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STUDIES OF THE MIRRORTRON ION ACCELERATOR CONCEPT AND ITS APPLICATION TO HEAVY-ION DRIVERS*

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The Mirrortron accelerator is a plasma-based ion accelerator concept that, when implemented, should permit both higher acceleration gradients and higher peak-current capabilities than conventional induction-type accelerators. Control over the acceleration and focussing of an accelerated beam should approach that achieved in vacuum-field-based ion accelerators. In the Mirrortron a low density (10^{10} to 10^{11} cm^{-3}) "hot electron" plasma is confined by a long solenoidal magnetic field capped by "mirrors". Acceleration of pre-bunched ions is accomplished by activating a series of fast-pulsed mirror coils spaced along the acceleration tube. The hot electrons, being repelled by mirror action, leave the plasma ions behind to create a localized region of high electrical gradient (up to the order of 100 MV/m). At Lawrence Livermore National Laboratory, an experiment and analyses to elucidate the concept and its scaling laws as applied to heavy-ion drivers are underway and will be described.

1 INTRODUCTION

Linear ion accelerators are candidate "drivers" for heavy-ion fusion (HIF) systems. Although conventional approaches, such as the induction linac, can be visualized in such a role, they are subject to some intrinsic physics limits, set by electrical breakdown and beam space-charge effects. These limits represent an economic penalty, both for the research phase and for their eventual use in HIF power plants. The use of plasma-based accelerators employing collective effects could offer a way out of both of the physics limits if means could be found to preserve a degree of control over the beam as precise as that achieved in vacuum-field-based accelerators. The Mirrortron[1] ion accelerator concept is aimed at meeting both requirements, i.e., utilizing collective effects to achieve high accelerating gradients and high beam current capabilities, while at the same time maintaining precise control of the beam quality.

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High transient space-charge potentials are generated in the Mirrortron by exploiting the mobility of plasma electrons relative to that of plasma ions. That is, if an impulsive force is applied to the electrons they will respond to this force much more readily than will the ions, leading to localized charge separation and, with it, a region of high potential. If, in addition, the plasma response is dictated by the usual quasi-neutrality constraint, the spatial and temporal distribution of the potential can be shown to be controllable from *outside* the plasma with a precision that should approach that attained by vacuum-field accelerators.

A Mirrortron ion accelerator would operate as follows. A low-density (10^{10} to 10^{11} cm^{-3}), hot-electron (several MeV), plasma is contained in an elongated mirror cell bounded by mirror fields at each end. Standard techniques, such as the use of two-frequency microwave heating, as pioneered by Dandl[2], and/or adiabatic magnetic compression, can be used to create such plasmas at relativistic energies. Special precautions must be taken to insure that, at the time the Mirrortron potentials are to be generated, the population of "cold" electrons is small compared to that of the mirror-confined hot-electron population. Mirror experiments, such as the "Constance" experiment[3] at the Massachusetts Institute of Technology, have demonstrated that this latter objective can be achieved. By exploiting the slow (seconds) decay time of the hot electron population following the turn-off of the microwave heating power and of the gas source (the ionization of which created the plasma), cold electrons are expelled, leaving only a hot population characterized by a "loss-cone" distribution function.

Having created a mirror-confined hot-electron plasma, the generation of transient potentials in the Mirrortron is accomplished as follows. At a point located between the end mirrors a new, pulsed, mirror field is turned on, typically within 10 to 20 ns. On this time scale, the plasma ions do not respond, so that their density remains locally constant. The hot electrons, however, feel the repelling force of the pulsed mirror and begin to be expelled from the region. At this point the quasi-neutrality constraint steps in so that a region of positive potential is set up that traps the bulk of the hot electrons in the potential well. Theory[1] shows that, to a close approximation, the equipotentials of the space-charge field are congruent with the contours of constant magnetic field (base field + pulsed field). The potentials are of the order of the electron temperature, i.e., megavolts in a plasma with relativistic electron temperatures. Figure 1, taken from Ref. 1, shows such equipotentials as calculated from the theory for a typical set of parameters. Note that an ion beam bunch situated on the "downhill' side of the potential would experience both acceleration and a radial focussing action.

