# Recuperation of Electron Beam in the Coolers with Electrostatic Bending

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M. Bryzgunov, V. Panasyuk, V. Parkhomchuk, et al.

# Recuperation of Electron Beam in the Coolers with Electrostatic Bending

M.Bryzgunov, V.Panasyuk, V.Parkhomchuk, V.Reva, M.Vedenev.

*Budker Institute of Nuclear Physics, Novosibirsk, Russia*

**Abstract.** An important aspect of the cooler operation is the collector efficiency. The low loss current improves the vacuum condition, the radiation condition and makes the easy design of the power supply system. This article deals with the reuse of collector at the electrostatic bending in the toroidal section. It's possible to compensate the centrifugal force for the secondary electrons by the electric field because the effect of both forces is independent from the direction of the electron longitudinal velocity. As result the secondary electrons may return into the collector after reflection from the gun. Nonzero loss current is defined mainly by the energy spectrum of the secondary electrons. The review of the experimental data for the different cooler is described in this article. The range of the electron energy is 2 – 300 keV. Some physical model is proposed for the experiment explanations.

**Keywords:** electron cooler, collector efficiency, recuperation and electrostatic bend.
**PACS:** 29.27

## INTRODUCTION

Two electron-cooling devices EC-35 and EC-300 were built at BINP and commissioned at IMP (Lanzhou in China) in 2003 – 2004 [1-2]. One electron-cooling device EC-40 [3] was built at BINP and commissioned at LEIR (CERN) in 2005. Recuperation of electron beam was investigated on these devices in energy range from *2.5 keV* to *200 keV*. The coolers are equipped by the electrostatic plates for bending in the toroidal sections.

These devices are equipped the same electron gun and collector. Ratio of magnetic field between the magnetic fields of the cathode ($B_{GUN}$) and the collector input ($B_{COL}$) is equal 2. Maximal values of $B_{GUN}$ are next: EC-300 – *5 kG*, EC-35 and EC-40 – *2.5 kG*. The bending toroids of these devices are like. The bending radius is $R = 100$ *cm*, the bending angle is π/2, the electrostatic plates are occupied near π/3 of bending arch. The maximal value of toroid magnetic field $B_{TOR}$ is *1.5 kG*. Magnitude of field in cooling section is usual such as in toroid. Thus, the described above devices are identical in respect of recuperation and obtained results are comparable. One may see layout of devices in [1, 2].

Condition of electron passage through bending along centerline without drift displacement is

$$U(T) = \frac{F_C}{e} \cdot \frac{\pi}{2} R \cdot \frac{d}{L}, \quad F_C = \frac{\gamma mc^2 \beta^2}{R} \tag{1}$$

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Here, $\pm U$ – required electrostatic plate voltages, $d$ – half-gap between plates, $L = \pi \cdot R/3$ – middle length of plates, $F_C$ – centrifugal force, $\gamma$ and $\beta$ calculates at electron kinetic energy $T_b$.

## PROFILE OF SECONDARY ELECTRON FLOW

The radial profiles of the flux of the secondary electrons were estimated in the experiments when the centrifugal force is compensated by combination of the magnetic and electric fields. Combining magnetic and electrostatic bending the primary electron beam is aimed to the collector. The secondary electron is shifted in the horizontal direction depending on ratio between the electrical field on electrostatic plates and magnetic field in the correction coils. At pure magnetic bending the secondary electrons has the maximal displacement so the large loss current is observed. At electrostatic bending the both primary and secondary beams don't drift and the leakage current is minimal (Figure 1, left picture).

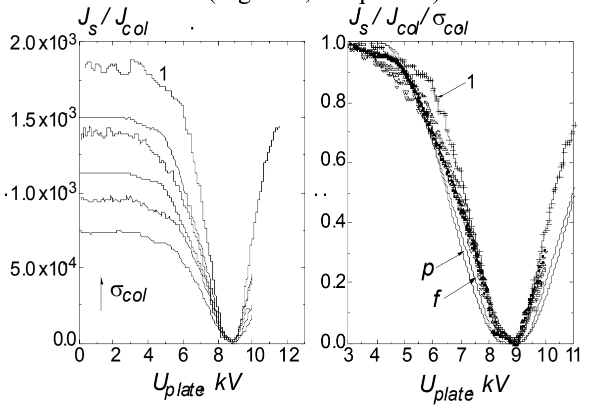


**FIGURE 1.** Loss current versus the electrostatic plates voltage for the different regimes. The left picture is the same but it is normalized on the collector efficiency (the loss current at $U_{plate}$=0). The curves p and f are constructed with a parabolic and flat profiles of the secondary electrons. The model of "moon-phase" is used for loss current estimation.

