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Magnetic Insulation of Secondary Electrons in Plasma Source Ion Implantation

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ABSTRACT

The uncontrolled loss of accelerated secondary electrons in plasma source ion implantation (PSII) can significantly reduce system efficiency and poses a potential x-ray hazard. This loss might be reduced by a magnetic field applied near the workpiece. The concept of magnetically-insulated PSII is proposed, in which secondary electrons are trapped to form a virtual cathode layer near the workpiece surface where the local electric field is essentially eliminated. Subsequent electrons that are emitted can then be reabsorbed by the workpiece. Estimates of anomalous electron transport from microinstabilities are made. Insight into the process is gained with multi-dimensional particle-in-cell simulations.

I. INTRODUCTION

Plasma source ion implantation (PSII)¹ is a novel technique that makes the known benefits of ion implantation practical. While PSII has significant advantages over conventional accelerator-based methods (*e.g.*, being non-line-of-sight and compatible with ultrahigh currents), there remain a number of issues unique to PSII which must be addressed. An important concern is secondary electron emission.

In traditional PSII, a negative high-voltage pulse is applied to a workpiece immersed in plasma composed of positive ions and electrons. As each ion is accelerated and implanted, secondary electrons are liberated from the workpiece and are rapidly accelerated through the sheath potential. In most experiments to date, the energetic secondaries stream along collisionless trajectories until they strike and are stopped by grounded objects such as the vacuum chamber walls. For many of the envisioned metallurgic applications, the secondary emission coefficient γ is large, often ranging between 5 and 20.² Therefore, uncontrolled secondary emission could reduce PSII system efficiencies to only 5%. Furthermore, the impact of high-energy electrons into the grounded walls generates potentially hazardous amounts of bremsstrahlung x-rays. These x-rays must be absorbed by shielding, usually placed outside the vacuum chamber walls. X-ray emission from PSII devices can be high; for example, on the Los Alamos PSII device,³ operated at 40-kV applied voltage, 25-A pulsed current, 20- μ s pulse width, and 500-Hz repetition rate, an x-ray dose of 13 R/hr is observed immediately outside a vacuum window and inside the 13-mm-thick steel shield. An unshielded dose of almost 800 R/hr is predicted with Monte Carlo simulations⁴ for 100 kV operation at these conditions.

Successful suppression of secondary electron currents could enhance the PSII process by significantly reducing the x-ray hazard and shielding requirements; moreover, it could improve system efficiencies by up to an order of magnitude. A number of methods to suppress secondaries immediately come to mind. An appealing technique involves the use of

negative ion sources and positive accelerating voltages. Negative ion sources have been developed for applications such as high-energy particle accelerators. The extrapolation of conventional negative ion sources to large average currents demanded by PSII remains a challenge; furthermore, maintaining a high negative ion to electron density ratio is essential to minimize unwanted primary electron currents and x-ray emission. Positive ion sources are a provocative solution and will be the subject of future studies.

Another potential solution to the secondary electron problem, and the subject of this paper, involves magnetic fields. We introduce the concept of magnetically-insulated plasma source ion implantation (MIPSII). In MIPSII a relatively weak magnetic field B is applied in the sheath region that surrounds the workpiece. The magnitude of B is chosen such that secondary electron trajectories are greatly altered, while ion motion is only slightly perturbed. This concept of magnetic insulation of electron currents has been successfully applied in intense ion beam accelerators developed for inertial confinement fusion (ICF) energy research.⁵ In Section II the fundamental concepts for MIPSII are developed in a simple analytical model. The conditions required to establish and confine a virtual cathode electron layer within the PSII sheath are estimated. The analytic model is complemented by multidimensional particle-in-cell simulations presented in Section III. The MIPSII concept is inherently a two or three dimensional process because of the vastly different electron mobility across and along the applied magnetic field. We discuss implications of our work in Section IV.

II. CONFINEMENT MODEL

In this study, we will restrict ourselves to the elongated, axisymmetric geometry illustrated in Figure 1. (This geometry is chosen for convenience. As discussed in Section IV, the essential conclusions are generic, however, and should remain applicable to other, more complicated configurations.) A cylindrical workpiece with radius a , length L , and

biased at voltage $-V_0$, is immersed in a plasma and a uniform applied magnetic field $\mathbf{B} = B\mathbf{z}$. Secondary electrons emitted from the workpiece surface move according to the equation of motion

$$m \frac{d\mathbf{v}}{dt} = q\mathbf{E} + \frac{q}{m} \mathbf{v} \times \mathbf{B} \quad (1)$$

