Magnetic Control of a Charge-Neutralized Ion Beam

R.E. Phillips and C.A. Ordonez

Department of Physics, University of North Texas, Denton, Texas 76203

Abstract

Charge-neutralized ion beam control is more complex than control of charged beams. While focusing techniques for charged beams have been widely studied, many of the tools available for controlling charged beams are not suitable for charge-neutralized beams. Presented here is a scheme for controlling charge-neutralized beams using a distortion of a magnetic guide field via the presence of two current carrying wires. The extent to which the beam can be controlled is evaluated using a classical trajectory Monte Carlo simulation.

1. Introduction

Charged neutralized beams have applications in a number of fields. Several studies have been carried out in the area of drift compression of a neutralized ion beam for the purpose of studying high energy density plasmas and fusion conditions [1]. Quality thin film deposition has been shown to depend on space charge neutralization as well [2]. Control of charge-neutralized ion beams must be handled differently than traditional set-ups used on charged ion beams. As such, novel complications and opportunities arise. For example, the work here uses a concept initially explored within a plasma confinement context [3] to exert control on a charge-neutralized ion beam. Deflection of a charge-neutralized ion beam is constrained by certain conditions however [4], and beam control can be difficult since standard electric field based techniques may not be effective. Ion beams can be space-charge neutralized when injected into a field free region with a source of electrons [5], and transport of space-charge neutralized,
unmagnetized ion beams has been investigated using a spatially periodic field to confine a plasma which serves as the source of electrons that neutralize the ion beam in flight [6]. Studies have also been carried out using a spatially periodic field to confine ions that drag along electrons such that the two species system of particles can be considered a neutralized drifting plasma [7]. Certain issues surrounding pure charged ion beam transport specifically for intense beam applications can be solved using charge-neutralization. An example is the mutual repulsion caused by the space charge of the beam in flight. This “blow up” of the beam diameter is one of the primary limitations on transport and final spot size for a given beam, and charge-neutralization allows for the beam’s space charge to be suppressed [8]. Many areas of physics, from heavy ion fusion studies [9, 10, 11, 12] to spectroscopy [13] to ion implantation [14, 15] and propulsion [16], benefit from a beam that is charge-neutralized.

2. Equations and Description of Simulation

Consider a charge-neutralized ion beam that travels parallel to a uniform magnetic field. Suppose magnetic field generating wires are immersed as shown in Fig. 1 in the beam’s path in such a way as to create shielded regions which the beam deflects around. Targets could be moved vertically into place near the wires while the shielding magnetic field is on. Once in position, the wire current is shut off allowing a processing step to take place (e.g., ion implantation or thin film deposition). Automation of the target insertion/extraction could lead to significantly increased throughput of targets. Applications that alter only small surface areas would benefit most from this such as drill bit hardening or certain treatments for small medical equipment like scalpel blades etc. In the work presented here, the shielding field is assumed to be the field produced by two straight, parallel, infinitesimally thin wires. Thus, the total magnetic field is a superposition of a uniform field and that produced by the wires. Larger arrays of wires lead to a spatially periodic field [17], which may serve to provide a larger number of regions that can be simultaneously shielded.

Figure 1: Two targets (horizontal lines) placed near two wires (solid dots) are shielded by the wires’ magnetic fields. An ion beam travels along the z axis from negative to positive (bottom to top) as indicated by the arrow. In the left panel particles, represented by colored lines, are deflected around the area near the targets by the magnetic field generated by the shielding wires. When the wire currents are turned off, beam processing such as ion implantation or thin film deposition occurs.
The magnetic field near the region of interest can be described in two parts: A constant uniform field \( B_0 \) defined to be in the \( Z \) direction, and a field generated by two infinitesimally thin, parallel, current carrying wires in the \( x, y \) plane:

\[
B(x, y, z) = B_m \beta \left( \frac{x}{\Delta z}, \frac{y}{\Delta z}, \frac{z}{\Delta z} \right) + B_0 \hat{k} \tag{1}
\]

