^{1/2} \quad . \tag{3}$$

As this wavelength approaches the cylinder radius, waveguide effects become increasingly important. The values for the betatron wavelength given in (3) have been verified by us in the numerical runs.

The simulations were conducted in the following manner: A plasma consisting of both ions and electrons and having a density $n_p \sim 3 \times 10^{16}$ cm^{-3} supports a current of 20 kA. At a time $t = t_o$, a relativistic electron beam ($\gamma \cong 7$, $n_b \cong 3 \times 10^{10}$) is injected into this channel. Besides analyzing for transport effects on the perpendicular beam velocity (Fig. 2), simulations were run to investigate the possibility of two-stream instabilities and resistive wall effects.

The cold beam growth rate δ_c for the beam-plasma instability is given by

$$\delta_c/\omega_{pe} = \frac{\sqrt{3}}{2\gamma}\left(\frac{n_b}{2n_p}\right)^{1/3} \tag{4}$$

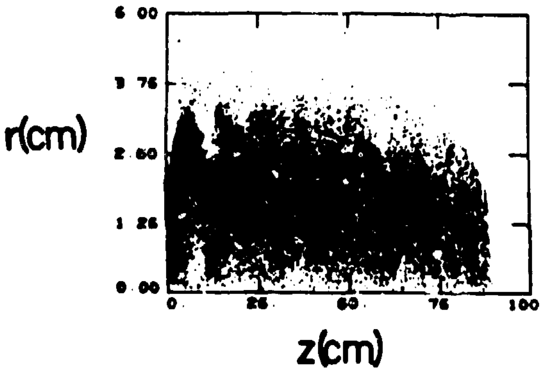

Fig. 2. Particle simulation plot of a relativistic electron beam traveling through a current channel. In the absence of tapering, beam focusing is accompanied by a large increase in beam perpendicular energy.

From the parameters given above, we find that $\delta_c/\omega_{pe} = 10^{-3}$ or $\delta = 10^{10}$ sec^{-1}. An e-folding time for this growth rate is 0.1 ns, so that two-stream effects in this injection scheme may pose a problem.

For relativistic electron beams scattered elastically by a thin anode foil, we calculate the parameter $a = 2/\bar{\theta}^2$, where $\bar{\theta}$ is the mean angle scatter defined by the ratio of the beam thermal velocity to the speed of light. If $a\delta_c/\omega_{pe} < 1$, or $\bar{\theta} > (2\delta_c/\omega_{pe})^{1/2} \cong 0.04$ we are in the kinetic regime [2]. In the NRL experiment $\bar{\theta} \cong 0.05$, so that the inequality is just satisified. Because we are on the threshold of the cold beam regime, we can approximate the relevant kinetic growth rate δ [Ref 3] by the cold beam growth rate given in Eq. (4).

Preliminary simulation results indicate, however, that the beam-plasma instability may not develop as expected. We have considered three possible scenarios for this phenomenon: 1) high plasma temperatures; 2) finite beam temperatures and collisions; and 3) axial plasma density gradients.

In the first case, an estimate for the plasma temperature required can be obtained by equating the growth rate (4) to that of Landau damping. However, for the beam energies typical of relativistic electron beams, plasma temperatures in excess of hundreds of kilovolts are needed, so that this does not describe the simulation results (T < 10 eV) or actual experimental conditions.

The beam-plasma instability can also be stabilized by finite beam temperature and collisions. The stabilization criterion is actually the relativistic generalization of the Singhaus criterion [2]. A rough estimate of the collisionality required for stabilization is found by setting the growth rate δ equal to the collision frequency, or ν 10^{10} sec^{-1}.

Using a typical channel resistivity of $\eta = 1.15 \times 10^{-14}$, one finds $\nu = 8.7 \times 10^{10}$ sec^{-1}, so that collisional effects may be strong enough to suppress the instability.

Finally, it is now known that axial density gradients tend to stabilize the beam-plasma instability [4-6]. The physical reason for this is essentially that the scale length over which the instability can develop (i.e., over which the plasma wave ω_p is in resonance with the beam wave $\omega_b - kv$) can become infinitesimally small. This effect may be quite pronounced even for small inhomogeneities [6], and may be the principal stabilizing mechanism for this injection scheme. However, because the theoretical scaling of this process with density gradient is a complicated and not well understood function of the beam and plasma parameters, further simulations will be needed to substantiate this contention. Thus, the use of a current tapering scheme to decrease the perpendicular velocity [1] may also have the advantage of stabilizing the injector against the two-stream instability.

Finally, a resistive wall physics package has been developed at Los Alamos to complement the particle-in-cell code CCUBE [7]. Preliminary results of resistive wall effects in this injection scheme have only recently been obtained and will be reported on at a later date.

Wiggler-Free Free Electron Laser

A variant of the transport scheme described in the last section is to consider the beam with the guide and toroidal magnetic fields included but without the inherent complications of an ambient plasma. This can be realized by substituting for the current channel a wire placed on the cylindrical axis carrying a current I (Fig. 3).

As in the free-electron laser (FEL) scheme, the interaction of the drifting beam with the static magnetic fields provides an incoherent source of "tickler" radiation to interact back on the beam. It may be possible to use this "tickler" source as a way of creating beam bunching and extremely phase-coherent microwave radiation at submillimeter wavelengths. In addition, the radiation at these high frequencies can be tuned to even higher frequencies by simply adjusting the current in the wire.

