EFFICIENCY OF THE FERMILAB ELECTRON COOLER'S COLLECTOR*

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Abstract

The newly installed Recycler Electron Cooling system (REC) at Fermilab [1] will work at an electron energy of 4.34 MeV and a DC beam current of 0.5 A in an energy recovery scheme. As a part of the Electron cooling project, the efficiency of the collector for the REC was optimized at a dedicated test bench to the level of relative current losses of $5\cdot10^{-6}$. The paper discusses the test bench measurements for several distributions of a transverse magnetic field in the collector cavity.

INTRODUCTION

The energy-recovery scheme used in the REC cooler makes the machine particularly sensitive to the efficiency of the electron beam collector in preventing the secondary electrons from escaping the collector cavity. A dramatic improvement of the efficiency was found with a transverse magnetic field applied to the collector cavity [2]. The role of the field is to break the reversibility of the trajectories, thus preventing first-generation secondary electrons from escaping the collector [3]. We present a simple model describing a mechanism of this prevention and results of measurements at a test bench.

A COLLECTOR MODEL

To estimate the range of parameters where application of a transverse field may be beneficial, let us consider the following simple model of a collector. A round, zero-emittance electron beam with radius R_b, current I and captured magnetic flux $\Phi = B_{cath}\cdot\pi R_{cath}^2$ enters a cylindrical collector cavity with electron velocities v parallel to the axis. Here, B_{cath} and R_{cath} are the strength of the longitudinal magnetic field on the cathode surface and the cathode radius. Further assume that a transverse magnetic field combines in the collector cavity with the fringe fields of an upstream solenoid so that the magnetic field lines from the collector entrance to its wall are 90° arcs with constant field strength B_{col} along them. For the central trajectory, the bending radius is equal to the radius of the cavity R_{col}. Due to bending, the primary electrons drift away from the field lines by $\rho_{\|}\cdot\frac{\pi}{2}$, where $\rho_{\|}\approx\frac{1}{B_{col}}\sqrt{\frac{2mU_{col}}{e}}$, e and m are the electron charge and mass, and U_{col} is the collector potential with respect to the cathode. Backscattered electrons on their way toward the collector entrance drift in the same direction by approximately the same amount. If the total displacement is larger than the initial distance from the electron trajectory to the entrance aperture, the backscattered electron is captured. The size of the aperture can be made close to R_b, and a capturing condition can be expressed as

$$\rho_{\|} = R_b\cdot C\ ,\quad C>\frac{2}{\pi} \tag{1}$$

where the coefficient C determines a safety margin.

An equilibrium beam radius can be estimated for the case $A=\frac{R_b}{R_{col}}<<1$ and a low enough beam current, when the electron motion with respect to the central trajectory can be treated in the paraxial approximation, as follows:

$$R_b = \rho_{\|}\sqrt{2K+\sqrt{4K^2+\frac{\varepsilon_B^{\ 2}}{\rho_{\|}^{\ 2}}}}\ , \tag{2}$$

where $K=\frac{eI}{2\pi\varepsilon_0 mv^3}$ and $\varepsilon_B\equiv\frac{\Phi}{2\pi\cdot mv}$. Combination of (1) and (2) put limitations on the parameters, such that:

$$C\sqrt{2K+\sqrt{4K^2+\frac{\varepsilon_B^{\ 2}}{\rho_{\|}^{\ 2}}}}=1\,\cdot \tag{3}$$

According to Eq. (3), a larger flux in the beam requires an increase of $\rho_{\|}$ and R_b. To have all electrons in similar conditions, the collector radius should be increased as well. The minimum collector radius can be estimated as

$$R_{col\_\min}=\frac{C}{A\cdot\sqrt{1-2K\cdot C^2}}\cdot\varepsilon_B\ , \tag{4}$$

For REC parameters (U_{col} = 2.5 kV, I = 0.5 A, ε_B = 1 mm) and assuming C = 1, A = 0.3, estimation (4) gives 3 mm, which does not impose any real limitations. However, for the parameters of CERN's AD's [4] cooler, for example, (4) gives 50 cm. Such a collector may be too cumbersome.

