Particle Trajectories through MIRRORTRON Configurations*

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Abstract

Numerical simulation using the r-z code GYMNOS shows the time evolution of the focusing and accelerating potentials found in Post's MIRRORTRON [1]. Formed in a strongly anisotropic loss cone plasma, the transient potential is generated by the application of an additional local mirror field produced by a strap coil. The current rise time in the strap coil must be on the order of tens of nanoseconds in order for the plasma ions to remain inertially confined while the hot electrons respond to the local mirror force. The plasma density is low in order to facilitate the penetration of the magnetic field into the plasma. Typical plasma densities in a Mirrortron are 10^{10}-10^{11} cm^{-3} with electron temperatures in the hundred keV to several MeV range. The magnitude of the potential produced is on the order of the electron temperature. We follow the formation of this potential peak and project test ions through the resulting fields in order to evaluate the feasibility of using a Mirrortron as a heavy ion accelerator.

I. INTRODUCTION

Particle accelerators envisioned for use as drivers for inertial confinement fusion (ICF) power plants typically represent a large percentage of the total cost of such a plant. The primary reason for this is the great length (4-10 km) required for conventional accelerators to impart sufficient energy to a heavy ion beam. Accelerating gradients in conventional induction linacs are limited, by surface breakdown, to 0.5-1.0 MV/meter.

The Mirrortron ion accelerator concept may offer significant advantages over conventional accelerator technology. These advantages include simultaneous acceleration and focusing and higher accelerating gradients, all of which lead to a much shorter physical structure. In addition, space-charge neutralization may allow the transport of higher beam currents [2].

The mirrortron is based upon the precise control of a local space-charge potential within a mirror confined plasma. A mirrortron ion accelerator would consist of a linear array of mirror cells, each of which would contain a low density, hot electron plasma confined between shallow mirrors (mirror ratio R_m=1.5).

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The rapid creation of a short local mirror midway between the ends of each cell would begin to expel electrons while the cold ions remained stationary due to their inertia. As a result, a high local potential arises in order to prevent the bulk of electrons from escaping. This local potential is predicted to have equipotentials determined by contours of constant magnetic field **B**. Because the constant **B** contours are subject to external control, spatial and temporal control over the accelerating fields is retained.

This paper discusses and summarizes recent results obtained from numerical simulations of a mirrortron cell using the particle-in-cell (PIC) code GYMNOS [3].

II. SIMULATIONS

GYMNOS is a cylindrically symmetric PIC code that uses a rectangular r-z grid. We allow the placement of arbitrary internal boundaries within the simulation region by utilizing a series of mask arrays. This permits us to treat the boundary conditions on each grid point independently. A variety of particle boundary conditions are included: absorption, thermal reemission, injection, and field emission. The following results are obtained using electrostatic and magnetostatic fields. Our intention is to extend the code by implementing a Darwin field solve in order to include magnetoinductive effects.

Formation of equipotentials

We model the formation of equipotentials within a mirrortron cell. The cold ion component is included as a stationary background. The hot (several tens of keV) electrons are modeled as an ensemble of macro particles. A symmetry plane is taken through the middle of the strap coil. The plasma density is constant out to a radius of 6 cm and then falls off exponentially. Boundary conditions on electrons encountering the symmetry plane (at z=0 cm) are taken to be perfectly reflecting. Electrons hitting the boundary at the other end of the box (z=18 cm) are absorbed and thermally reemitted with a velocity satisfying the initial loss-cone velocity distribution constraints. A significant population of low energy electrons would tend to screen the potential being produced as the hot electrons respond to the local mirror field; therefore, the electrons are initialized with a minimum allowed energy criterion which depends upon the chosen mirror ratio.

Numerous runs show us that the equipotentials resulting from a rising local magnetic field can indeed have the predicted focussing and accelerating characteristics. The behavior of a beam of test particles run through a mirrortron field configuration frozen at the peak of the current rise shows just what one would expect. The particles slow as they climb the potential hill and accelerate as they fall down the other side. It is difficult to observe any beam focussing in these initial runs due to the gyromotion of the beam particles in the applied magnetic fields. However, no dramatic degradation of beam quality is observed.