It is important to note that the mechanism of potential generation that has just been described could not occur in an isotropic, Maxwellian electron population. In such a case theory shows that, to lowest order, the potential would be zero. Anisotropy of the hot electrons, together with minimizing the presence of cold, isotropic electrons, is essential for the Mirrortron concept to work.

To design a Mirrortron ion accelerator, one would follow the same prescription used in ion linear accelerators employing radio-frequency cavity resonators. That is, a series of pulsed mirrors would be utilized, turned on in synchronism with the arrival

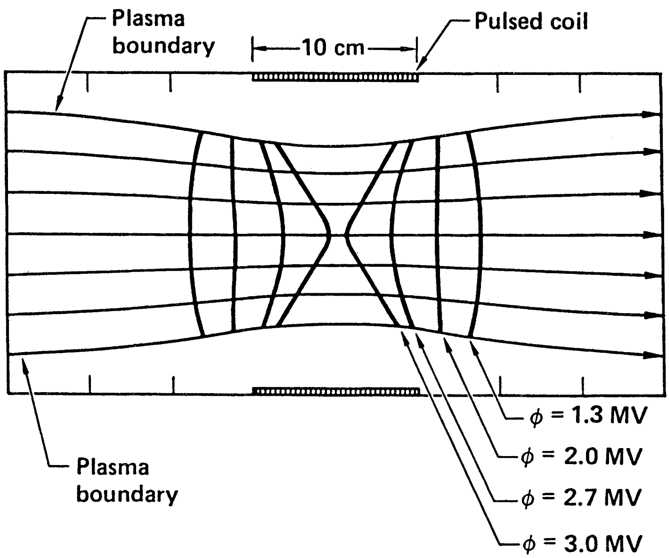

FIGURE 1 Calculated equipotentials (heavy lines) for plasma in a pulsed field of 5000 G superposed on a dc solenoidal field of 5000 G. The plasma electrons have a loss-cone distribution function (mirror ratio = 1.5) with kT = 2.0 MeV. A bunched ion beam incident from the left and arriving at the midplane at the time of appearance of the potential should experience both acceleration and a net radially inward focusing force from the electric field to the right of the midplane.

of a bunched ion beam. Although individual cells could be employed, a more desirable configuration would be to use a long mirror cell in which traveling potential wave would be set up by sequentially pulsing a series of closely space mirror coils. The ion bunch would then ride just forward of the crest of this potential wave, like a surfer on an ocean wave.

2 SCALING LAWS FOR THE ACCELERATING FIELDS

An approximate theoretical expression for the magnitude of the potential in a Mirrortron is given in Ref. 1. Rephrasing this relationship in terms of plasma parameters, ε and β (defined below), yields a scaling law for the electric field of the form[4]

$$E = \frac{1}{\sqrt{2}} \varepsilon \beta^{1/2} K \Delta B F[R_m, \Delta B/B_0] \quad \text{Statvolts/cm,} \tag{1}$$

where the function F is given by the expression

$$F[R_m, \Delta B/B_0] = 2(2 - R_m) \left\{ 1 + \left[\frac{R_m - 1}{2 - R_m} \right] \left[\frac{\frac{\Delta B}{B_0}}{1 + \frac{\Delta B}{B_0}} \right] \right\} \tag{2}$$

In these expressions the plasma parameter ε is defined as the ratio of the Debye length to the radius of the plasma (as approximated by the radius of the pulsed coil), and β is the plasma "beta" value, $\beta = 8\pi n_e kT_e/B_0^2$. The parameter K is the "coil gradient factor" = 0.76 (max) for a single-turn loop. Simple modifications in the pulsed coil configuration should allow one to increase the gradient over this value at the front of the pulsed wave, at the expense of a weaker gradient on the trailing edge. Thus it might be reasonable to achieve values of $K \approx 1.0$. In the function F, R_m is the mirror ratio, ΔB is the peak magnitude of the pulsed mirror field, and B_0 is the base field.