MEASUREMENTS

Test Bench Setup

Prescriptions described above were realized in the recent version of the REC collector. A sketch of the collector mounted at a test bench is shown in Fig. 1. The collector is a stainless steel cylinder with water cooled side walls. Its length is 40 cm, R_{col} = 13 cm, and the enter aperture radius is 2.5 cm. Transverse magnetic field in the collector cavity is provided by five 1"×2"×3" NdFeB permanent magnets placed on a 300 mm × 300 mm × 3 mm steel plate outside the cavity with another steel plate without magnets on the other side of the collector 300 mm apart. The field strength in the center is ~15 G. The longitudinal magnetic field configuration in the collector region is close to that in the Pelletron. Magnetic field

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strength was 200-700 G at the cathode and 80 – 250 G in the drift tube.

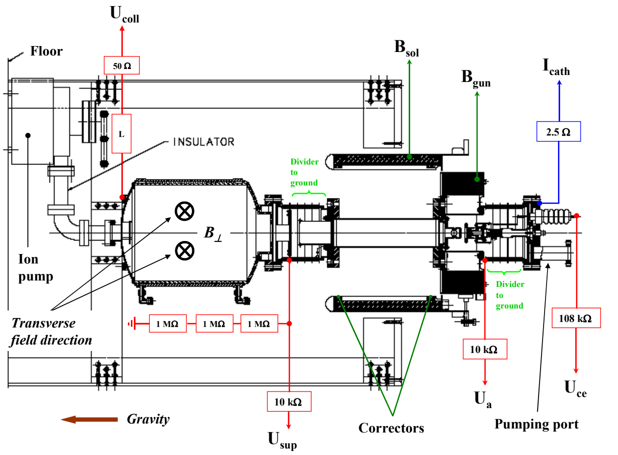

Figure 1: Mechanical drawing of the test bench including an outline of the electrical circuit. and some nomenclature: U_a, anode voltage; U_{ce}, control electrode voltage; U_{sup}, suppressor voltage; U_{col}, collector voltage; I_{cath}, cathode current. Plates creating the transverse field are not shown.

Measurements without Transverse Magnetic Field on the Collector

The first phase of measurements was done without a transverse field. The maximum current was limited by 0.2 A due to the bottom being only air-cooled. The current loss was found to be proportional to U_{sup} (Figure 3) and agrees well with the estimate in Ref [5], Eq.(12), for a collector without any magnetic field.

This configuration was used to estimate how well the loss measured at the test bench may predict losses in the Pelletron. In systems with longitudinal magnetic field, a portion of secondary electrons may fly all the way to the gun, be reflected from the area near the cathode, and return to the collector [6]. This "recovered" portion δI_r may even be much larger than the lost part δI_{lost} (for example, [7]). While being reflected, these electrons change the space charge distribution in the gun. In the simplest approximation of monoenergetic flows, the cathode current changes by $\delta I_{cath} = 2\ \delta I_r$.

To estimate this effect, a 22 kHz, 0-300V modulation was applied to the suppressor electrode. The AC component of the cathode current was recorded by a spectrum analyzer and was found approximately linear with the beam current and the modulation amplitude. The ratio of the cathode current change to the value of δI_{lost} calculated from a DC curve was about 100% at U_{sup} = 0.5 kV, U_{col} = 1 kV, I_{cath} = 0.2 A. Hence, the test bench measurements underestimate the loss by about 50%. However, in similar measurements made in the configuration with permanent magnets on the collector, the cathode current changes were below the noise level.

Measurements with Transverse Magnetic Field on the Collector

Three field distributions were studied on the test bench. In the nominal configuration (described above and referred later as A), field lines coming out of the solenoid enter the plate with permanent magnets. Other configurations differed by flipping either all (B) or only one of the permanent magnets (C).

