AN IDEAL CIRCULAR CHARGED-PARTICLE BEAM SYSTEM*

T. Bemis, Beam Power Technology, Inc., 150 Lincoln Street, Suite 3C, Boston, MA 02111, USA
R.J. Bhatt#, C. Chen, J. Zhou, MIT Plasma Science and Fusion Ctr., Cambridge, MA 02139, USA

Abstract

A theory is presented for the design of an ideal non-relativistic circular beam system including a charged-particle emitting diode, a diode aperture, a circular beam tunnel, and a focusing magnetic field that matches the beam from the emitter to the beam tunnel. The magnetic field is determined by balancing the forces throughout the gun and transport sections of the beam system. OMNITRAK particle trajectory simulations are performed, validating theory. The ideal circular electron beam system has wide applications in space-charge-dominated accelerator research, high energy density physics (HEDP) research, vacuum electronics, and medical and industrial accelerators,

INTRODUCTION

High-brightness, space-charge-dominated charged-particle beams are of great interest because of their applications in particle accelerators, material processing such as ion implantation, medical applications, and vacuum electron devices. When the beam brightness increases, the beam becomes space-charge-dominated. In the space-charge-dominated regime, the beam equilibrium is characterized by a beam core with a transversely uniform density distribution and a sharp edge where the beam density falls rapidly to zero in a few Debye lengths.

For particle accelerators, high-brightness, space-charge-dominated charged-particle beams provide high beam intensities. For medical accelerators, they provide high radiation dosage. For ion implantation, they improve the uniformity of ion deposition and doping speed. For vacuum electron devices, they permit high-efficiency, low noise operation with depressed collectors.

However, there are significant theoretical, design and experimental challenges in the generation, acceleration, focusing, and collection of high-brightness charged-particle beams. The traditional approach to charged-particle dynamics problems involves extensive numerical optimization over the space of initial and boundary conditions in order to obtain desired charged-particle trajectories. The traditional approach is numerically cumbersome and will not obtain a globally-optimal solution. As a result, beam systems designed using these approaches will result in a degradation of beam brightness, increased noise, particle loss, and reduced efficiency.

An essential component of charged-particle beam systems is the beam generation and acceleration diode, consisting of a charged-particle emitter and an electrostatic gap across which one or more electrostatic potential differences are maintained. The potential differences accelerate the emitted charged particles, forming a beam that exits the diode through an aperture and then enters a beam transport tunnel. Conventionally Pierce type diodes [1] are employed. Compression is often used in Pierce type diodes in order to generate the desired beam current, while scrapers are used to chop off the nonuniform beam edges [2] in order to obtain a uniform density profile. The compression and scrapers introduce a mismatch into the beam systems, resulting in a degradation of beam brightness.

A second essential component of charged-particle beam systems is the transition from the diode to the beam focusing tunnel. In the focusing tunnel, combinations of magnetic and electrostatic fields are used to confine a beam such that it maintains (usually) parallel flow. If the proper focusing field structure is not applied, the beam can undergo envelope oscillations that contribute to beam brightness degradation and particle loss. While the rigid-rotor equilibrium is well-known for a uniform solenoidal focusing field [3], a good matching of a circular beam from a Pierce type diode into the rigid-rotor equilibrium has been not been reported until this invention [4].

A third essential component of many charged-particle beam systems is the depressed collector placed at the end of the beam transport tunnel to collect the remaining energy in the beam. A well-designed depressed collector minimizes the waste heat generated by the impacting beam while maximizing the electrical energy recovered from said beam. Modern high-efficiency multiple-stage depressed collectors (complicated structures with multiple electrodes held at different potentials) can obtain collection efficiencies approaching 90%.

IDEAL CIRCULAR-BEAM SYSTEM

A method is presented for the generation, acceleration, focusing, and collection of a high-brightness, space-charge-dominated circular charged-particle (electron, positron, proton, antiproton, ion) beam. As illustrated in a cross sectional view shown in Fig. 1, the beam system comprises [4]

a) a flat circular emitter which emits charged particles (electrons, positrons, protons, and ions),
b) a diode with one electrode at the emitter and at least one additional electrode which accelerates the charged particles,
c) a beam tunnel which is connected electrically to at least one of the additional electrodes,
d) an applied axisymmetric magnetic field for charged-particle beam focusing, and

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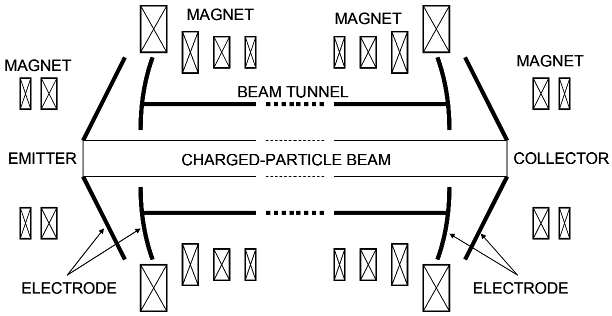

Figure 1: Cross sectional view of a high-brightness circular charged-particle beam system.

e) a depressed collector which collects the charged-particle beam.