When evaluated at $R_m = 1.5$ (where the analytical form for the distribution function used to calculate Eq. (2) applies), F is a slowly varying function of $\Delta B/B_0$, varying only between 1.0 and 1.6 over the range $0 < \Delta B/B_0 < 1.5$. We may therefore, to lowest order, ignore the variation of F in considering the scaling of E.

An important result emerges from an examination of Eq. (1). We see that, to lowest order, if ε and β are held constant, the accelerating field is *independent* of the magnitude of the base field, B_0. This means that when it is especially important to maintain a precise control over beam focusing—for example, at the entry (low-energy) end of the linac—for a given value of ΔB it is possible to operate in the regime $\Delta B/B_0 \ll 1$ while still maintaining a relatively high gradient. The only price is that of maintaining the plasma parameters constant as B_0 is increased. On the other hand, once the beam has been accelerated to higher energies, where the beam is "stiffer" and thus less sensitive to focusing aberrations, it should be possible to relax the requirement $\Delta B/B_0 \ll 1$, increase the values of ε and β, and thereby achieve substantially higher gradients.

Putting in what should represent attainable values for the plasma parameters and pulsed B into Eq. (1), one finds peak acceleration gradients in the range of 5 to a possible 50–100 MV/meter. The lower of these is about an order of magnitude higher than that usually assumed to be the limit for induction-type ion linacs. Parameters for the lower gradient (injection end) of the accelerator might be $\beta = 0.1$, $\varepsilon = 0.1$, $\Delta B = 5$ kG, $B_0 = 15$ kG, and $K = 1.0$, giving an estimated (Eq. 1) peak accelerating gradient of 4.2 MV/m. After acceleration to higher energies, one might employ the parameters $\beta = 0.3$, $\varepsilon = 0.3$, and $\Delta B = 15\text{ kG} = B_0$, yielding an estimated peak gradient of 78 MV/m.

3 PEAK ION CURRENT; SPACE-CHARGE SCREENING

In addition to the need for high gradients and precision control of beam focusing, another important attribute of any prospective heavy-ion driver is its peak current capability. This parameter is limited by two factors. The first is the way in which the acceleration energy is delivered to the beam, and the second is the limit set by beam blow-up due to space-charge effects. The Mirrortron differs from vacuum-field ion accelerators in both categories. In the limit $\Delta B/B_0 \ll 1$, most of the acceleration energy is derived from the stored kinetic energy of the hot electrons, rather than from a Poynting vector flux across a vacuum gap. Also, in the limit $\varepsilon \ll 1$, the same quasi-neutrality constraint that insures precision control of the space-charge potentials will operate greatly to reduce the self-space-charge potential carried by the beam bunch. Furthermore, being local in nature, this screening effect is independent of the dimensions of the beam bunch, by contrast with the unscreened potential, which scales up (at constant space–charge density) with the square of the bunch dimensions. This result implies that the screening factor may be made increasingly effective by taking advantage of dimensional scaling. In a typical driver-relevant case, an unscreened potential was calculated to be reduced from 6 MV to 300 kV for a beam bunch traversing the mid region of a 1-MJ, 10-GeV accelerator employing mass-200 ions with charge $Z = 3$.

4 COMPUTER SIMULATION OF MIRRORTRON POTENTIALS

The particle-in-cell code GYMNOS has been applied to formation of equipotentials within a Mirrortron cell. GYMNOS is an r-z particle-in-cell (PIC) code with electric and magnetostatic fields. Simulations to date have shown that equipotentials, as predicted by theory, follow the contours of constant magnetic field. In addition rough quantitative agreement has been obtained with the theory[1] for the magnitude of the potential produced. Figure 2 is a graph of the ratio of the computed potential to the calculated potential vs $\Delta B/B$. The perpendicular electron temperature ranges from 9 keV to 90 keV.

