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BEAM INTERACTIONS WITH MATERIALS AND ATOMS

Artificially Structured Boundary for a high purity ion trap or ion source

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A R T I C L E I N F O

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A B S T R A C T

A plasma enclosed by an Artificially Structured Boundary (ASB) is proposed here as an alternative to existing ion source assemblies. In accelerator applications, many ion sources can have a limited lifetime or frequent service intervals due to sputtering and eventual degradation of the ion source assembly. Ions are accelerated towards the exit canal of positive ion sources, whereas, due to the biasing scheme, electrons or negative ions are accelerated towards the back of the ion source assembly. This can either adversely affect the experiment in progress due to sputtered contamination or compromise the integrity of the ion source assembly. Charged particle trajectories in the proximity of an ASB experience electromagnetic fields that are designed to hinder ion–surface interactions. Away from the ASB there is an essentially field free region. The field produced by an ASB is considered to consist of a periodic sequence of electrostatically plugged magnetic field cusps. A classical trajectory Monte Carlo simulation is extended to include electrostatic plugging of magnetic field cusps. The conditions necessary for charged particles to be reflected by the ASB are presented and quantified in terms of normalized parameters.

1. Introduction

In the application of ion sources for accelerator physics, plasma physics, or plasma processing purposes, a *clean* source of ions is desirable when unwanted sputtered contamination is detrimental for the experiment at hand or for the ion source assembly itself. In addition, in the accumulation of rare species of ions or antimatter particles, good confinement is particularly important due to the limited availability of the particles being trapped. Ions within an ion source that impinge on a surrounding material surface can alter the physical properties of the surface. Furthermore, ion sources that employ reactive metals can require frequent service intervals. The study presented here proposes a configuration that can minimize the interaction of a plasma with material surfaces.

An Artificially Structured Boundary (ASB) is described here as a material boundary that produces electrostatic and magnetostatic fields for the purpose of modifying charged particle trajectories when charged particles approach the boundary. Such an ASB is considered here to form a periodic set of cusping magnetic fields with electrostatic potential barriers at the location of the magnetic field cusps. An ASB that produces purely magnetic fields, without the electrostatic barriers, is described in [1]. Two properties of such an arrangement are notable: (1) The ASB is capable of simultaneously reflecting charged particles of either sign of charge, but only when the particles are incident at shallow angles. (2) A nearly field free region occurs away from the ASB so that the field only modifies charged particle trajectories close to the material boundary. Charged particle trajectories that are normal to the ASB can escape through magnetic field cusps if no electrostatic plugging is present. Preliminary experimental research has been reported in which a plasma interacts with a segment of an ASB with electrostatic plugging [2]. Also, theoretical research has been reported on possible applications of an ASB for lining an electrostatic storage ring [3] and for bounding a confined plasma [4]. The current study assesses the effect that incorporating electrostatic plugging of the magnetic field cusps can have on the confinement of charged particles of a single sign of charge. The configuration may serve to confine a two-species plasma, with the first species confined by the ASB and the second, oppositely signed species, confined by the space charge of the first species [4].

2. Theory

The current study considers the interaction of a single charged particle with an ASB. The effects due to the collective nature of plasmas are not taken into account here. Charged particle trajectories near an ASB are determined by solving Newton's second law. Fig. 1 depicts the characteristics of the simulation environment.

