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Title: ION BEAM GENERATION AND PROPAGATION FOR PLASMA PROCESSING APPLICATIONS

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Submitted to: Beans 94 Conference, San Diego, California
June 20-24, 1994

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Los Alamos
NATIONAL LABORATORY

ION BEAM GENERATION AND PROPAGATION FOR PLASMA PROCESSING APPLICATIONS

R. J. Faehl and D. J. Rej

Abstract

Intense ion beams are being employed at Los Alamos to deposit thin films. Extraction geometry magnetically-insulated ion diodes (MID) are used to generate ion beams with currents up to 35 kA at 450 kV in a one-half microsecond long pulse. Multidimensional electromagnetic particle-in-cell (PIC) simulations have been performed to model the generation, extraction, and focusing of proton beams in realistic geometries. A ballistically focused MID has been studied to achieve the high deposition rates needed to form ablation plumes that preserve stoichiometric ratios. A high density waist with a diameter less than 8 cm is calculated near the geometrical focus. Extraction efficiency, beam divergence downstream of the aperture, and neutralization issues have been studied with the simulations.

1. Introduction

Magnetically insulated ion diodes (MID) are being employed at Los Alamos to generate ion beams for a variety of plasma processing applications. One of the most promising of these applications involves deposition of ion beam energy in a small enough target area to create an ablation plume. If the absorbed energy density is sufficiently great, the "hot" plume will maintain the same stoichiometric ratio as the original material[1,2]. Condensation of this plasma onto a substrate will yield thin films with the same constitution as the bulk target material. We are using a ballistically-focused extraction geometry MID to obtain the high energy densities needed for this process. This paper presents the results of a series of 2 1/2-dimensional electromagnetic particle-in-cell (PIC) simulations performed to study ion beam propagation and neutralization in the Los Alamos configuration..

Intense ion beam space-charge neutralization has been the subject of many studies, conducted for ion space propulsion[3], high current ion accelerators[4,5], and ion beam fusion[6]. The concern arises from the magnitude of space-charge fields associated with high current ion beams. If unneutralized, such fields will defocus, diverge, and destroy beam transport in inconveniently short distances. Intuition suggests that highly mobil, relatively light electrons, if any happen to be in the vicinity, will rush in and neutralize the positive charge of the more massive ions. This expectation is not completely groundless; many intense ion beam experiments show a high degree of charge neutralization and good transport characteristics. The issue is a quantitative one. How much neutralization occurs and under what conditions?

Before proceeding, it is appropriate to describe the Los Alamos intense ion beam accelerator which motivated this study[7]. The accelerator is a relatively long pulse width, 0.4-1.0 μs diode machine, directly connected to a 1.2 MV, 300 kJ Marx generator. With typical MID loads, it produces a peak ion current of 30-40 kA with energies ranging between 250-500 keV. It was built specifically for materials processing applications.

2. Numerical Methods

The basic numerical code, the procedure for computing initial magnetic field structure in the presence of flux excluding materials, and the computational strategy were described in a paper in the previous conference proceedings[8]. Interested readers may consult that document. The ballistic-focusing MID configuration has not been previously discussed. The configuration is shown in Fig. 1. The ion beam in this figure is typical of early time operation of the diode, for which little diode gap closure has occurred.

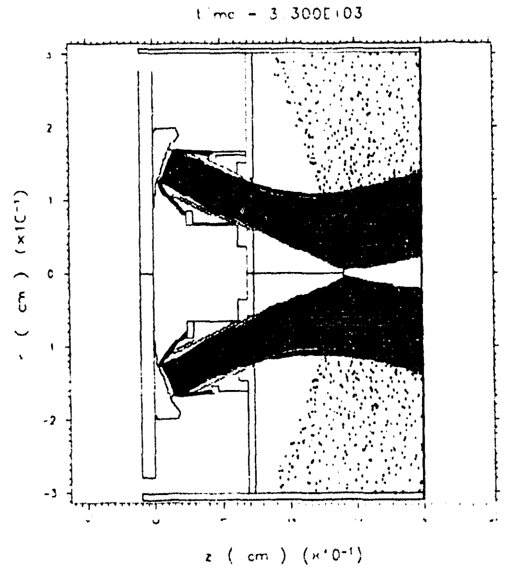

Fig 1. Configuration of the Los Alamos MID experiment, as simulated. Diode voltage is 495 kV, and diode current, 2.5 kA. The ion species are protons(M_i/ m_e=1836).

