ELECTRON BEAM COLLECTOR WITH A TRANSVERSE MAGNETIC FIELD

A.Shemyakin, FNAL, Batavia, IL60510, USA

Abstract

Relative current losses from an electron beam collector are hardly achievable at the level below 10^{-4}, if trajectories are reversible in the collector cavity. The Fermilab electron cooler collector is equipped by a system of permanent magnets, such that its magnetic field destroys the reversibility and suppresses the escaping of secondary electrons. The paper describes a design of the collector and results of measurements of its properties at a dedicated low-energy test bench.

1 INTRODUCTION

A stable electron beam transport in the Fermilab electron cooling device [1] requires a current loss below 10 μA at the Ampere-range beam currents. One of the sources of the loss is a back-flow δI of secondary electrons from the beam collector. Collectors, traditional for the electron coolers, can not provide such low value of δI because of the reversibility of trajectories in the collectors. To decrease the back flow further, a transverse magnetic field in the collector should be applied.

2 CURRENT LOSS FROM A COLLECTOR AND TRAJECTORY REVERSIBILITY

The main portion of losses from an efficient collector is formed by secondary electrons moving without collisions from the place of their origin to the collector entrance. In standard collectors, the position of these particles in the 3D phase space of secondary electron velocities at the place of their origin is determined by reversibility of electron trajectories. Namely, if a trajectory equation is invariant with respect to the time reverse, a secondary electron with the kinetic energy equal to the energy of the primary one can come out of the collector following the trajectory of the "parent" electron. In this case, the back-flow from the collector is determined by secondary particles with velocities close to the velocity of this specific electron. The collector design cuts down a volume ΔV_{3_escape} in the 3D phase where electrons can escape the collector, while the relative phase density ρ_3 inside the volume is determined by properties of the irradiated surface, the primary electron energy, and incidence angle. Here, the density is normalized to the material's coefficient of secondary emission $\sigma = \int \rho_3 dV_3$. High collector efficiency can be achieved only if V_{3_escape} occupies a small portion of the total phase space, so that the density is approximately constant over it. Hence,

$$\delta I = \int_S \rho_3 \cdot \Delta V_{3\_escape} \cdot j \cdot dS\ , \quad \int_S j \cdot dS = I \qquad (1)$$

where the integral is taken over the whole irradiated collector surface *S*, and *j* is the beam current density. There are several important cases.

A. Electrostatic collector. If the influence of magnetic field on electron motion inside a collector cavity is negligible, trajectories are strictly reversible. The back flow from an electrostatic collector can be estimated by a simple formula in the case of the equal length *L* for all trajectories inside the collector [2]:

$$\frac{\delta I}{I} = 2 \cdot k \cdot \left(\frac{R_{ent}}{L} \right)^2 \cdot \frac{U_{\min}}{U_{coll}}\ , \qquad (2)$$

where the coefficient $k \approx 0.1$ is determined by the backscattering coefficient of the collector surface, R_{ent} is the radius of the collector entrance, U_{coll} is the collector potential, and U_{min} is the value of the potential minimum in front of the collector (both with respect to the cathode).

B. Axially symmetric magnetized collector. Generally speaking, trajectories are not reversible in the presence of a magnetic field, but in the case of an axial symmetry the equation of motion in (r,z) plane is reversible if the beam-generated magnetic field B_θ is negligible. The reversibility is obvious in the well-known paraxial limit (for example, [3]) but can be easily shown for a general case as well. So, if a primary electron strikes the collector surface with the velocity (V_z, V_r, V_θ), a secondary electron knocked with the velocity $(-V_z, -V_r, V_\theta)$ has the same radial offset along its trajectory and, therefore, escapes from the collector. A simple formula can be used for the case of a collector with a potential minimum and an adiabatic "magnetic mirror" [8]:

$$\frac{\delta I}{I} = k \cdot \left(\frac{U_{\min}}{U_{coll}} \right)^2 \cdot \frac{B_c}{B_0}\ , \qquad (3)$$

where B_0 and B_c are magnetic field strength in the potential minimum and at the collector surface, correspondingly.

C. Collector with a strong longitudinal magnetic field. If the magnetic field inside a collector is not axially symmetric but strong enough, both primary and secondary electrons are "frozen" into the same magnetic field lines, and one can tell about reversibility of the motion of the "Larmor circle" center. Violation of the reversibility in this case is caused by electron drifts, arising from the curvature of the magnetic field lines and by electric fields, which displace the secondary electron trajectory near the entrance by Δ_{drift} with respect to the initial offset of the corresponding primary electron. Formula (3) is still valid when the displacement is small, $\Delta_{drift} << R_{ent}$.

