Phase space of positron trajectories exiting a charged particle source through a magnetic field point cusp

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Abstract

A configuration of magnetic fields using properties of cylindrically symmetric permanent magnets is presented as a candidate to produce a high purity charged particle source or trap. Cylindrically symmetric hollow permanent magnets produce magnetic field point cusps on the axis of symmetry. A magnetic field point cusp reflects all particles that lie outside a narrow region of phase space, a region dependent on particle kinetic energies and on the magnetic field intensity. An analysis of the phase space of positron trajectories entering and exiting a magnetic field point cusp is presented and quantified with respect to magnetic field intensity and particle kinetic energy. Preliminary experimental results support the use of point cusps for ion source applications.

Keywords: Ion source, Point cusp, Classical trajectory Monte Carlo simulation, Plasma trap

1. Introduction

Permanent magnets are a low cost alternative to current carrying coils for developing charged particle sources and traps. A feature of axially magnetized cylindrically symmetric hollow permanent magnetic cylinders is a pair of magnetic field point cusps on the axis of symmetry. Each of these cusps provides a true magnetic field null at an infinitesimal point with increasing magnetic field intensity in all directions. These point cusps allow only particles within a well-constrained phase space to pass and reflect all other particles, with a strong dependency on particle kinetic energy and magnetic field strength. Permanent magnets are open magnetic field sources, with field lines that both originate and terminate on the surface of the magnet. This introduces a caveat in the use of permanent magnets for source and trap applications. Particles following magnetic field lines can impinge on the surface of a permanent magnet at the terminal ends of a field line. A simple solution is to deflect particles away from these regions using electrostatic fields. This will in turn produce a high purity particle beam so long as the apparatus is properly biased to reflect particles from the end surfaces of the magnet. The two magnetic field point cusps are the only likely exits from the source. Any particle leaving the source will have migrated into the correct region of phase space and passed through either point cusp.

Figure 1: A two-dimensional cross-sectional view of the simulated apparatus along with the magnetic field.

Figure 1 depicts the apparatus considered here. The elements labeled V1 and V2 are copper electrodes and the large central element M1 is the hollow permanent magnetic cylinder. The black arrow heads mark the location of the point cusps and the location of the particle emitter is at the origin. The elements are grouped into V1 and V2 by electrostatic potential. The magnet M1 is equipotential with electrode group V2. The gray arrows denote magnetic field direction.

2. Method and Theory

A simulation has been developed that computes trajectories of single positrons within the axisymmetric magnetic field and monitors the dynamic parameters in regions of interest. The Lorentz force is the only force acting on the particles, and the system is adiabatically closed. The Lorentz force is

$$\mathbf{F}(x, y, z) = q[\mathbf{E}(x, y, z) + \mathbf{v}(x, y, z) \times \mathbf{B}(x, y, z)].$$

Here, $\mathbf{v}$ is particle velocity, $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic field, $\mathbf{F}$ is the force on the particle, and q is the particle's charge. The numerical integrator/particle mover used to calculate particle trajectories is a Boris-Buneman method, and the full algorithm is provided in Ref. [1]. The magnetic fields are calculated using the program Radia, a numerical magnetostatic field solver utilizing a boundary integral method described in Ref. [2]. Each electrode, labeled V1 and V2, is 3 mm and 5 mm long, respectively, and all electrodes and the magnet are spaced 1 mm apart. The central magnet is 50 mm long. The electric field is obtained from the electric potential computed by the finite element method used in the program FEMM [3]. The electric potential was solved out to 0.5 m past either end of the central magnet and 0.1 m radially from the longitudinal axis of symmetry z . The computed region was, thus, a cylindrical volume 1.05 m long and 0.2 m in diameter, with the electrostatic potential set to zero as the boundary condition along the surface of that cylinder. The magnetic field source is a virtual hollow cylindrical permanent NdFeB magnet with a peak residual surface magnetization of 1.4 T. The emitter is assumed to be a disk 2 mm in radius and 1 mm thick, placed co-axially with the center at the origin. In this simulation, positrons were emitted from randomly-sampled positions on the disk with fixed kinetic energy and randomly directed velocities. The simulation considers only mono-energetic positrons for simplification of phase space analysis, and the kinetic energies used were 10 eV, 30 eV, and 50 eV. These energies were tested for three central magnets and electrode groups of outer radii 2 cm, 3 cm, and 4 cm, with fixed inner radii of 1 cm. This effectively varied the magnetic field strength around the cusps. The phase space parameters recorded were the transverse Cartesian particle coordinates x and y , and the transverse fractions of velocity v_x/v_z and v_y/v_z . The analysis locations were at $z = 25$ mm and at $z = 425$ mm, the former 1 mm before a point cusp and the latter in a region of negligible magnetic field. Any positron that does not impinge back onto the particle emitter or come in contact with a surface of the permanent magnet or an electrode will eventually fall within the correct region of phase space and pass through a point cusp. To reflect any positrons following the open magnetic field lines into the surface of either side of the central magnet, the electrode group V2 was suitably biased with respect to the group V1 to reflect the positive charge. This also had a small focusing effect on exiting positrons.

