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ELECTRON BEAM PLASMA INTERACTIONS

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ELECTROMAGNETIC EFFECTS IN RELATIVISTIC ELECTRON BEAM PLASMA INTERACTIONS

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ABSTRACT

Electromagnetic effects excited by intense relativistic electron beams in plasmas are investigated using a two-dimensional particle code. The simulations with dense beams show large magnetic fields excited by the Weibel instability as well as sizeable electromagnetic radiation over a significant range of frequencies. The possible relevance of beam plasma instabilities to the laser acceleration of particles is briefly discussed.

INTRODUCTION

Beam-plasma instabilities are of interest in many applications. These include plasma heating, space and astrophysical plasmas, the generation of radiation, and perhaps even some laser particle accelerators. There's been a great deal¹ of previous theory and computer simulation of beam-plasma instabilities, primarily motivated by applications to plasma heating. Our work is motivated by some recent experiments² by Kato, Benford and Tzsch. In these experiments, the electromagnetic radiation due to a relativistic electron beam interacting with a plasma was measured. When the beam density was comparable to the plasma density, it was found that a significant fraction of the beam energy was converted to microwaves (of order 0.2%). These waves had a broad range of frequencies, extending to many times the electron plasma frequency ω_{pe} , rather than simply having frequencies of ω_{pe} and its harmonics.

To investigate the beam-plasma interaction, we have used a two-dimensional electromagnetic, relativistic particle code.³ The beam travels in the x-direction, and the evolution of E_x , E_y and B_z is followed in the x-y plane. We started with the simplest problem-following the temporal evolution of an electron beam in a uniform plasma with no guide magnetic field. The boundary conditions were doubly-periodic, and the simulation box was rectangular with $L_x = 10.9 c/\omega_{pe}$ and $L_y = 50.2 c/\omega_{pe}$, where c is the velocity of light and ω_{pe} is the electron plasma frequency. The results changed by less than about 20% when both L_x and L_y were halved. The ions were

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usually treated as a fixed neutralizing background, and 800,000 electrons were used. Initially the beam had a kinetic energy of approximately 0.5 Mev (i.e., $\gamma = 2$) with a very narrow thermal spread of 50 eV. The background electrons had a temperature of 2.5 keV and were initialized with a drift in order to balance the initial beam current. The beam density (n_b) ranged from 0.05 to 0.5 of the total electron density (n_t).

The beam-plasma interaction in these simulations is dominated by two instabilities. The first is the well-known electron-electron beam instability, in which electrostatic waves are driven unstable. For a beam with a narrow spread in energy and angle and for $n_b/n_p \gamma_b < 1/20$, the results for the frequency and growth rate of the most unstable mode are

$$\frac{\omega}{\omega_{pe}} = 1 - \frac{1}{2} \left(\frac{n_b}{2n_p \gamma_b} \right)^{1/3} f(\theta)$$

$$\frac{\gamma}{\omega_{pe}} = \sqrt{3/2} \left(\frac{n_b}{2n_p \gamma_b} \right)^{1/3} f(\theta), \quad (1)$$

$$\text{where } f(\theta) = \left(\sin^2 \theta + \frac{\cos^2 \theta}{\gamma_b^2} \right)^{1/3}.$$

Here $n_b(\gamma_b)$ is the density (gamma) of the beam, n_p the plasma density, and v_b is the beam velocity. In addition, θ is the angle between the wave vector k and v_b , and $k \cdot v_b = \omega_{pe}$. The other instability corresponds to a purely growing, spatially varying magnetic field transverse to the beam. The maximum growth rate occurs for $\theta = 90^\circ$ and is

$$\frac{\gamma}{\omega_{pe}} = \left(\frac{n_b}{\gamma_b n_p} \right)^{1/2} \frac{k v_b}{(k^2 c^2 + \omega_{pe}^2)^{1/2}}, \quad (2)$$

This Weibel instability occurs since parallel currents attract. Hence beam electrons tend to bunch together or coalesce into filaments, as do also the background electrons carrying the return current. Of course, this instability also produces an electrostatic field which expels background electrons from a filament in order to preserve quasi-neutrality.