A comparison of the magnitude of the potential produced by the mirrortron as predicted by analytic theory [1] with that seen in various code runs shows fair agreement (Figure 1). The current rise time for all runs is 10 nsec and the background magnetic field varies from 500 to 1000 gauss. The ratio of the magnitude of the change in **B** due to the pulsed coil to the background field magnitude, $\frac{\Delta B}{B}$, ranges from 0.25 to 0.5. Perpendicular electron temperatures vary from 22 keV to 90 keV. All runs use a mirror ratio $R_m=1.5$, which is implemented in the initial velocity distribution.

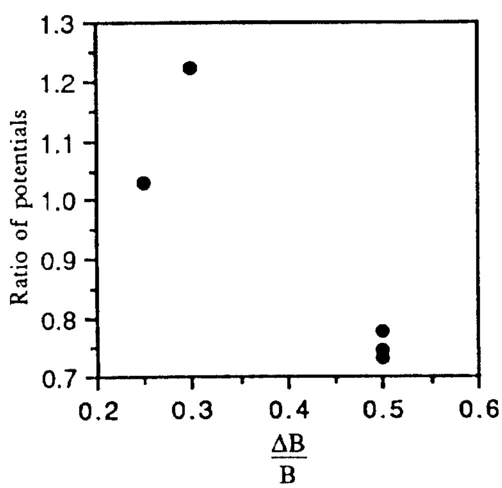

Figure 1. Ratio of the potential computed numerically to that computed analytically vs $\frac{\Delta B}{B}$.

Magnetic pulse propagation

We are also investigating the effect of plasma density on the penetration of the magnetic field. The following table summarizes parameters for a series of six runs:

Table 1.

Run	density (cm^{-3})	$\frac{\Delta B}{B}$	T_e (keV)
A	$5x10^{10}$	0.3	22
B	$5x10^{10}$	0.5	22
C	$5x10^{9}$	0.3	22
D	$5x10^{9}$	0.5	22
E	$5x10^{9}$	0.3	2.2
F	$5x10^{9}$	0.5	2.2

The background magnetic field for these runs is 500 gauss.

Runs A and B, both at high density and high temperature, do not exhibit the anticipated focussing and accelerating potential contours, nor do they display a distinct rise in electric field energy as the magnetic field energy increases. These characteristics are evident in lower density runs C and D. They are also present in the low density cases E and F, runs in which the Debye length is equal to that in runs A and B. Since the low density, low temperature runs (E and F) show a rise in electric field energy and accelerating and focussing potential contours, the lack of this behavior in runs A and B must not be a consequence of electrostatic shielding.

An analysis [4] of extraordinary mode (inductive E perpendicular to B_0) propagation yields an expression for the evanescence length of a magnetic pulse penetrating a plasma:

$$Z_0 = 8.25x10^9 \frac{B_0}{n_e} \qquad (1)$$

In this expression B_0 is the magnitude of the background magnetostatic field. As long as the evanescence length is much greater than the plasma radius, the pulse should penetrate with little attenuation. The above expression yields $Z_0 = 0.83$ cm for the high density cases (A and B) and $Z_0 = 8.3$ cm for the lower density runs (C,D,E, and F). Since the plasma radius in these runs is approximately 6 cm, our results are consistent with this explanation. Attenuation of the magnetic pulse is not expected to be a problem in an actual mirrortron because the relativistic mass increase for hot electrons reduces the dispersive property of the plasma. For $T_e>m_ec^2$, the pulse should propagate almost as if in a vacuum.

Ion beam simulations

As mentioned earlier, we have studied the dynamics of a beam of test particles passing through a static field. The time dependent case is considerably more complicated. Maintaining a well-bunched beam will require careful timing between the pulsed field and the arrival of the beam at the midpoint of the mirrortron cell. Also, due to the rapid field rise, the effects of inductive fields should be considered. Implementation of a Darwin field model will allow us to determine the effects of inductive fields without the boundary condition problems of a fully electromagnetic field model.

III. References

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[4] R.F. Post, private communication.