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CURRENT NEUTRALIZATION IN HIGH ν/γ RELATIVISTIC ELECTRON STREAMS*

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by

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Introduction

This paper presents several features of beam-physics research carried out at Physics International over the last two years. The goal of previous work has been that of efficiently propagating mulimegampere relativistic electron beams over several meters, and concentrating the energy of such 10^{12} W sources in small volumes. Quite recently the work has been directed toward the acceleration of background gas ions through the beam-plasma interaction. Initial experiments to determine the time dependence, charge state, and momentum distribution of accelerated ions have been carried out (Reference 1), but the actual mechanism of acceleration is still a subject of contention (References 2 to 5). This report will focus primarily on beam transport.

Until early this year our work has utilized machines which consist of oil dielectric, coaxial transmission lines with an impedance range of 6 to 8Ω (Reference 6). The transmission line is switched into a field emission diode whose impedance can be varied in the range of 1 to 8Ω. Typical beam parameters are 200-keV to 1-MeV mean electron energy, 100 to 200-kA peak current, and 50-nsec pulse duration (full width at half maximum), which gives a range of ν/γ, I (amps)/17,000 $\beta\gamma$, from roughly 1.0 to 10.0. Within the last few months we have begun to explore the problems of handling beams in the megampere range using 0.1 to 0.25Ω mylar-strip transmission lines and low inductance diodes (Reference 7). Only the results of our work in the $\nu/\gamma \sim 10$ range, which have partially appeared in the open literature (Reference 8), are summarized here.

Diagnostics

Drift chamber diagnostics include segmented graphite and thin-foil depth-dose calorimeters, wall-current shunts, and Rogowski coils. Faraday cups were also used to measure the primary current at various distances and a scintillator-photodiode to measure the time-of-flight of the beam. Diode diagnostics have included voltage and current monitors to give the spectrum of electrons injected into the drift region. Initial observations involved open-shutter photography to determine general features of beam propagation and magnetic probes to determine the net current.

Discussion

It was discovered early in our work that the value of ν/γ, based on the net current, had to be less than one for the beam to propagate without undergoing rapid turn around in a large chamber within a few centimeters of the anode. In this way our first qualitative confirmation of the Lawson critical current resulted. We have shown since then that by using a guide pipe the size of the beam, wall stabilization occurs, and the beam does propagate, although beam front erosion is quite severe. It was obvious that current neutralization was necessary to propagate beams over any sizable distance.

The problem of very high ν/γ beams propagating into a neutral background gas is a coupled phenomenon of beam dynamics, electromagnetic fields, and plasma properties. This problem will be discussed by breaking it down into each of these component parts.

First, consider a sub-MeV, several hundred thousand ampere beam propagating into a chamber filled with nitrogen in the 1-Torr range. There is roughly a 2-nsec delay before collisional ionization can build up sufficient ion density to allow forward propagation of the beam. Prior to this force neutralization, the beam blows up radially in fields of order of 1 to 10 MeV/cm. Force neutralization occurs when the ratio of ion to electron densities is equal to $1/\gamma^2$ and the beam can then propagate in the forward direction. After this time, but before the fields can substantially change the background gas properties, the net current is equal to the primary current and the electric field is longitudinal and governed by dI/dt. The dimensions of the region over which this electric field exists, and the ratio of the voltage drop across this region to the kinetic energy of the electrons, will govern the degree of perturbation of their velocity. In particular, we have measured values of dI/dt of the order of 2×10^{12} amps/sec, giving fields of 200 kV/meter. Measurements of the actual values of dI/dt as a function of transport distance have been used to calculate the rate of energy loss, and this compares very well with beam front velocity.

The second point to note is that fields of this magnitude will accelerate the secondary electrons and cause avalanche with a formative time that depends on the collision time of the secondaries with the background gas atoms. This formative time has been measured by other workers in pulsed low-pressure avalanche experiments (Reference 9), and we have been able to use these date to predict the current neutralization phenmena in air and other gases such as argon and helium (Reference 10). Measurements in these gases have agreed with our predicitions. Once avalanche occurs, the conductivity of the background gas rises rapidly, allowing the longitudinal electric field to be shorted out by the plasma current. If the gas breaks down rapidly and the conductivity is large after breakdown, then the degree of current neutralization is large. On the other hand, if breakdown occurs late in the pulse or if the conductivity after breakdown is small, the degree of current neutralization is small. We see, additionally, that after breakdown, the electric field is governed by the diffusion of the magnetic field in the conducting plasma and will be considerably smaller than it was prior to breakdown. Electrons within the body of the beam will propagate with almost constant velocity. The actual drift velocity of these electrons is governed by the value of $(\nu/\gamma)_{net}$ and would be some fraction of the initial β because of their transverse motion in the net magnetic field (Reference 11).

Within the body of the beam there will be little work done on electrons and that portion of the beam will propagate efficiently if the value of $(\nu/\gamma)_{net}$ is consistant with the transverse energy initially contained within the beam; that is, for the beam to propagate without energy loss to the walls there must be a radial balance of magnetic pressure and kinetic pressure of the electrons. Unfortunately this balance is impossible if any current neutralization occurs because the value of $(\nu/\gamma)_{net}$ in the diode can be quite large (>10), allowing the transverse energy to be a considerable fraction of total energy. With current neutralization, this transverse energy will be lost to the walls. As a result, one finds that if the drift-chamber pressure is sufficiently low to prevent rapid buildup of plasma conductivity, then the return current will flow in the walls rather than in the plasma, causing magnetic repulsion of the beam, and energy loss will only occur because of beam-front erosion. On the other hand, at pressures in the range of 1 Torr, breakdown occurs quite rapidly and beam front erosion is minimal. However, here the net current is too low to provide for containment of the transverse energy components and again the beam propagates with diminished efficiency.

The prospects for solving the problem of propagating very high ν/γ beams rely on providing a means to both eliminate beam front erosion and contain transverse energy components. We have suggested that both can be achieved by injecting the beam into a high-current linear pinch. We are presently engaged in developing the technique.

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