where q and m are the electron charge and mass, respectively. Electrons are released at $r = a$ with relatively little energy W_0 of a few eV, so we may assume the initial condition $\mathbf{v}(t=0) \approx 0$. B is considered to be sufficiently large, that the electric field $\mathbf{E} = -E\mathbf{r}$ is constant over an electron orbit. In this limit, Eq. 1 reduces to a simple analytical expression for cycloidic electron trajectories

$$r(t) = a + (v_E / \Omega) \cdot (1 - \cos \Omega t) \quad (2a)$$

$$\theta(t) = -\Omega \int_0^t dt' / \{1 - a\Omega/v_E(\cos \Omega t' - 1)\} \quad (2b)$$

where $v_E = E/B$ is the azimuthal " $\mathbf{E} \times \mathbf{B}$ " drift velocity and $\Omega = eB/m$ is the electron cyclotron frequency. In the r - θ plane, the secondary electrons are confined in an "e-layer" of thickness $\delta = 2v_E/\Omega$. For the constant E assumption to be valid, δ should be sufficiently smaller than the PSII sheath thickness s . An electron trajectory for the case $B = 0.04$ T, $E = 10^6$ V/m, $a = 0.05$ m is plotted in Figure 2.

The configuration in Fig. 1 is similar to the "barrel diode" geometry for the magnetically-insulated ion diodes (MID) used in ICF.^{5,6} Following this analogy, one can define the characteristic MID insulation parameter β which is the magnitude of B normalized to the critical field B_* where electron excursions completely fill the diode anode-cathode gap (or ion sheath for PSII). In the limits constrained by our model, we consider the overinsulated case $\beta \gg 1$.

Since electrons actually emerge from the workpiece with finite W_0 in all directions,

they are free to move unperturbed in the axial direction. When they reach the ends of a straight cylinder, the electrons are rapidly accelerated from the workpiece and are lost from the system. Away from the ends, electron orbits ideally should return to intersect the workpiece surface. If there are no losses (*e.g.*, scattering or radiation), electrons might be reabsorbed by the workpiece; however, reabsorption is not observed in magnetically-insulated power flow experiments. Electrons are accelerated to energies $W_e \gg W_0$, typically several keV. Minute inhomogeneities, time dependences, and/or scattering losses that deflect even a small portion of W_e could prevent secondaries from returning to their initial radial position. It is more likely that they will float away along z following the cycloidal $r-\theta$ orbits until they are lost from the ends. Electrons leave with a characteristic transit time $\alpha L / \omega_{pe}$, where $\omega_{pe} = (n_p e^2 / \epsilon_0 m_e)^{1/2}$ is the electron plasma frequency with n_p the background plasma density, while α is a "screw-up" factor due to the helical trajectories caused by B . For any practical system, however, this time will always be short compared with the primary ion acceleration time $\omega_{pi}^{-1} = (\epsilon_0 M_i / n_p e^2)^{1/2}$. Thus, PSII system efficiency will not be improved. On the other hand, one should be able to better shield bremsstrahlung x-rays in this situation since secondary electrons are emitted as two confined beams out the ends (see Sec. IV).

Significant suppression of secondary electron current losses from reabsorption by the workpiece might be achieved if one suppresses the local E near the workpiece surface. This condition could occur when a sufficient density of secondaries are confined to form a "virtual cathode" in the e -layer surrounding the workpiece. After the virtual cathode is formed, any further secondary electrons are created in a low electric field environment, and they could be reabsorbed by the workpiece. Virtual cathode electrons are energetic with $W_e \approx eE\delta$ of a few keV, and they are free to move axially. To suppress consequent end losses, one could add "limiters," shown schematically in Fig. 1 as disks mounted on the ends of the workpiece. The limiters float at the pulsed voltage $-V_0$ and extend radially a distance Δ

beyond the workpiece. Energetic secondaries should be electrostatically reflected by the limiters provided $\Delta > \delta$.

The amount of surface charge needed to neutralize E in the virtual cathode is

$$\sigma = \epsilon_0 E \quad , \quad (3)$$

or about $10^{-5}E(\text{kV/mm})$ coul/m². The virtual cathode electron density is

$$n_e = \sigma / e\delta \quad , \quad (4)$$

or approximately $6 \times 10^{16} E(\text{kV/mm})/\delta(\text{mm}) \text{ m}^{-3}$.

The virtual cathode is established over the time scale

$$\tau_1 = en_e\delta/\gamma j_i \quad (5)$$

where j_i is the primary ion current density. When combined with Eqs. 3 and 4, Eq. 5 reduces to

$$\tau_1 = \epsilon_0 E / \gamma j_i \quad , \quad (6)$$

or in practical units, $\tau_1 (\mu\text{s}) = 10 E(\text{kV/mm})/\gamma j_i(\text{A/m}^2)$.

