PS/AR/Note 89-12 2 November 1989
IM/AS/afm

SOME REMARKS CONCERNING THE COLLECTOR FOR ELECTRON COOLING DEVICES

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1. NOTES ABOUT RECUPERATION OF THE ELECTRON BEAM ENERGY

The task of energy recuperation of the electron beam is to accept the beam with current I to the collector wall with minimal potential U_C and minimal level of current losses ΔI. Two phenomena are important for this process: space charge of the beam and secondary electron emission.

We can discuss the influence of these phenomena in the simple case of the homogeneous electron flow between two places (Fig. 1). It is well known that the limiting current density between the plates ("anode" and "collector") with potentials U_A and U_C is:

$$j_L = \frac{1}{9\pi}\sqrt{\frac{2e}{m}}\,\frac{U_A^{3/2}}{d^2}\,[1 + (U_C/U_A)^{1/2}]^3$$

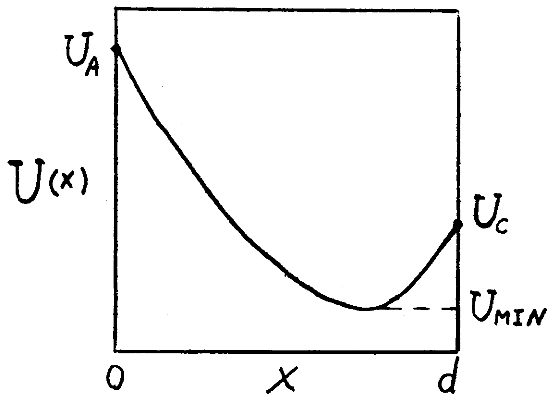

Fig. 1

If we have a small distance d between the plates we can accept the whole electron flow without reflection of primary electrons to the col-

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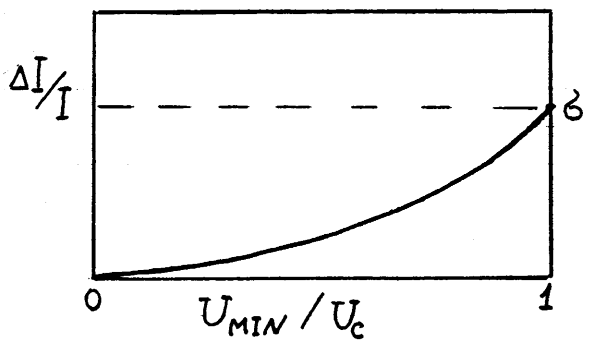
lector plate with a potential near zero. But in this case all secondary electrons will hit the anode plate. To catch them it is necessary to have some point with a potential U_{MIN} less than U_C between the plates. The measurements show that the ratio $\Delta I/I$ of secondary electrons, which go through the barrier U_{MIN} depends mainly on U_{MIn}/U_C (and more weakly on U_C and the material of the collector surface). This dependence is sketched in Fig. 2.



σ = total coefficient of secondary emission

Fig. 2

If the injected current j is near j_L, there is a stable potential minimum because of the space charge of the electrons. For the flat plate case its depth can be calculated. The result is the following:

- for some range of parameters there are two solutions of Poisson's equation without reflection, but the solution with the lower potential minimum is unstable;
- the minimal ratio $(U_{MIN}/U_C)_{MIN}$ for the stable state is achieved with the limiting current density $j = j_L$;
- (U_{MIN}/U_C) increases (and, respectively $(\Delta I/I)_{MIN}$ increases) with decreasing U_C/U_A.

So, for a given j, U_A, we can make series of "optimal" collectors with different d and corresponding U_C (so that $j = j_L$ in each case). The choice depends on the aim: we can choose a big distance between the plates and have small losses but large collector potential, or a small distance and have low U_C but big losses. It is convenient to use the conception of the collector perveance $P_C = I/U_C^{3/2}$. In these terms it is necessary to search for a compromise between the collector perveance and the losses. The same calculations were made for a conically diverging beam. The results of experiments with both kinds of collectors without magnetic fields (Sharapa,

1977) agree with theory.

The situation in a real collector is much more complicated because of the three-dimensional distribution of the potential inside the beam, but the main feature is the same: the collector with large distance between the electrodes and high anode and low collector potential has small losses but a low perveance and vice versa. For the collectors without transformation of the beam shape it is possible to draw a rough curve of the dependence of the minimal losses on the perveance (Fig. 3).