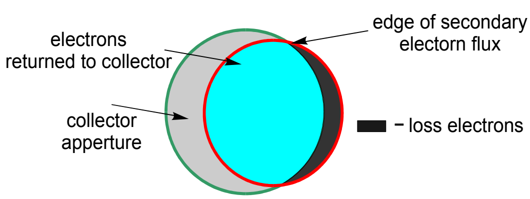


**FIGURE 2.** Model of the secondary model losses.

The theoretical model of the loss current is based on the picture of the phases of the moon (Figure 2). The flow of the secondary electrons leaves the effective collector aperture and is lost. Not only the geometrical size but also the shape of the electrostatic equipotential surface and the distribution of the magnetic field in the collector define the collector aperture.

Measurement accuracy is enough for compare measured dependence $J_S(U_{plate})$ with estimated curve $J_{APPR}(U_{plate})$ calculated with some axial-symmetric density profiles.

The typical results of such comparison are shown in Figure 1 (right picture). Measured normalized dependences $J_S(U_{plate}/(J_{col}\cdot\sigma_{col}))$ are shown by set of points. It is seen that curve shapes are similar except for curve 7 where other value $B_{COL}$ . This is narrowed as $\sqrt{B_{COLL\_7}/B_{COLL}}$ . Constructed dependences $J_{APPR}$ $(U_{plate})$ for some selected profiles are shown by solid lines ($B_{COL}$ = 0.8 kG). The curve p is constructed with parabolic profile and curve f is constructed with flat profile. It is seen that measured curves are narrower in minimum. Non-zero secondary current density outside of beam radius results from comparison.

Fitting results are shown for some variant in details (Figure 3). The corresponding beam density profile is shown too ($U_{grid}/U_{anode}$ =0.2).

## OPTIMAL PLATE VOLTAGES

The accuracy of experiments is enough for determination of optimal plate voltage. The optimal plate voltages are dependent as $\gamma\cdot\beta^2$ (see Eq.1) but measured values $U_{opt}$ correspond to electron energy $T_b - (2\pm0.5)$ keV. Probably such difference results from energy spread of the secondary electrons.

Due to the electron collision with metal surface the secondary electrons have roughly flat spectrum. The width of the energy spread relates with the suppressor voltage $\delta T_s \approx e\cdot U_{sup}$. The effective value of width defines by suppressor potential sagging and beam volume charge into collector. If the ground surface is located on a larger radius than the suppressor or the anode electrode then there is an additional way to form energy spread of the secondary electron beam. The secondary electrons impact with anode and collector and generate the flow of the new emission electrons. The energy spread defines by maximal value from $e\cdot U_{anode}$ and $e\cdot U_{coll}$. Such situation was observed on EC-300.

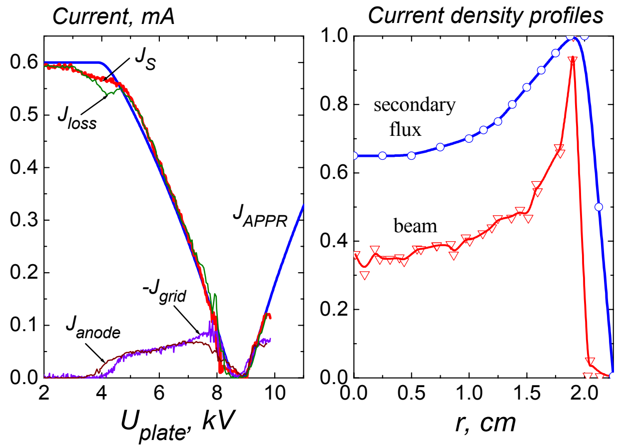


**FIGURE 3.** Loss current versus the voltage of electrostatic plates (left picture). The estimation of the current density profile of the secondary electrons leaving collector (right picture). The electron beam parameters: $U_{an}$=3 kV, $U_{grid}$=0.54 kV, $U_{cath}$= –100 kV, $U_{sup}$=0.4 kV, $U_{col}$=1.9 kV, $J_{col}$=0.5 A. All voltages are counted off from the cathode.

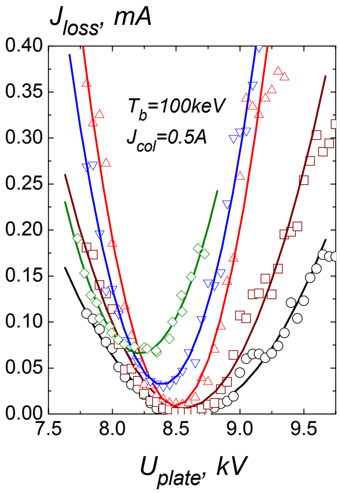


**FIGURE 4.** Loss current versus the voltage of electrostatic plates for the different value of the suppressor voltage. The electron beam parameters: $U_{an}=3$ *kV,* $U_{grid}=0.5$ *kV,* $U_{cath}= -100$ *kV,* $U_{sup}=0.42$*, 1.0, 2.1, 3.0 and 4.5 kV* (from right to left)*,* $U_{col}=4.1$ *kV,* $J_{col}=0.5$ *A* (left picture); $U_{an}=3$ *kV,* $U_{grid}=-0.2$ *kV,* $U_{cath}= -100$ *kV,* $U_{sup}=0.42$*, 1.0, 2.1, 3.0 and 4.5 kV* (from right to left)*,* $U_{col}=4.1$ *kV,* $J_{col}=0.1$ *A* (right picture). All voltages are counted off from the cathode.