Here,

\[
\beta(x_n, y_n, z_n) = \left[ -\frac{z_n}{(x_n-1)^2 + z_n^2}, 0, \frac{(x_n-1)}{(x_n-1)^2 + z_n^2} \right] - \left[ -\frac{z_n}{(x_n+1)^2 + z_n^2}, 0, \frac{(x_n+1)}{(x_n+1)^2 + z_n^2} \right] \tag{2}
\]

And \( B_m = \frac{\mu_0 I}{2\pi S} \) is the standard expression for the magnetic field at a distance \( S \) from a single wire with \( I \) the magnitude of current, \( \mu_0 \) the permeability of free space, and \( S \) half the distance between the wires. Note that the currents carried by the two wires must flow in opposite directions to generate a magnetic field as shown in Fig. 2.

![Figure 2: Illustration of the combined magnetic field in (x,z) plane. The solid dots represent the wires extending parallel to the y axis.](image)

Studying the trajectories of charged particles in this field is possible with a classical trajectory Monte Carlo simulation. To keep the results most generally applicable, all parameters are normalized [17]. Normalization is achieved by setting \( m_n = q_n = k_n = S_n = 1 \). Here \( m_n \) is the normalized mass, \( q_n \) is the normalized charge, \( k_n \) is the normalized kinetic energy, and \( S_n \) is the normalized length. Other parameters needed for the simulation are defined using their un-normalized counterparts. The position is normalized as \( r_n = \frac{r}{S} \), the velocity as \( v_n = v \sqrt{\frac{m}{k}} \), the acceleration as \( a_n = \frac{amS^2}{k} \), time as \( t_n = t \left( \frac{1}{S} \right) \sqrt{\frac{k}{m}} \), and magnetic field as \( B_n = \frac{B_0 S}{\sqrt{mk}} \). The un-normalized counterparts are then solved for and substituted into the Lorentz force law, \( ma = qv \times B \). A normalized version of the Lorentz force law is then obtained:

\[
a_n = v_n \times B_n \tag{3}
\]
In executing the Monte Carlo simulation, this vector equation is solved numerically. However, an expression for the combined normalized magnetic field is needed.

Returning to the uniform field \( \mathbf{B}_0 \), \( \mathbf{B}_0 \) can be used to define a parameter \( r_0 \),

\[
B_0 = \sqrt{\frac{2mK}{q^2r_0^2}}
\]  

\( r_0 \) is the cyclotron radius of a particle trajectory in the uniform field \( \mathbf{B}_0 \) with kinetic energy \( K \) associated with motion transverse to the magnetic field. Combining the expressions for the various magnetic fields into a single normalized expression yields

\[
B_n(x_n,y_n,z_n) = \frac{sgn(q)\sqrt{2}}{r_{0m}} \left[ \beta_0 \beta_n(x_n,y_n,z_n) + k \right]
\]  

Here, \( sgn(q) = \frac{q}{|q|} \) is the sign of charge, \( \beta_0 = \frac{B_0}{B_n} \) is the field strength ratio, and \( r_{0m} = \frac{r_0}{5} \) is the normalized cyclotron radius. Revisiting Eq. (3) and splitting it into vector components yields the normalized equations of motion,

\[
x_n''(t_n) = \frac{sgn(q)\sqrt{2}}{r_{0m}} \left( y_n'(t_n)(1 + \beta_0 \beta_n x_n(t_n), y_n(t_n), z_n(t_n)) - z_n'(t_n)(1 + \beta_0 \beta_n x_n(t_n), y_n(t_n), z_n(t_n)) \right)
\]  

\[
y_n''(t_n) = \frac{sgn(q)\sqrt{2}}{r_{0m}} \left( z_n'(t_n)(1 + \beta_0 \beta_n x_n(t_n), y_n(t_n), z_n(t_n)) - x_n'(t_n)(1 + \beta_0 \beta_n x_n(t_n), y_n(t_n), z_n(t_n)) \right)
\]  

\[
z_n''(t_n) = \frac{sgn(q)\sqrt{2}}{r_{0m}} \left( x_n'(t_n)(1 + \beta_0 \beta_n x_n(t_n), y_n(t_n), z_n(t_n)) - y_n'(t_n)(1 + \beta_0 \beta_n x_n(t_n), y_n(t_n), z_n(t_n)) \right)
\]  