The emitter consists of a flat, circular disk. A circular charged-particle beam is emitted from the emitter with a uniform density. The current emission is space-charge-limited, obeying the Child-Langmuir law. The electrodes and applied axisymmetric magnetic field are designed to preserve the beam cross section in the accelerating section. The method for designing the required electrodes and applied axisymmetric magnetic field is described as follows.

As a first step, the beam dynamics is modeled with an OMNITRAK simulation with no applied magnetic field. This provides the electric field database which is used to iteratively compute the applied magnetic field required to preserve the cross section of the charged-particle beam at the accelerating section. As an illustrative example, Fig. 2 shows the results of the OMNITRAK simulation for a circular electron beam which is emitted from a circular emitter (cathode) with a radius of 1.52 mm circular cathode, a current of 0.11 ampere, and a cathode-to-anode distance of 4.11 mm at radius $r = 1.52$ mm. The diode voltage is 2300 V. In this illustrative example, the electrodes at the cathode and the anode are equipotential surfaces which are analytically computed to yield a Child-Langmuir flow in the absence of the anode aperture. A circular aperture at the anode is chosen, and it has a radius of 1.55 mm. A larger circular beam tunnel with a radius of 6.0 mm is connected to the anode.

As a second step, an estimate of the required applied magnetic field is obtained by balancing all of the radial forces on the electrons on a line whose radius corresponds to the root-mean-square (rms) radius of the emitter (i.e., at radius of 1.075 mm). The line starts at the cathode disk and continues through the anode aperture.

Because the radial forces are balanced on this radius, the radial velocities of the electrons will remain zero, upon successive iterations. If the radial velocity and acceleration are held at zero for all values of z, there is no radial velocity and displacement. The beam cross section is preserved as it is transported through the aperture and into the beam tunnel. The resulting beam has a variable rotational velocity, providing a magnetic confinement force that precisely balances the centripetal and space charge repulsion forces for all values of z at $r = 1.075$ mm.

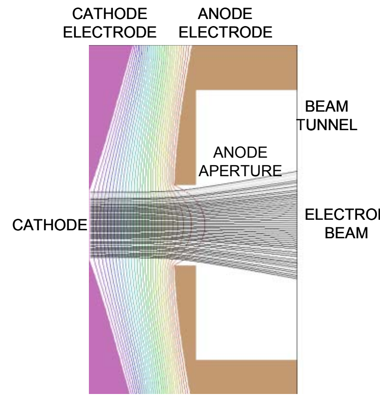

Figure 2: Simulation of the dynamics of an electron beam emitted from a flat circular cathode with a radius of 1.52 mm and a current of 0.11 amperes in the absence of an applied magnetic field. Here, the cathode-to-anode distance is 4.11 mm at $r = 1.52$ mm, the circular anode aperture has a radius of 1.55 mm, and the beam tunnel has a radius of 6.0 mm. The diode voltage is 2300 V.

For a thin charged-particle beam, an expression for the required magnetic field is derived to achieve the radial force balance at any radius in the beam core. The magnetic vector potential for an applied axisymmetric magnetic field is in the azimuthal direction. An applied axisymmetric magnetic field is expressed in terms of the vector potential in a cylindrical coordinate system as

$$\mathbf{B} = \hat{\mathbf{e}}_z \frac{1}{r}\frac{\partial}{\partial r}(rA_\theta) - \hat{\mathbf{e}}_r \frac{\partial A_\theta}{\partial z} . \quad (1)$$

In the thin-beam approximation,

$$\mathbf{B} = B_z(0,z)\hat{\mathbf{e}}_z - \frac{1}{2}\frac{\partial B_z(0,z)}{\partial z} r\hat{\mathbf{e}}_r . \quad (2)$$

Inspection of Eq. (1) and (2) gives

$$A_\theta(r,z) = \frac{r}{2} B_z(0,z) . \quad (3)$$

The conservation of canonical angular momentum yields the expression for the azimuthal velocity,

$$\upsilon_\theta(r,z) = -\frac{q}{2m}\left[B_z(0,z) - B_z(0,0)\right] r , \quad (4)$$

where use has been made of $\upsilon_\theta(r,0) = 0$ at the emitter, and q and m are the particle charge and rest mass, respectively. The radial force balance equation is

$$\frac{qE_r(r,z)}{m} = -\frac{\upsilon_\theta^2(r,z)}{r} - \frac{q}{m}\upsilon_\theta(r,z)B_z(r,z) . \quad (5)$$