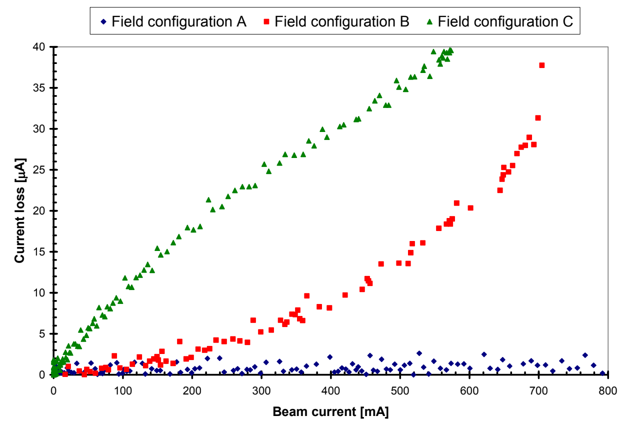

Figure 2: Comparison of the collector efficiency. U_a = 20 kV. Other parameters were chosen to minimize the current loss. For field configuration A and C, $U_{sup} = U_{col}$ = 2 kV. For field configuration B, U_{sup} = 0.5 kV, U_{col} = 4.5 kV.

Figure 2 shows the current loss as a function of the beam current for these three cases. For I_{cath} = 0.5 A, the relative current loss varies by more than one order of magnitude between case A and C (from $\leq 0.5\times10^{-5}$ to 7×10^{-5}).

These results show that only quite specific transverse field distributions are effective. The best version was found to great extend by experimenting with various distributions of the magnetic field, because we have no tools to make a realistic 3D simulation of the collector. Using the described simple model, simulations of the beam envelope in the axially symmetrical case, and measured magnetic fields, we can speculate about the results of Fig. 2 as follows.

Case C corresponds to twice lower strength of the transverse field. The bending angle of the field lines in the collector becomes much smaller than 90°, and efficiency of the suppression drops.

In case B, the field lines turn toward the plate without magnets, where the field strength decreases. A portion of the beam never comes into a region with a high transverse field, and the collector behaves similarly to the axially symmetrical case. For example, it was found optimal to increase the collector voltage to maximum and decrease the suppressor potential to nearly reflecting the primary beam. Note that in case A there is an optimum collector potential, which depends on the transverse magnetic field strength, and dependence of the loss on the suppressor potential has a shallow minimum near U_{col} (Fig. 3).

Based on these measurements, the unexpectedly high current losses reported in [8] are explained by a change of the field polarity in all Pelletron solenoids at the time of switching operation from a short to a full-scale beam line to match field directions at the cathode and in the cooling solenoids. In particular, the field direction was changed in the collector solenoid, which is equivalent to the transition from case A to case B. In the REC cooler, currently under commissioning, this was taken into account, and the observed relative loss is 5×10^{-6}.

Note that all measurements were made in a DC mode, and ion compensation in the collector cavity plays a significant role in the observed high collector perveance of 15 $\mu A/V^{3/2}$ (2.5 A at U_{col} = 3 kV and δI_{lost} = 4 μA). In a "negative pulsing" mode, where the gun was closed for 2 μs every second, the maximum current dropped by a factor of two.

Also, although most measurements were carried out at a magnetic flux on the cathode of 80 G cm^2, which corresponds to the REC parameters, the collector was tested to perform identically for larger fluxes up to 300 G cm^2.

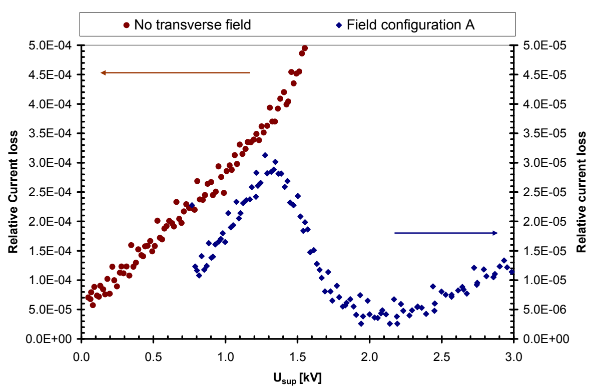

Figure 3: Relative current loss as a function of the suppressor potential with and without transverse magnetic field. U_a = 20 kV, U_{col} = 2 kV. Note the difference in scale for both data sets. The beam current is 70 mA for the case with no transverse field and 520 mA for case A.

CONCLUSION

Transverse field applied to the collector cavity can effectively suppress a secondary electron flow if magnetic field lines in the cavity are bent ~ 90° and all electrons of the primary beam follow a similar bent pass. The relative current loss of 5×10^{-6} at the beam current of up to 2 A was demonstrated.

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