These equations are solved numerically via a classical trajectory Monte Carlo simulation for single particles. Note that all forces in the system are conservative. Thus, conservation of energy will hold for particles in the system. However, conservation of energy is not employed within the simulation, so evaluating the total kinetic energy difference between the initial and final points of a trajectory can serve as an indicator of numerical accuracy for the simulation [17]. The kinetic energy of the simulated trajectories varies typically by less than 0.01% in the present work.

Two cylindrical regions, one centered at each wire, are each defined with a normalized radius \( a_n \) inside of which no trajectories pass. The size of these regions is some function of the ratio of strengths between the two parts of the total magnetic field \( \beta_0 = \frac{B_0}{B_n} \) and the normalized cyclotron radius \( r_{0m} \). This parameter \( a_n \) is the parameter of interest and has values \( 0 < a_n < 1 \). \( a_n \) cannot have larger values because at least a few trajectories pass between the wires relatively unimpeded (see Fig. 1). Each value of \( a_n \) is numerically determined. Evenly spaced test points are spread across the range of \( a_n \) at increments of 0.01, though any arbitrarily fine resolution could be used. For each value of \( a_n \), every combination of values for \( r_{0n} \) and \( \beta_0 \) in increments of 0.1 is simulated to determine if any prevent all trajectories from crossing within the circle described by \( a_n \) by evaluating the position of the simulated particle in relation to the wires at each time step of the equation of motion solution. The maximum values used for \( r_{0n} \) and \( \beta_0 \) were determined by executing several successively finer grained simulations over very large ranges and finding that no behavior of interest appears to exist past the ranges stated here.

The initial conditions for particle trajectories are:

\[
x_n(0) = x_{n0} = R_x,
\]  

\[
y_n(0) = y_{n0} = 0,
\]  

\[
z_n(0) = z_{n0} = -5,
\]  

at time \( t_n = 0 \). Here, \( R_x \) has a range of

\[-2 \leq R_x \leq 2\]

and is a random number equally likely to have any value in the above range. This insures that particle trajectories are initially spread evenly across the entire region of the deformed magnetic field near the wires enabling comprehensive simulation of effects. Due to the kinetic energy being normalized to \( 1 = K_n = \frac{1}{2} m_n v_{n0}^2 \), each particle’s initial normalized speed is \( \sqrt{2} \). The simulated particles are considered to be a monoenergetic beam. Thus, the initial velocity components are as follows:

\[ v_{nx}(0) = v_{ny}(0) = 0 \]

\[ v_{nx}(0) = v_{ny}(0) = 0 \]

\[ v_{nx}(0) = v_{ny}(0) = \sqrt{2} \]

Equations 9-14 are the six initial conditions needed to solve the equations of motion. Each trajectory is simulated for a maximum time \( t_{n_{\text{max}}} = 20 \frac{|x_{n0}|}{\tau_{n_{\text{ni}}}^{10C}} \sqrt{2} \).