A dielectric flashover anode is employed on the MID. Impedance for this system is observed to decrease throughout the voltage pulse. The detailed material flow responsible for this effective gap closure has not yet been unambiguously determined. There seems to be a consensus that the anode surface in this type of diode exhibits little expansion. The cathode plasma associated with explosive emission from a cold surface is a more likely candidate. Quantitative studies are needed to confirm this mechanism. There has also been speculation that charge exchange may contribute to the impedance fall. We do not attempt to resolve this issue in the present study. Instead, we model the diode state as a fixed geometry anode, the original cathode structure, plus an additional cathodic plume which extends from the cathode edge toward the anode. We expect this plume to expand at velocities on the order of one cm/µs, but our simulations last for only about 100 ns. The effect of plume expansion is modeled by a fixed, conducting, emitting "plume", which has a size depending on which 100 ns slice of the full voltage pulse we wish to simulate. This artifice yields a very satisfying drop in the MID impedance, as computed in the simulation.

3. Numerical results

Neutralization becomes significant in an extractor region downstream from the diode gap. Understanding the neutralization in this region is complicated by the presence of a highly nonuniform magnetic field. This field is designed so that it is nearly transverse (B_r) in the acceleration region, but it proves to be both large and inhomogeneous in the extractor region. Its direction varies from virtually longitudinal (B_z) near the center of the extractor to dominantly transverse at the ends of the region. In an earlier numerical investigation, Poukey and Humphries[4] found that magnetic fields could actually improve neutralization. This phenomenon is presumably due to rotation of electron motion into longitudinal and azimuthal components. This transfer of radial flow into other directions inhibits electric field driven motion across the radial extractor dimensions. Electrons spend more time in the region occupied by the ion beam. Such a model, while physically reasonable, is difficult to quantify and may depend upon specific configurational parameters, such

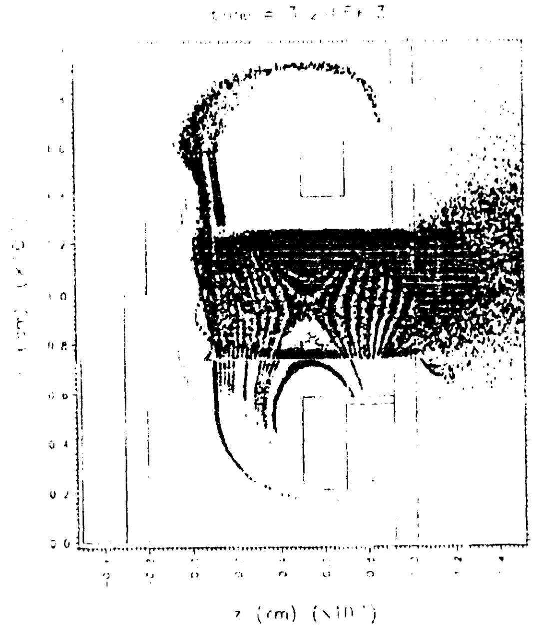

Figure 2. Snapshot of r-z distribution of electrons which have been field-emitted from extractor walls in response to ion beam space-charge fields. Magnetic field has a magnitude B = 1.5 kGauss at z = 5-8. Ion beam current is 4.2 kA, ion energy is 155 keV.

as ion current, magnetic field strength and extractor aspect ratio. Despite a lack of quantitative understanding of the process, however, our simulation show that a high degree of charge neutralization is established for the parameters appropriate to the Los Alamos experiments.

The electron distribution in the extractor is more readily illustrated for a straight, cylindrical structure than for the focused one. Fig. 2 shows a snapshot of electrons which have been field-emitted from the extractor wall when a 4.2 kA, 155 keV ion beam is propagated through it.

The peak potentials which were calculated in this environment are approximately 12 kV. We expect that an ion beam with these parameters would lead to potentials of in excess of 1 MV. Analysis of motion for electrons emitted from each surface shows that both have undergone many mirror transits in the extractor space.

Relatively little ion divergence is added to the ion beam in the extractor section. Significant radial divergence, however, has already been imposed on the beam by the time it reaches the extractor, from unneutralized space-charge fields in the diode gap. This results in beam expansion and wall scrape-off as it propagates through the extractor. We estimate that 15-25% of the beam current can be lost in an extractor with our dimensions. Since this is due to transverse momentum added to the beam before it arrives in the extractor, there may be little which can be done within the extractor to avert this loss.