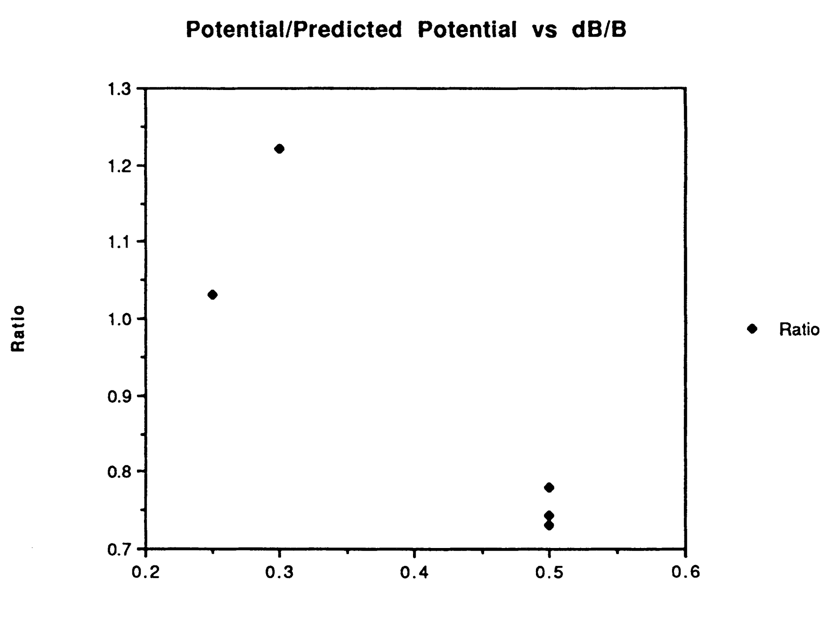

FIGURE 2 Plot of the ratio of the potential computed by the GYMNOS particle-in-cell code to the analytically calculated potential vs $\Delta B/B$.