3. Evaluation of Simulation Results

Figures 3 and 4 illustrate separately the relationships \( a_n \) versus \( \beta_n \) and \( a_n \) versus \( r_{nn} \). The fits in Fig. 3 are

\[ a_n(1.5, \beta_n) = 0.395 \times \text{erfc}[0.829(1.733 - \beta_n)], \]

\[ a_n(3.0, \beta_n) = 0.339 \times \text{erfc}[0.571(2.517 - \beta_n)], \]

\[ a_n(4.5, \beta_n) = 0.297 \times \text{erfc}[0.492(3.080 - \beta_n)], \]

where \( \text{erfc}[ ] \) is the complementary error function. The fits for both Fig. 3 and Fig. 4 were determined using the least squares method. In Fig. 4, the fits are

\[ a_n(\tau_{nn}, 1.5) = -0.093 + 0.038\tau_{nn} + 1.093e^{-\tau_{nn}}, \]

\[ a_n(\tau_{nn}, 3.0) = 0.666 - 0.093\tau_{nn} + 0.334e^{-\tau_{nn}}, \]

\[ a_n(\tau_{nn}, 4.5) = 0.817 - 0.078\tau_{nn} + 0.182e^{-\tau_{nn}}, \]

In both cases, the fits match the data to within 6.4% determined by the largest residuals. The shielded radius increases with increasing field ratio \( \beta_n \) but decreases with increasing cyclotron radius \( \tau_{nn} \). Note however, that the maximum radius of the shielded region is approximate because a finite number of trajectories is simulated (160 in this case). Simulations over larger sample sizes and finer resolutions can refine the edge of the shielded region to any arbitrary certainty desired given enough computation time.

The results obtained match the trend that would be expected from the system. As the field strength \( B_m \) of the wires becomes larger, the field ratio gets larger, and an increase in the radius of the shielded region is seen. Conversely, as the uniform field strength \( B_0 \) becomes significantly larger than the wire field, the effects of the wire
fields are suppressed. Varying the cyclotron radius effectively gives the shielded radius as a function solely of the field strength $B_0$.

Figure 5 presents a surface plot of the relationship between all three parameters. As expected, larger values of $a_n$ may be achieved with smaller values of $r_{0n}$ and larger values of $\beta_0$. A two parameter fit expression for $a_n$ is found by assuming independence (and therefore separability) between $r_{0n}$ and $\beta_0$:

$$a_n(r_{0n}, \beta_0) = \left[0.367 - 0.044r_{0n} + 0.215e^{-r_{0n}}\right] \cdot \left[\frac{2}{3} \cdot 2.097 \cdot \text{erfc}\left(\frac{1.996 - \beta_0}{1.894\sqrt{2}}\right)\right]$$

(21)

Here, the fitting constants are determined via the least squares method. Equation (21) matches the simulated data in Fig. 5 to within 40.4%.

By way of example, given a wire separation of 10cm such that $S=0.05$m and a 5KeV singly charged Boron ion beam with $B_n=B_{in}=0.5T$ such that $\beta_0=1$, $r_0=6.7cm$ and $r_{0n}=1.3$. This would make the unnormalized shielded radius $a = a_n \times S = 1.2cm$.

Figure 3: $a_n$ versus $\beta_0$ for values $r_{0n} = 1.5$ (circles), $r_{0n} = 3.0$ (squares), $r_{0n} = 4.5$ (diamonds). The lines are Eqs. (15)-(17).
Figure 4: $a_n$ versus $r_{0n}$ for values $\beta_0 = 1.5$ (circles), $\beta_0 = 3.0$ (squares), $\beta_0 = 4.5$ (diamonds). The lines are Eqs. (18)-(20).

Figure 5: Surface plot of $a_n$ versus $\beta_0$ versus $r_{0n}$.

Figure 5: Surface plot of $a_n$ versus $\beta_0$ versus $r_{0n}$.
4. Conclusion

Proposed here is a two wire control scheme for directing charge-neutralized ion beams and selectively shielding their targets. The regions shielded by the wire fields are quantified as cylindrical with a normalized radius \( a_w \). A relationship between the shielded radius \( a_w \), the ratio of strengths between the two parts of the magnetic fields \( \beta_r \) and the normalized cyclotron radius \( r_{\alpha n} \) is found via a classical trajectory Monte Carlo study. The resultant numerical values were fit using an exponential decay relationship between the shielded radius \( a_n \) and the normalized cyclotron radius \( i_n \) and an error function relationship between the shielded radius and \( \alpha_n \).

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