The virtual cathode will be maintained when the energetic electrons are confined for a time scale $\tau_2 \geq \tau_1$. To significantly reduce secondary losses, better confinement, $\tau_2 \gg \tau_1$, is required. Classical confinement times (*e.g.*, arising from electron-neutral scattering) will satisfy this criterion for PSII systems. However, secondary electron confinement is expected to be anomalously poor, since microinstabilities are likely in this non-neutral plasma. As often done in MID theory, we conservatively estimate the microinstability-induced transport with the Bohm diffusivity, $D_B = W_e/16eB$. The resulting confinement time $\tau_2 \approx \Delta^2/D_B$ may be expressed as

$$\tau_2 = 8e\Delta^2 B^3 / mE^2 \quad (7)$$

A set of self-consistent parameters for a realistic MIPSII experiment is listed in Table I. To obtain the 40 ns Bohm confinement time for this situation, electrons must be confined over a 2-m-long trajectory.

Another issue with MIPSII is ionization of the background gas by virtual cathode electrons. Ions created in the e-layer are accelerated to low energies of $\delta V_0/s$ or less, and are implanted into the workpiece. This low-energy ion current j_1 is undesirable because of the shallow implant depth and increased sputtering that will result. Ideally there should be little or no E to accelerate these ions into the workpiece. The upper bound for j_1 is the ion creation rate $j_1 = en_e n_0 \langle \sigma v \rangle_i \delta$ where n_0 is the neutral particle density and $\langle \sigma v \rangle_i$ is the ionization reaction rate which is usually a constant for electron energies $W_e > 100$ eV. When combined with Eqs. 3 and 4, this upper bound reduces to

$$j_1 = \epsilon_0 E n_0 \langle \sigma v \rangle_i \quad (8)$$

For $n_0 = 6 \times 10^{18} \text{ m}^{-3}$ (0.2 mtorr), $\langle \sigma v \rangle_i \approx 10^{-13} \text{ m}^3/\text{s}$, and $E = 1 \text{ kV/mm}$, one estimates $j_1 \leq 6 \text{ A/m}^2$ which is a fraction of the primary implanted ion current. Thus, MIPSII should be performed at the lowest practical fill pressure to minimize the secondary ion current.

III. SIMULATIONS

Insight into MIPSII is gained by numerical simulations with a fully-electromagnetic, two-and-one-half-dimensional particle-in-cell (PIC) code.⁷ Cylindrical symmetry is assumed. The ion and electron equations of motion are solved self consistently with Maxwell's equations for all velocity, **E**, and **B** components at approximately 3-ps time steps over a grid spacing between 5 and 15 mm. Collisions are ignored.

First simulations have been performed for an elongated workpiece geometry, $L = 1.8 \text{ m}$, $a = 0.04 \text{ m}$, immersed in a N_2^+ plasma with initial uniform density of 10^{15} m^{-3} .

A -50 kV potential is applied to the workpiece over a 100 ns rise time. A uniform axial magnetic field B is applied. As each ion implants into the workpiece, γ secondary electrons are emitted. The secondary coefficient depends on workpiece material and ion energy E_i . In these simulations we use assume, $\gamma \approx 15 (E_i/20 \text{ keV})^{1/2}$, which is roughly consistent with N_2^+ on aluminum.

The external magnetic field is found to significantly alter initial sheath dynamics, as evident from the electron density contours at time $t = 150 \text{ ns}$ plotted in Figure 3 for the cases: (a) $B = 0$ with no limiters; (b) $B = 0.04 \text{ T}$ with no limiters; (c) $B = 0.04 \text{ T}$ with limiters. When $B = 0$, both primary and secondary electrons are rapidly evacuated in the vicinity of the workpiece on the ω_{pe}^{-1} time scale to form the ion matrix sheath. The finite B , on the other hand, impedes radial motion. Instead, the sheath is formed from axial diffusion and acceleration which occurs on the $\alpha L/\omega_{pe}$ time scale. The limiters further inhibit axial transport.

An e-layer of secondary electrons is clearly observed in the simulation. Radial electron density profiles near the axial midplane are plotted in Figure 4. The e-layer density n_e is an order of magnitude larger than n_p ; however, a virtual cathode with $E \approx 0$ is not evident at $t = 150 \text{ ns}$. The e-layer density continues to rise in time indicating that a steady-state balance between secondary emission and axially losses has not yet been achieved. These PIC simulations will be continued for later times until a steady-state with a virtual cathode is obtained. Cross-field transport, consistent with Bohm diffusion, will also be included in the near future.