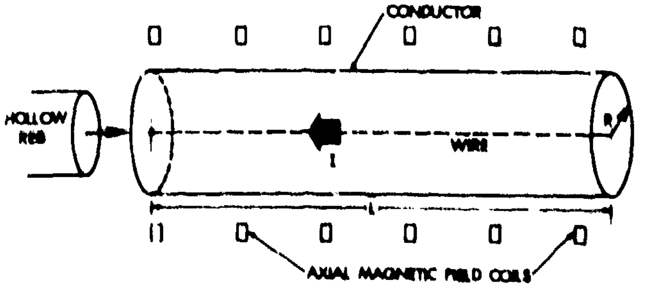

Fig. 3. Microwave generation scheme by current carrying wire.

This device is more similar to the FEL than other wiggler-free schemes [8,9] in that the magnetic field structure is more or less the same. Other concepts [8,9] envision electron motion in a simple uniform magnetic field giving rise to radiation with an up-shifted Doppler cyclotron frequency. Interestingly enough, this gyrotron-type mode may also have been observed in our simulations.

As in the previous section, the equation of motion for a single particle in the crossed B_z and B_θ magnetic fields is

$$\frac{d}{dt}(\gamma m \underset{\sim}{v}) = -\frac{|e|}{c}\,\underset{\sim}{v} \times \underset{\sim}{B} \tag{5}$$

where now, however, $B_\theta = 2I/cr$. If we assume that $(r_o - r)/r_o \ll 1$ where $r_o = r(t = 0)$, we obtain the following approximate solutions:

$$r(t) = r_o + \rho\,(1 - \cos\alpha t)$$

$$z(t) = v_o t[1 - (2I/I_A)(\rho/r_o)] - (2I/I_A)(v_o\rho/\alpha r_o)\sin\alpha t$$

where $I_A = (mc^3/e)\beta\gamma$ is the Alfven current, $\alpha = (r_o^2\Omega_z^2/v_o^2 - 2I/I_A)^{1/2}$, and $\rho = (v_o^2/r_o\alpha^2)(2I/I_A)$. The axial wavelength of a particle orbit is then

$$\lambda = (2\pi v_o/\alpha)[1 - (2I/I_A)(\rho/r_o)].$$

A typical simulation plot is shown in Fig. 4. This simple calculation accurately predicts the axial particle wavelength for $\lambda < R$ and $(r_o - r)/r_o \ll 1$.

Microwave radiation wavelengths in the simulations are determined by Fourier analysis of the electric field probes placed in the computational box at $r \approx 0.2$ cm and $z \approx 100$ cm. It has been found that unless the magnetic field B_θ is tapered to allow the beam to be adiabatically injected into the device, the E_r and E_θ electric field probes show excessive noise, making resolution of distinct frequency peaks difficult. Even with such background noise effects,

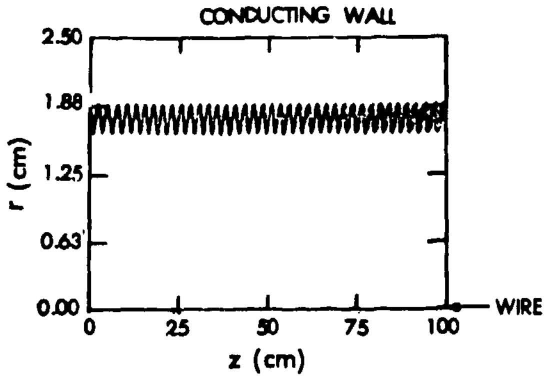

Fig. 4. Particle beam orbits in a helical magnetic field.

there do exist distinct microwave peaks in the spectrum of E_z for almost every simulation run [Fig. 5]. These peaks are also correlated with numerical Poynting vector information to substantiate the correctness of our observations.

The "wiggler-less" wavelength in the helical fields is given by $\lambda_w = r_0(B_z/B_\theta)$. If we assume FEL scaling $\lambda = \lambda_w/2\gamma^2$ we can write

$$\lambda = \frac{c r_0^2 B_z}{4\gamma^2 I} \quad .$$

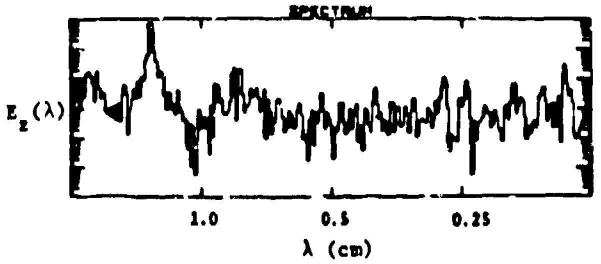

Fig. 5. Fourier spectrum of electric field E_z probe near wire at z = 100 cm. Radiation peak at $\lambda \cong 2$ cm is displayed.

To "tune" the device to millimeter wavelengths with the Anomalous Intense Driver (AID) facility at Los Alamos (B_z = 100 kG, γ = 7) a current I = 50 kA is required for $r_0 \cong 1$ cm. The tunability of this device (especially for high frequencies) may have distinct advantages over the usual FEL since one need only adjust the wire current to tune the radiation frequency.

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