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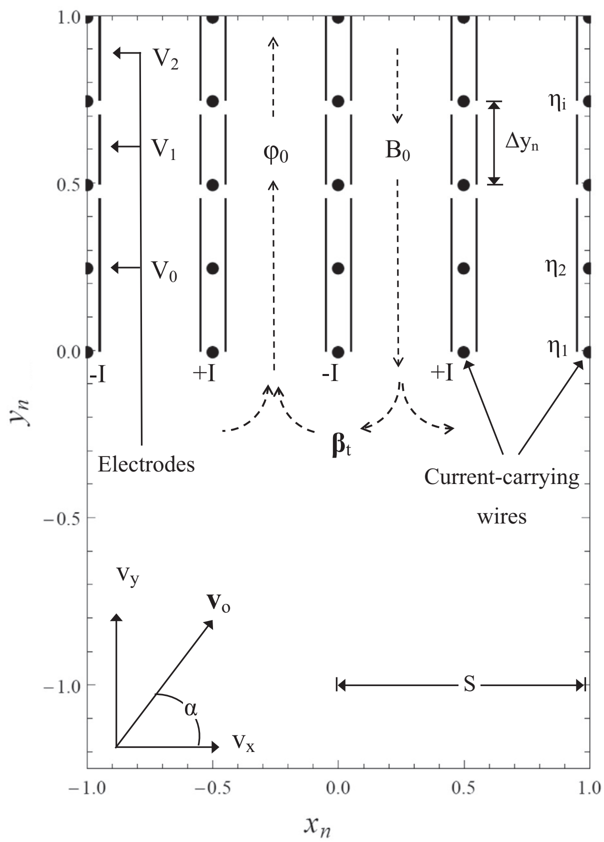

Fig. 1. Simulation environment representing two periods of a planar ASB. Ions are confined to the region below the ASB ($y_n < 0$). The lower edge of the ASB is located at $y_n = 0$. The dots mark the positions of the current carrying wires, with current that alternates in sign from one column of wires to the next, $\pm I$. Magnetic field cusps are produced with the direction of the magnetic field labeled by $\boldsymbol{\beta}_t$. The electrodes are marked by lines, which represent their lengths and locations in the simulation environment. The current carrying wires and the electrodes are infinite in extent in the z dimension. The electrostatic potential energy barrier is located in the region $0.5 \leqslant y_n \leqslant 0.75$, at the location of V_1. V_0 and V_2 are at ground potential. ϕ_0 is the electric potential at the center of the anode gap, where the magnetic field has a magnitude B_0. See Eq. (2) for details regarding η_i and Δy_n.

The magnetic field developed in [5] is used here, except that (1) the magnetic field dependence on the coordinates is changed, and (2) the strength of the field is defined by the conditions necessary for magnetic confinement. Such a field has the form [5]

$$\boldsymbol{B}(x,y,z) = B_0 \boldsymbol{\beta}_t\left(\frac{x}{S},\frac{y}{S},\frac{z}{S}\right), \tag{1}$$

with

$$\boldsymbol{\beta}_t(x_n,y_n,z_n) = \sum_{i=1}^{N} \eta_i \boldsymbol{\beta}(x_n, y_n - (i-1)\Delta y_n, 0), \tag{2}$$

and

$$\boldsymbol{\beta}(x_n,y_n,z_n) = \frac{-\cos(2\pi x_n)\sinh(2\pi y_n)}{\cos(4\pi x_n)-\cosh(4\pi y_n)}\hat{\boldsymbol{x}} + \frac{\sin(2\pi x_n)\cosh(2\pi y_n)}{\cos(4\pi x_n)-\cosh(4\pi y_n)}\hat{\boldsymbol{y}}. \tag{3}$$

Here $\boldsymbol{r}_n = x_n\hat{\boldsymbol{x}} + y_n\hat{\boldsymbol{y}} + z_n\hat{\boldsymbol{z}} = \frac{\boldsymbol{r}}{S}$; $\boldsymbol{\beta}(x_n,y_n,z_n)$ describes the direction of the magnetic field created by a planar array of current carrying wires that has a spatial period S, that is infinite in z dimension and coincides with the $y = 0$ plane; and η_i assigns relative current factors for each of the $N(=10)$ planar arrays that are stacked Δy_n apart. $\eta_1 = \eta_{10} = 1.27$ and $\eta_i = 1$ for $2 \leqslant i \leqslant 9$. B_0 is approximately equal to the magnitude of the magnetic field at the center of the anode gap. An expression for B_0 will be developed in Section 2.1.