The efficiency of the majority of the electron cooler collectors can be estimated by formula (3). Minimum of the ratio of U_{min}/ U_{coll} is determined by the space charge, and it is about 0.3 for the interesting range of beam parameters (I~ 1A, U_{coll}.~ 3-5 kV). The ratio of B_0/B_c is close to the ratio of the beam area in the potential minimum to the area of the collector cross section where the beam begins to irradiate the wall; typically, it is not less than 0.01. Hence, a realistic estimation for the value of $\delta I/I$ is 10^{-4}. A further decrease of the value is possible with violation of trajectory reversibility in the collector cavity by means of a transverse magnetic field.

3 COLLECTOR WITH A TRANSVERSE FIELD

A serious disadvantage of a collector with a transverse magnetic field is difficulty of its simulation in a space charge regime that results in an increase of the number of variants to be tested experimentally. In two series of measurements, in Novosibirsk BINP in 1997 (together with A.Sharapa) and at FNAL in 1999-2000, several dozens of different magnetic field geometries were tested.

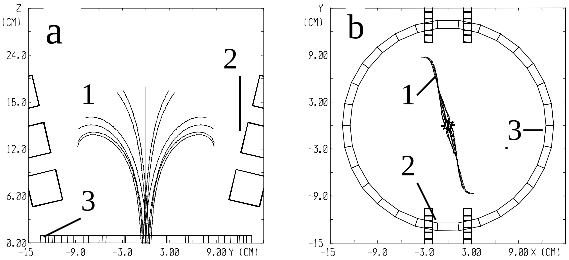

Figure 1: The simulation of electron trajectories in the equipotential space: a- YZ plane, b- XY plane. 1- beam trajectories, 2- square contours with currents of 7.3 kA representing permanent magnets, 3- solenoid near the collector entrance. Electron energy is 5 keV, magnetic field inside the solenoid 3 is 150 G.

The collector developed in the first set of experiments [4] was initially optimized for operation without a longitudinal field. Its transverse field was formed by two groups of 6 Nd-Fe-B square permanent magnets (Fig.1), mounted on both sides of the collector. Magnets of each group are magnetised in opposite directions along X axis and create a quadrupole field configuration with gradient of 10-15 G/cm in the vicinity of Z axis. The field focuses electrons in X direction and defocuses in Y, so that the beam is absorbed on collector walls mainly along a narrow band near the plane X=0. The transverse field in this region, with the magnitude 50 –70 G, effectively confines secondary electrons. The only exception is the electrons entering the collector with small X offsets. They move through the whole collector, hit its bottom, where there is no transverse field, and the produced secondary particles have the probability of escaping even higher than without the transverse field. Measurements of the collector efficiency at different beam positions at the collector entrance, made with a low-current, small size beam, shown a narrow band of the beam positions with high current losses (up to $1\cdot10^{-3}$) near Y axis. At higher currents, when the beam size is comparable with the entrance opening, the beam can not be shifted from the high-loss region, and the total efficiency was determined by the beam part overlapped with the band. The best result in the symmetric configuration was above $1\cdot10^{-5}$. To eliminate the effect, the magnets on one side of the collector were shifted along Z with respect to the other side group that resulted in a displacement of the band position from the center. This geometry demonstrated losses below $3\cdot10^{-6}$ at the beam current of up to 0.6 A at the test bench [4] and (5-20) $\cdot10^{-6}$ in experiments with MeV- range beam recirculation [5]. Note that even though the beam was received to one side of the collector in this geometry, the presence of magnets on the other side was important to avoid problems with beam transport outside the collector because of the long-range dipole field.

The gun in the 5 MeV test facility, which is now under construction at Fermilab [6], is immersed into a longitudinal magnetic field of up to 600 G. The beam originating in the field behaves outside the solenoid as having a large transverse emittance [7]. To transport such a beam, a longitudinal field has to be created in the collector region as well. The field significantly changes the collector properties. Tests of the collector described above with a solenoid placed near its entrance, performed at a dedicated low-energy test bench at Fermilab, demonstrated a possibility to work with a higher current but also revealed significantly higher losses. For the current of 1.5 A, the relative current loss was $2.5\cdot10^{-5}$at U_{coll}=4.2 kV. An example of simulation of electron motion made by MAG3D code [8] without taking into account the beam space charge is shown in Fig.1. The main reason for the increase of the maximum current and the loss is an additional focusing by the solenoid field of both primary and secondary electrons. At the field strength necessary for the beam transport, which was 150-300 G inside the solenoid and a half of this at the collector entrance, the measured width of the high loss band was always about the diameter of the collector anode. Furthermore, the formed ribbon beam is inclined with respect the XZ plane (Fig.1b). As a result, electrons reach the collector wall in a place with a lower transverse magnetic field component. The inclination angle approaches to 45° with decrease of the electron energy or increase of all magnetic fields, when electrons moves along the magnetic field lines adiabatically. In such a regime the collector becomes similar to the one described above in section 2, case C.