Propagation in a ballistically focusing geometry is similar to that described for straight, cylindrical configurations. After the ion beam exits the extractor aperture, the focusing aspect introduces different features. In both configurations, fringe magnetic fields in the aperture interfere with good charge neutralization. For low current beams, up to a few kA currents, the divergence induced by aperture effects is relatively minor. The propagation shown in Fig. 1 is quasi-ballistic, with expansion beyond the waist being almost laminar.

High current beams, with currents above 10 kA, show a much more pronounced divergence near the aperture and more of a pinched-beam character beyond the waist. Fig. 3 depicts the same configuration as in Fig. 1, except that the diode ion current is 17. kA.

The apparent pinching of the inner envelope of the beam is the result of space-charge fields near the aperture. It is not seen in Fig. 1 because of the inclusion of a conical extension conductor in that calculation. This extension, which is used in many ion beam experiments at Los Alamos, scrapes off the inner diverging part of the beam, but leaves a colder, more ballistic core to propagate downstream.

Fig. 4 is a comparison of the radial ion density profiles for the high and the low current simulations near the waist of both beams, z = 28.5 cm Both beams are conspicuously hollowed near the axis.

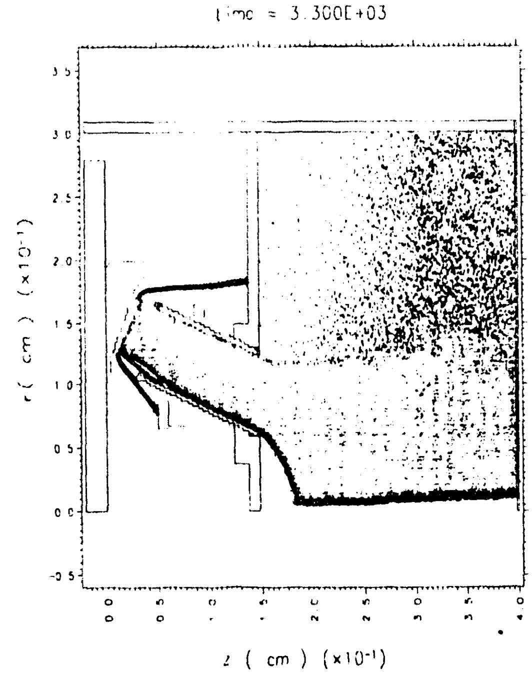

Fig. 3 Snapshot of ion beam propagation in the same configuration as in Fig. 1, except with a reduced A-K gap and higher ion current. Diode voltage is 435 kV and diode ion current is 17.0 kA.

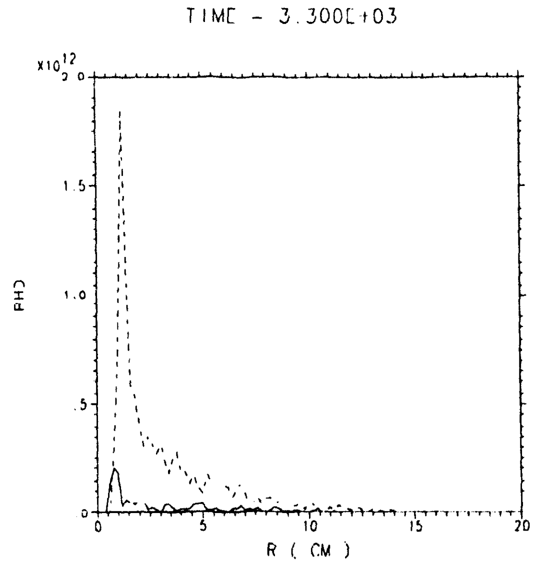

Fig. 4 Radial ion density profiles near the waist, (a) voltage is 495 kV, ion current is 2.5 kA, (b) voltage is 435 kV, ion current is 17. kA. Curve (a) has been multiplied by a factor of 9 so that more direct comparisons can be made.

The profile of the high current beam is reminiscent of a Bennett distribution, except for the hollowing near the axis. The slow expansion of the inner envelope is qualitatively different for the higher current beam. More analysis is required to understand the high current behavior quantitatively.

In conclusion, we have presented the results of numerical simulations of intense ion beam propagation and neutralization in a ballistically-focused MID. We find significant differences in the structure of low current beams, on the order of 1 kA, and higher current beams, above 10 kA, especially near the focus. These results are currently being analyzed, with the goal being a predictive model for the behavior of focused ion beams.

Acknowledgments

I would like to thank Harold Davis for useful and perceptive discussions on this work. This work was performed under the auspices of the U.S.D.O.E.

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