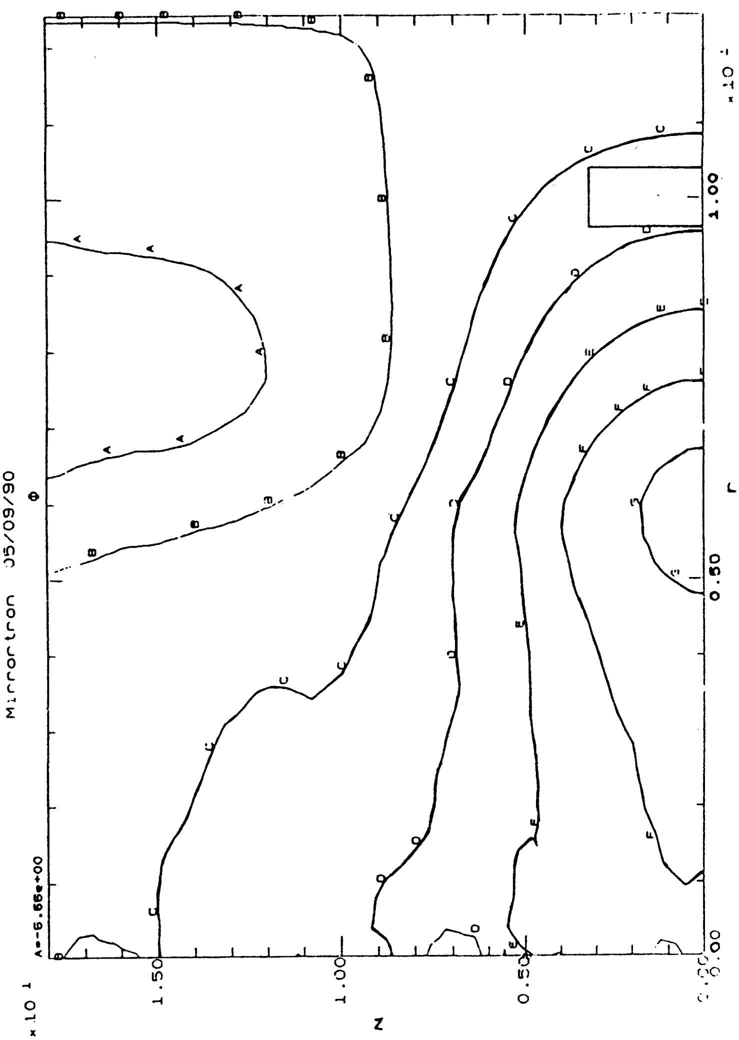

FIGURE 3 Equipotentials computed by the GYMNOS code at the peak of the current rise. The single-turn coil lies at $r = 10$ cm and the plasma boundary is at approximately 6.5 cm.

Calculated equipotentials at the peak of the current rise are shown in Figure 3. A symmetry plane is placed at the midpoint of the single-turn strap coil, which lies at $r = 10$ cm. The plasma boundary is located at approximately 6.5 cm. Particles are reflected at the z boundaries. Note the focusing character of the potential beneath the pulsed coil. The somewhat ragged nature of the equipotentials near $r = 0$ is believed to arise from statistical effects associated with the relatively small number of electrons (15 per cell) used to populate the plasma in the simulation.

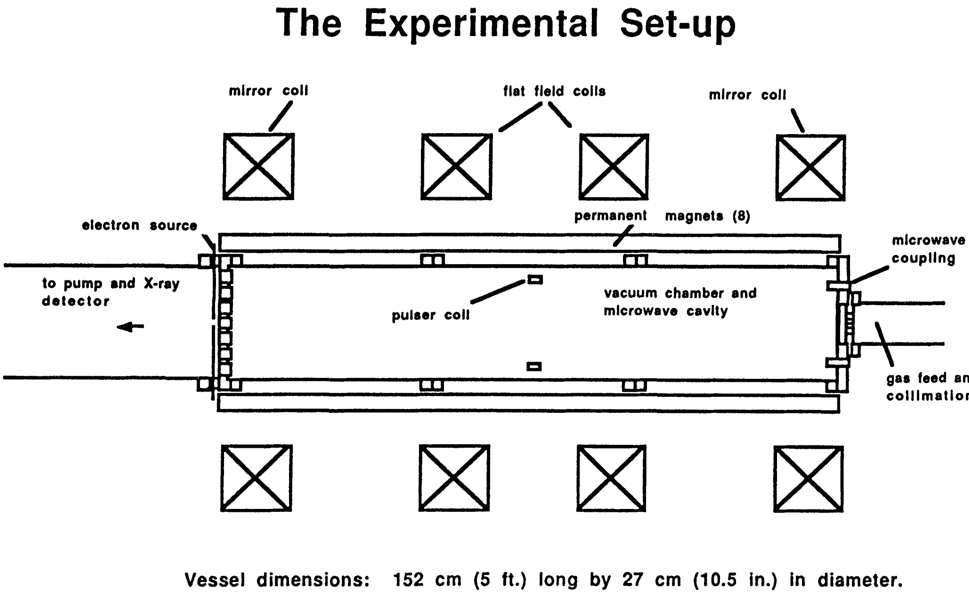

FIGURE 4 Schematic drawing of the Mirrortron experimental set up. DC coils provide the main mirror fields and an array of ferrite permanent magnet bars is used for MHD stabilization.

5 THE MIRRORTRON EXPERIMENT

A small experiment aimed at showing that high transient potentials can be created by exploiting the Mirrortron concept has been constructed at LLNL. In the first phase of this experiment a hot-electron plasma ($T_e \cong 100$ keV) has been created, using 50 W of microwave power at 2.4 and 3.6 GHz fed into a resonant cavity immersed in a dc mirror field with a midplane value of 600 G.