On the other hand, the longitudinal field improves a “rigidity” of the electron motion outside the collector and makes it possible to use dipole solutions. One of them is placing all previously used magnets onto one side of the collector close to its entrance. The relative loss of $8{\cdot}10^{-6}$ was achieved in this variant, but the beam irradiated only a narrow region of the collector surface so that the heat demand was too high for an extended operation.

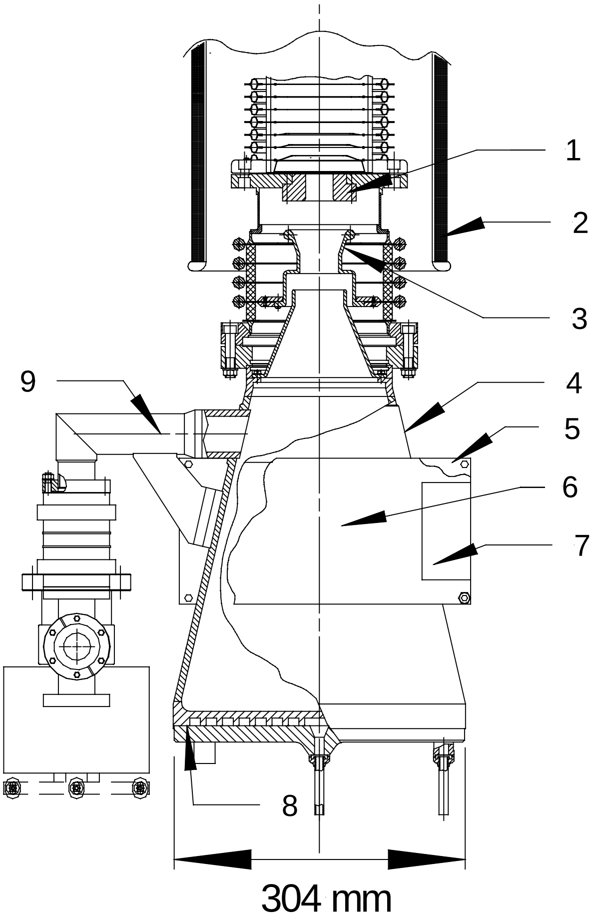

Figure 2: The collector used in the low-energy tests. 1- collector anode, 2- solenoid, 3- suppressor electrode, 4- collector body, 5 and 6- steel plates, 7- permanent magnets, 8- water cooling, 9- pumping.

The final solution seems now more natural and almost obvious. In all previous geometries, the beam size in one direction was kept small by applying a rapidly decreasing field to bring the entire beam into a high transverse field. Instead, the same ratio between the beam size and bending radius can be done for much larger beam size and nearly homogeneous weak transverse magnetic field covering the greater part of the collector cavity. In the arrangement shown in Fig.2, the field of about 15 G was formed by two steel plates with 1” X 2” X 4” ferrite permanent magnets attached outside each plate. The strength can be adjusted by the distance between plates and was determined by the collector voltage. In turn, the voltage was chosen according to the maximum desired current to be transported inside the collector cavity. The current loss in this variant were found to be below $8{\cdot}10^{-6}$ with no cooling problems.

4 CONCLUSION

Transverse magnetic field in the collector cavity breaks trajectory reversibility and can effectively suppress escaping of secondary electrons from the collector. Presence of a longitudinal magnetic field near the collector, generally speaking, degrades the collector efficiency. A simple solution with a low-strength, nearly homogeneous transverse field provides relative current loss below $8{\cdot}10^{-6}$ up to the beam current of 1A at the collector voltage of 3 kV.

5 ACKNOWLEDGEMENTS

Many original contributions to this work belong to A.Sharapa who passed away in 1998. The author acknowledges useful discussions with S.Nagaitsev and participation of V.Vostrikov in a part of experiments. Also, the author is thankful to T.N.Andreeva for the assistance in computer simulations and to the entire Electron Cooling group personnel for their technical support.

REFERENCES

[1] S.Nagaitsev et al., Nucl.Instr.and Meth.-A441(2000) 241
[2] A.N.Sharapa and A.V.Shemyakin, Nucl.Instr.and Meth., A396 (1997) 110
[3] M.Reiser, “Theory and Design of Charged Particle Beams”, J.Wiley & Sons, Inc. (1994)
[4] A.Sharapa, A.Shemyakin, and S. Nagaitsev, Nucl.Instr.and Meth.-A417(1998) 177
[5] A.C.Crawford et al., Nucl.Instr.and Meth.-A435 (1999), 339
[6] A.Shemyakin et al., Status of the Fermilab Electron Cooling Project, these Proceedings
[7] A.Burov et al., “Optical principles of beam transport for relativistic electron cooling”, submitted to Phys. Rev. ST-AP. Available at: http://fnalpubs.fnal.gov/techpubs/pubs_lists.html.
[8] M.A.Tiunov, B.M.Fomel,. INP 83-150, 1983 (in Russian).