The scanning with combined electric and magnetic bending was carried out on EC-300 in order to investigate dependence of optimal voltages $U_{opt}$ from suppressor voltages $U_{sup}$. (Figure 4). The scanning regions were selected near optimum for the primary beam. The experiments was done at $B_{TOR} = 0.95$ *kG*, $B_{COL} = 0.8$ *kG*, $U_{cath} = -99.4$ *kV*, $U_{coll} = 4.1$ *kV*, $U_{anode} = 3$ *kV*. One series of measurements was done at circle profile of primary beam (left picture) and parabolic beam (right picture).

The optimum voltage of the electrostatic plates is shifted to the low value at the increasing of the suppressor voltage. In this case the collector is more “open” and the electrons with large energy spread leave the collector. The minimum leakage current is observed at tuning of the electrostatic bend on the typical energy of the secondary electrons. The primary beam falls into the collector in any case.

The effect of the electron current value on the recuperation level is shown in Figure 5. The large current in the collector locks the secondary electrons into the collector due to the space charge effect. So, the best recuperation results was observed at the electron current about *0.5-1.0 A* (left picture).

Moreover, the potential sagging in the beam at low energy leads to the shift of the optimum voltage of the electrostatic plates to the low voltage. The optimal voltages $U_{opt}$ weakly dependents from beam current $J_{coll}$ at $T_b \geq 24$ *keV* (right picture).

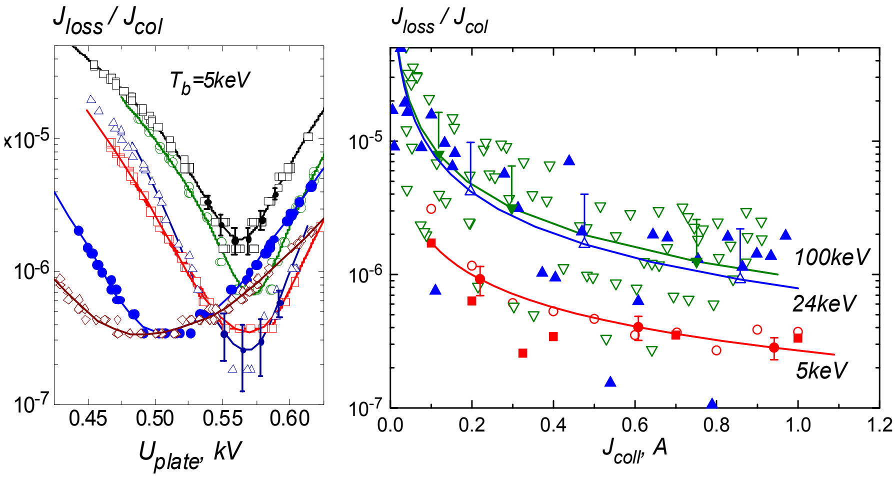


**FIGURE 5.** Leakage current versus at the different electron current $J_{coll} = 0.2, 0.33, 0.4, 0.7$ and $1\ A$ (left picture). Recuperation level as function beam current at different beam energies (right picture).

# SUMMARY

The collector can be reused at some optimal plate voltages $U_{opt}$. The main part of the secondary electrons is returning into the collector and the recuperation level can be done ($\sim 10^{-6}$) that is much less than degree of collector efficiency ($\sim 10^{-3}$). The density profile of secondary electron flux depends on beam density profile weakly. The flux density in outer layer is equal or some larger than inside. The important detail is presence of outputting secondary electrons in small gap ($0.25\ cm$) between the collector aperture and the beam.

The optimal plate voltages $U_{opt}$ for leakage current minimization are proportional to $\gamma{\cdot}\beta^2$ but the measured values $U_{opt}$ correspond to energy of leaving electrons which some less than the beam energy $T_b$. The observed energy shift may be explained by energy spectrum of secondary electrons.

Measured recuperation levels at $U_{plate} \approx U_{opt}$ change inversely proportional to $J_{coll}$, i.e. inversely proportional to space charge potential into collector. Recuperation levels appreciably depend on suppressor voltage. Optimal voltages $U_{opt}$ is independent of beam current $J_{coll}$ at $T_b \geq 24\ keV$.

If the ground surface is outside than the anode or suppressor electrodes then the secondary electrons can form the population of the trapping electrons here. The continuous process of the absorbing and emitting electrons in this domain produces the large current to the anode or suppressor electrodes.

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