IV. DISCUSSION

The MIPSII concept should be applicable to more complex workpiece geometries, provided a satisfactory virtual cathode is established. Secondary electrons trajectories will be complicated around a convoluted workpiece surface, but in principal, should remain confined

by limiters placed near the ends. End losses from the limiters appear unavoidable in all cases. Clearly, the MIPSII system efficiencies are highest for elongated workpieces with minimum Δ/a . This result is achieved with a high magnetic field. However, B must be kept below a practical limit $B_{\max}$ to minimize perturbations to the primary ion orbits. The ion gyroradius must be kept small relative to the sheath width, *i.e.*,

$$B_{\max} < < [2M_i V_o / es^2]^{1/2} \quad (9)$$

For a N_2^+ plasma, $V_o = 100$ kV, and $s = 0.3$ m, this limit is 0.8 T.

It may be possible to mitigate the x-ray hazard in PSII with a simpler configuration without limiters and the virtual cathode. In this situation, secondary electrons are likely to be lost as two magnetically-confined beams directed axially away from the workpiece along the magnetic field. As mentioned in Section II, the system efficiency for this configuration will not improve. However, the energetic secondaries may be intercepted with low bremsstrahlung-yield materials, while more compact external shielding will be needed only on the ends. X-ray production may be further reduced by slowdown of the secondary electrons in the background plasma. Classical slowdown is unimportant; however, anomalous losses due to microinstabilities could be significant. For example, the electron-electron two stream mode should occur with a linear growth rate⁸

$$\text{Im } \omega = \omega_{be}^{2/3} \omega_{pe}^{1/3} / 8 \quad (10)$$

where ω_{be} and ω_{pe} are the electron plasma frequency for the beam of energetic secondaries and the background plasma, respectively. For sufficiently high ω_{be} (or n_{be}), the characteristic growth time $\tau_g = (\text{Im } \omega)^{-1}$ can be short. The growth rate may be enhanced with an applied magnetic field which concentrates the secondaries into a collimated, high current density beam. For example, a 100-kV, 5-kA/m² beam moving through a 10^{15} m⁻³ background

plasma will excite a two-stream instability with $\tau_g \approx 3$ ns. The characteristic scale length for this mode is 0.6 m. Beam energy can be dissipated by non-linear interactions of the beam and plasma waves. The two stream interaction has been simulated for planar geometry with the 1.5-dimensional PIC code PDP1.⁹ Preliminary results, for a 30-kV, 50-A/m² beam traversing a 10¹⁵ m⁻³ plasma are shown in Fig. 5. Beam and plasma phase space distributions for times (a) $t = 100$ ns, and (b) 300 ns are plotted. Beam slowdown and plasma heating is evident.

In summary, we have introduced the concept of magnetic insulation to suppress the secondary electron current in PSII. A dramatic improvement in system efficiency is possible if this current can be quenched. A virtual cathode, comprised of secondaries confined near the workpiece, is probably required. Two-dimensional PIC simulations show that a magnetic field can effect sheath formation. The ion matrix is developed on a longer time scale since primary electrons are mostly in the axial direction. The X-ray hazard may be reduced with a more straightforward approach that involves diverting secondary electron currents along the magnetic field in a relatively small cross-sectional area. Further decreases in x-ray emission might be realized by beam-plasma instabilities which reduce secondary electron energies. Further 1.5 and 2.5-dimensional PIC simulations of MIPSII are planned in the near future. In addition, the MIPSII concept will be tested experimentally in the Los Alamos PSII facility.

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Table I

Plausible MIPSII Parameters

E	10^6 V/m
B	0.04 T
v_E	2.5×10^7 m/s
Ω	7×10^9 rad/s
σ	10^{-5} coul/m²
j_i	100 A/m
γ	10
δ	7 mm
Δ	21 mm
n_e	8×10^{15} m⁻³
W_e	7 keV
D_B	10^4 m²/s
τ_1	10 ns
τ_2	40 ns

FIGURE CAPTIONS:

Fig. 1: Schematic diagram illustrating the MIPSII concept.

Fig. 2: Trajectory of a secondary electron for the case: $B = 0.04$ T, $E = 10^6$ V/m, $a = 0.05$ m.

Fig. 3: Electron density contours at time 150 ns predicted by 2.5-dimensional PIC simulations of PSII with (a) $B = 0$, no limiters; (b) $B = 0.04$ T, no limiters; and (c) $B = 0.04$ T, with limiters.

Fig. 4: Radial profile of the electron density near the axial midplane at time 150 ns predicted by 2.5-dimensional PIC simulations of PSII with $B = 0$ (solid line), and $B = 0.04$ T (dashed line) without limiters.

Fig. 5: Beam - plasma electron phase space plots at times (a) $t = 100$ ns and (b) 300 ns predicted from a 1.5-dimensional PIC simulation.

D. J. Rej *et al.*, Figure 1

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