SIMULATION RESULTS

To illustrate the simulation results, let's consider a robust example in which $n_b = n_p$. The electrostatic field energy (EL) versus time is shown in Fig. 1.

Fig. 1. Evolution of the electrostatic field energy in a 2-D simulation ($\gamma_b = 2$, $n_b = n_p$).

Note that early in time there is very rapid growth ($\gamma \approx 1/2 \omega_{pe}$), followed by a period of slower growth as the beam nonlinearly develops a significant spread in energy and angles. Finally, the wave energy saturates at about 12% of the initial kinetic energy of the beam as the velocity distribution becomes monotonic. The wave energy thereafter slowly decays.

The magnetic field energy ($B^2/8\pi$) versus time is shown in Fig. 2. The magnetic field due to the Weibel instability initially grows very rapidly ($\gamma \approx 1/2 \omega_{pe}$), and then grows more slowly as the beam spreads in energy and angles. Finally the magnetic field saturates at a quite large value which corresponds to $\omega_{ce}/\omega_{pe} \approx 0.5$, where $\omega_{ce} = eB/mc$ is the electron cyclotron frequency for a nonrelativistic particle.

As the unstable waves grow and saturate, electromagnetic waves are generated as shown in Fig. 3. In this example, the transverse electric field energy (EM) reaches about 2% of the kinetic energy of the beam (KE_b). These electromagnetic waves have a significant range of frequencies, rather than just a

Fig. 2. Evolution of the magnetic field energy in a 2-D simulation.

Fig. 3. Evolution of the transverse electric field energy (EM) in a 2-D simulation.

frequency of ω_{pe} and its harmonics. Figure 4 shows the Fourier transform of B_z at a given location in the plasma.

Fig. 4. Fourier transform of the magnetic field at a specific location in the plasma ($\gamma_b = 2$, $n_b = n_b$)

Note the large peak at $\omega = 0$, which is due to the Weibel instability, followed by a signal extending from ω_{pe} to 3-4 ω_{pe} , which is due to light waves. A broad range of frequencies is generated, a feature noted in the experiments. However, the amplitude of the light waves falls off more rapidly with frequency than experimentally observed.

Weaker beam densities have also been simulated. For a $\gamma_b = 2$ beam with $n_b/n_t = 0.3$, the peak magnetic field is $\omega_{ce}/\omega_{pe} \approx 0.17$, and about 0.3% of the kinetic energy of the beam is converted to transverse electric fields. For $n_b/n_t = 0.05$, $\omega_{ce}/\omega_{pe} \approx 0.017$ and the fraction into transverse electric fields is only about 0.06%. In all these cases, the beam loses about 40% of its energy to the plasma. The beam ends up with a spread in velocity comparable to its initial velocity as well as a broad range of angles.

Although we obtain many of the qualitative features observed in experiments, our simulations are very idealized. The transient temporal problem does not do justice to effects such as those associated with ion motion. For example, note in Fig. 1 that the electrostatic field rises and decays in a time of $\approx 100 \omega_{pe}^{-1}$, which is too quick for the ions to respond. A spatial problem in which the beam is continually injected would be more realistic and would also admit boundary conditions closer to

those in experiments. Allowance for spatial variations in the background plasma density and beam quality may also be important for details of the radiation generation and the power spectrum.

Finally our simulations indicate that beam plasma interactions (electrostatic and electromagnetic) might play a role in schemes such as the beat wave accelerator.⁴ The effect of these instabilities will depend on factors such as the beam density, energy, and spatial width and structure. In experiments currently planned at UCLA,⁵ it is estimated that $n_b/n_p \approx 10^{-2}$ and $\gamma_b \approx 20$. The growth rate of the electron-electron beam instability is then $\approx 0.05 \omega_{pe}$, and that of the Weibel instability is $\approx 0.02 \omega_{pe}$. For future applications, the beam density (and γ_b) will be significantly larger. However, it is not clear that these instabilities will have a deleterious effect. The finite radial extent of the beam can be a stabilizing influence, limiting the wave vectors of the unstable waves. In addition, the finite extent of the beam bunch may allow the beam to "outrun" the unstable fluctuations,⁶ particularly since they have wave vectors at significant angles to the beam. Improved simulations can help clarify potential limitations as well as guide experiments.

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