To provide the pulsed magnetic field, an eight-fold azimuthally segmented "single-turn" pulsed mirror coil and a simple mechanically triggered (puncturing of a dielectric) 16-arm copper-foil/mylar-film Blumlein pulser array have been built and tested and are now being readied for installation on the experiment. This coil/pulser set-up can deliver a field rising to a peak value of 150 G ($\Delta B/B_0 \cong 0.25$) within 70 ns. The segmented coil has a radius of 10 cm. Also in preparation is an electron beam diagnostic that will be used to measure the rate of rise and magnitude of the transient space-charge potentials expected to result from pulsing the coil. With the presently available plasma parameters it is predicted that potentials of order 20 kV will be produced—higher if greater electron temperatures can be obtained.

Figure 4 is a schematic drawing of the experiment, and Figure 5 shows a measured x-ray spectrum as observed by a detector located on axis near one end of the cavity resonator.

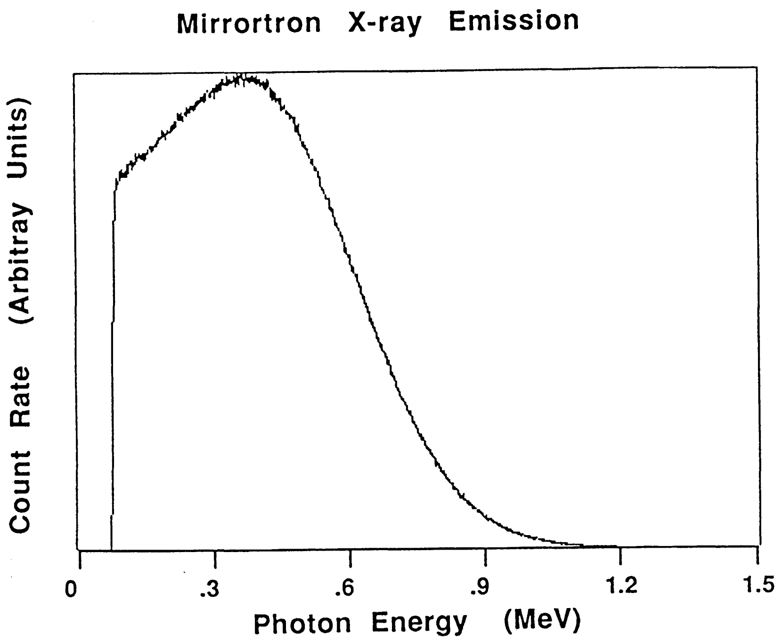

FIGURE 5 X-ray spectrum measured by a detector located on axis 215 cm from the center of the plasma. Neutral gas pressure (hydrogen) at the time the data were taken was approximately 5×10^{-6} torr with approximately 50 watts of (two-frequency) microwave power turned on.

6 CONCLUSION

Approximate theoretical analyses, computer simulations, and initial phases of an experimental test of the Mirrortron ion accelerator concept have been performed. The Mirrortron concept has some unique features that could be of particular value in a search for better linac-type heavy-ion drivers for inertial fusion applications. Among these is the theoretically predicted possibility of a degree of control over the acceleration and focussing of beam bunches approaching that achievable in vacuum-field linacs. At the same time the accelerating electric field, being derived from space-charge effects, is not subject to vacuum-field breakdown-limited values, and may also derive much of its energy from the stored kinetic energy of the hot electrons. Collective effects will also operate to reduce the self-space-charge potential of the beam bunch, leading to a predicted marked increase in the beam-current capability of Mirrortron accelerators over that of vacuum-field accelerators such as the induction linac.

Next phases of the research include completion of the present experiment, extension of the theoretical analyses, and the introduction of beam bunches into the computer simulations.

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