3. Results and Discussion

Results are shown in Fig. 2. Figure 2a is an estimate of probable particle location via the probability density functions at the $z = 425$ mm plane. The probability density functions were generated from a distribution of 10,000 successfully exiting positrons per kinetic energy per cylindrical magnet outer radius. These can be used to calculate the probability of finding a positron for a given range of x axis locations, an effective estimate of beam spread. Figure 2b and Fig. 2c are the half transverse phase space diagrams for the planes at $z = 25$ mm and $z = 425$ mm, respectively. These phase space diagrams were fitted to the distribution of x coordinates and matching transverse velocity fractions v_x/v_z for 10,000 positrons. The half transverse phase space uses a Cartesian component of the cylindrical coordinate $\rho = \sqrt{x^2 + y^2}$ and the fraction of transverse velocity in that same Cartesian component to simplify analysis of cylindrically symmetric phase space. This is done because ρ is always positive, obscuring some relevant information. The ellipses in Fig. 2b were fitted to enclose the phase coordinates for the first 10,000 positrons to reach the plane at $z = 25$ mm for each tested central magnet outer radius and positron kinetic energy. The ellipses in Fig. 2c were fitted to enclose the phase coordinates for approximately 10,000 positrons that successfully passed through a point cusp and reached the $z = 425$ mm plane for each tested central magnet outer radius and positron kinetic energy.

Figure 2: Probability density functions (a) and v_x/v_z versus x phase space diagrams at $z = 25$ mm (b) and at $z = 425$ mm (c). Magnet(and electrodes) has an outer radius of 4 cm (black lines), 3 cm (gray lines), or 2 cm (dotted lines).

Plots of y versus v_y/v_z are identical and not displayed. The ellipses were fitted to encompass 95% of the probability distribution in phase space. The electrostatic potential between electrode groups V2 and V1 was fixed at 2.5 times the positron kinetic energies tested. The particle source displays increasing brightness with stronger magnetic fields, directly increasing the range of particle energies with which the apparatus can be effectively used.

Preliminary experimental results have been obtained by imaging electrons transmitted through a point cusp with an electron detection system. The detection system is a Chevron pair of micro-channel plates (MCPs) with front and rear faces biased to +500 V and +2300 V from ground, respectively. The cascade produced by electrons incident on the MCP assembly are converted to visible wavelength photons by a phosphor screen assembly biased to +2.8 kV from ground. The photons corresponding to incident electrons are recorded by an ST-7XMEI SBIG CCD camera located outside the vacuum chamber. The images recorded thus far are with a single particle energy and show an axisymmetric spot of constant diameter independent of variations in intensity. The spot intensity is indicative of the number of incident particles on the MCP assembly. This is ideal behavior for ion source applications.

4. Conclusion

These results show the potential of this apparatus for handling expensive or difficult-to-handle charged particle species at low kinetic energies. In this study no particle impacted any surfaces of the electrodes or magnet over the time periods and kinetic energies simulated. The phase space regulating capabilities of magnetic field point cusps are well displayed by the decrease in tangential velocity spread by roughly a factor of ten. A possible application for this apparatus is to confine a two-species plasma, with the first species confined both magnetically and with the externally applied electric field and the second, oppositely signed species confined by the space charge of the first species, as analyzed in Ref. [4]. An apparatus of this sort would be well suited for preconditioning particles for further focusing using an einzel lens to provide a high quality compact low kinetic energy particle source.

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