The electric field used for electrostatic plugging of the magnetic field cusps is obtained by numerically computing the electrostatic potential $\phi(x,y,z)$ and then using $\boldsymbol{E}(x,y,z) = -\nabla\phi(x,y,z)$. The numerical computation of ϕ is described in Section 2.3.

2.1. Normalization

Consider a collisionless, non-drifting, unmagnetized plasma that follows a Maxwellian velocity distribution. From this point onward, an ensemble of charged particles is loosely referred to as a *plasma*. T is the temperature, in units of energy, associated with the Maxwellian distribution and m is the mass of a plasma particle. Assume that the plasma is composed of a single species of charged particles, each of which has a positive charge q (e.g., $q = 2e$ for a doubly ionized positive species, and e is the electronic charge). In what follows, the quantities m, q, S, and $3T/2$ are employed to carry out a normalization procedure. S is the spatial period of the magnetic field, and $3T/2$ is the average kinetic energy per particle in a Maxwellian source of particles. The normalized parameters are $t_n = \frac{t}{S}\sqrt{\frac{3T}{2m}}$, $\boldsymbol{v}_n = \boldsymbol{v}\sqrt{\frac{2m}{3T}}$, $\boldsymbol{r}_n = \frac{\boldsymbol{r}}{S}$, $\boldsymbol{a}_n = \boldsymbol{a}\frac{2mS}{3T}$, $\boldsymbol{B}_n = \boldsymbol{B}Sq\sqrt{\frac{2}{3mT}}$, $\boldsymbol{E}_n = \boldsymbol{E}\frac{2Sq}{3T}$, and $\phi_n = \frac{2q\phi}{3T}$, which are the dimensionless normalized time, position, velocity, acceleration, magnetic field, electric field, and electric potential, respectively. Newton's second law for a charged particle that experiences a Lorentz force is

$$\boldsymbol{a}_n = \boldsymbol{E}_n + (\boldsymbol{v}_n \times \boldsymbol{B}_n), \tag{4}$$

when written in terms of the normalized parameters. The normalized electric field is

$$\boldsymbol{E}_n = -\nabla\phi_n(x_n,y_n,z_n). \tag{5}$$

Consider a positive charged particle in a region with electrostatic potential ϕ, which is positive or zero everywhere accessible to the particle. In particular, consider the electrostatic potential present in the ASB described in Fig. 1, where $\phi = \phi_0$ at the center of the anode gap between electrodes labeled by V_1. The electrostatic potential energy barrier, $U_0 = q\phi_0$, reflects charged particles that start at zero potential with less kinetic energy than is required to overcome the potential energy barrier. Define the ratio of the electrostatic potential energy barrier, at the location of ϕ_0, to the average kinetic energy of a plasma particle to be the normalized potential barrier,

$$\phi_{n0} = \frac{2q\phi_0}{3T}. \tag{6}$$

The Larmor radius, R_L, is used to specify a condition for magnetic confinement. At the center of the anode gap, the magnetic field has a magnitude specified by B_0, so that $R_L = \frac{mv_p}{qB_0}$. Here v_p is the magnitude of the velocity component perpendicular to the direction of the magnetic field at the location of B_0. In order for a charged particle to experience magnetic confinement in the anode gap, its Larmor radius must be much smaller than the space between two adjacent columns of wires, i.e. $R_L \ll \frac{S}{4}$. Let the average thermal energy be available to a plasma particle's motion perpendicular to the magnetic field. In such case $\frac{3}{2}T = \frac{m}{2}v_p^2$, which leads to

$$B_0 = \frac{\sqrt{3mT}}{qR_L}. \tag{7}$$

With the magnetic field given by Eq. (1), and defining an inverse normalized Larmor radius $\delta = \frac{S}{R_L}$, the normalized magnetic field becomes

$$\boldsymbol{B}_n = \sqrt{2}\delta\boldsymbol{\beta}_t(x_n,y_n,z_n), \tag{8}$$