Substituting Eq. (4) into Eq. (5) yields the expression for the required applied magnetic field on the beam axis, i.e.,

$$\frac{qE_r(r,z)}{m} = \frac{q^2 r}{4m^2} B_z^2(0,z) , \quad (6)$$

where use has been made of the boundary condition $B_z(0,0) = 0$. Equation (6) produces a relationship between E_r / r and $B_z(0,z)$. It should be emphasized that for a thin beam, the function E_r / r is only a function of z, which is evaluated from the electric field database from OMNITRAK simulations. From Eq. (2), the magnetic field database is expanded to produce a three dimensional magnetic database on a uniform rectangular grid for OMNITRAK simulations.

By iterating the second step described above, better estimates of the required magnetic field are obtained. Typically, results converge after two or three iterations.

Figures 3 and 4 show, respectively, plots of E_r versus z at $r = 1.0$ mm and $B_z(0,z)$ versus z from the OMNITRAK simulations after two iterations. In Fig. 3, the radial field vanishes at the emitter (i.e., at $z = 0$). The effect of the aperture is most pronounced at $z = 4.2$ mm. The radial electric field approaches to a small, constant value as the beam propagates further inside the beam tunnel. In Fig. 4, the axial applied magnetic field is computed using the results in Fig. 3 and Eq. (6). The axial magnetic field at the emitter vanishes. It increases to 640 G at the aperture, and then falls to about 160 G well inside the beam tunnel.

Figure 5 shows the corresponding circular electron beam in the OMNITRAK simulation after two iterations. Figure 6 shows the electron trajectories as they intersect the plane at $z = 4.11$ mm. Detailed analyses of the simulation results show that the outer beam radius remains to be the same as at the cathode radius, and the beam density remains to be uniform in the beam core.

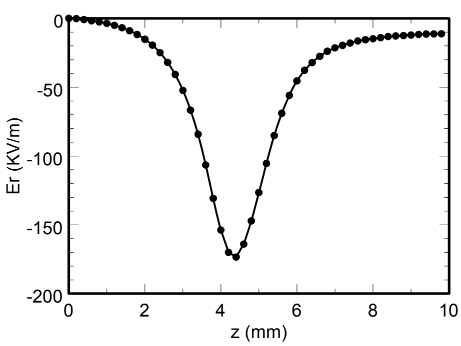

Figure 3: Plot of E_r versus z from the OMNITRAK simulations after two iterations.

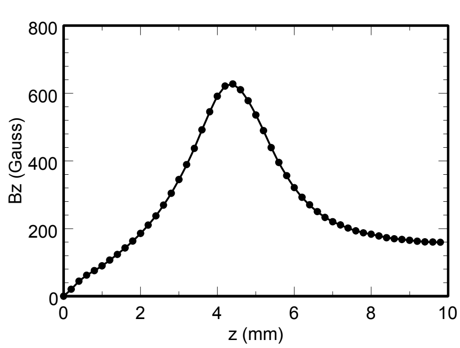

Figure 4: Plot of $B_z(0,z)$ versus z from the OMNITRAK simulations after two iterations.

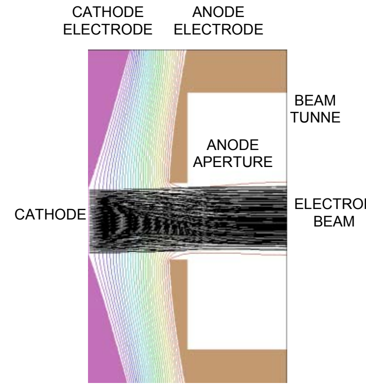

Figure 5: Circular beam is force balance matched with calculated B_z database.

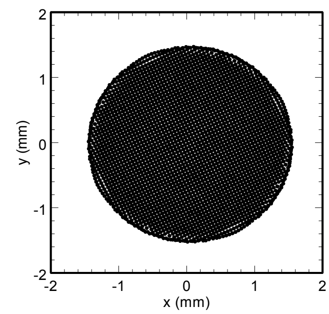

Figure 6: Circular beam is force balance matched with calculated B_z database.

Because the beam is in laminar flow, a depressed collector is designed using the same geometry as the charged-particle emitting diode, where the circular emitting disk is the beam collecting surface, and the diode voltage is slightly lower (i.e., a fraction of a percent lower) than the diode voltage but has a negative bias. Such a depressed collector has a collection efficiency of nearly 100%.

CONCLUSIONS

A high-brightness, space-charge-dominated circular charged-particle beam system was described. The method was presented for designing a high-brightness, space-charge-dominated circular charged-particle (electron, proton, or ions) beam system, including the beam generation, acceleration, focusing, and collection processes.

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