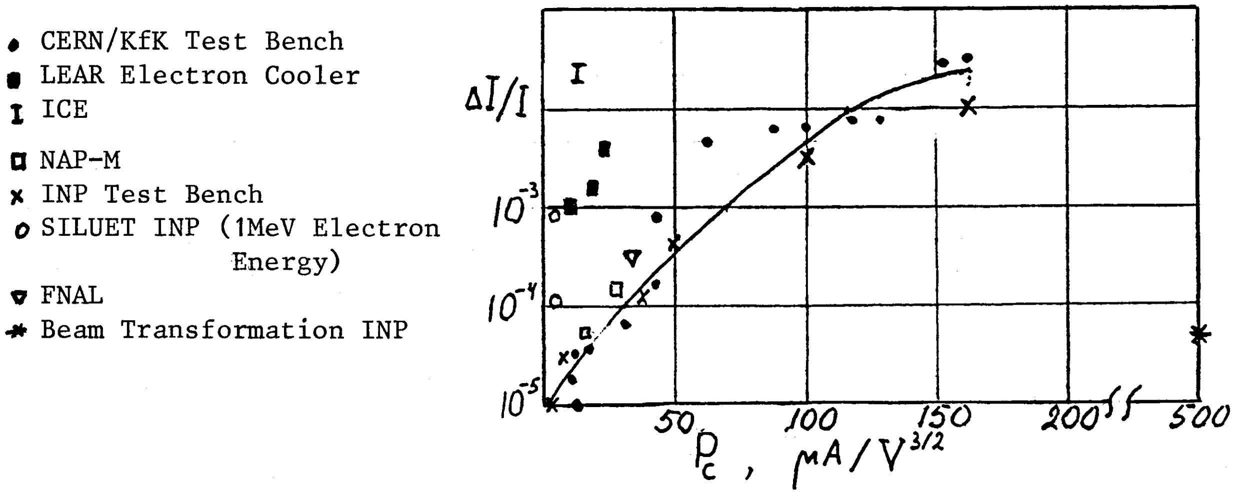


Fig. 3

We would like to note that the lowest losses were achieved in a so-called "Faraday-cup" type of collector with its almost equipotential cavities. Maybe the reason is the closed potential minimum inside the collector and ions trapping in it.

The guiding magnetic field offers an additional possibility to decrease the losses. Firstly, it may act as a "magnetic mirror". If magnetic field changes slowly in comparison to the Larmor rotation, the electrons move adiabatically and the adiabatic invariant is approximately constant.

$$P_1^2/H \sim \text{const, if } \varrho_L << l, \; \varrho_L = (\sqrt{2W/m})/(eH/mc)$$

Here, P_1 is the transversal momentum and W the energy of electrons, H the local magnetic field strength, l the characteristic length of the field variation. The secondary electrons, which have a high transversal momentum P_{1c} near the collector surface, can be reflected in an increasing magnetic field in a point where:

$$P_1 = \sqrt{2mW} = P_{1c} \cdot \sqrt{H/H_c}$$

where W and H are the kinetic energy of the electrons and magnetic field strength in the reflecting point, respectively. This reflection is possible only if the magnetic field increases more rapidly than the potential. Further, in a strong longitudinal magnetic field the losses can be less than the total number of secondary electrons which escape from the collector. To come to the walls of the vacuum chamber, electrons must cross the magnetic field. This is possible only due to slow processes (in comparison with the flight time for example, because of "collisions" with the electrostatic mirrors near collector and gun). During the time of such a drift, some parts of these electrons can be caught by the collector like the primary beam.

In this way, a perveance of about 100 $\mu A/V^{3/2}$ was achieved in a short collector with losses of 10^{-3}. But this method means a large space charge of the secondary electrons in the drift region and, as a result, a decrease of the gun current.

2. *THE PRESENT LEAR COLLECTOR*

An important constraint for the ICE collector was the severe size limitation. Apparently, the main idea was to obtain a beam spreading inside the collector using a transverse electric field and a rapidly decreasing magnetic field.

Some features of this design now used in LEAR are unsdertandable from the computer simulation (Fig. 4, A. Wolf). Firstly, there are particles near the axis which are pushed very strongly in the transformation region (in the vicinity of the spike). In Fig. 4 the particle trajectory with the smallest initial radius ($r_0 \sim 1$ mm) comes to the spike, which is on the cathod potential. This is the result of calculation errors. In reality, such particles would be reflected and leave the collector. To estimate roughly the value of these losses $(\Delta I/I)_s$ we can suppose that all particles with a starting radius $r \leq r_0 \sim 1$ mm are not caught in the collector. Then

$(\Delta I/I)_s \sim (r_0/r_B)^2 \sim 1.5 \cdot 10^{-3}$, $r_B \sim 2.5$ mm beam radius.

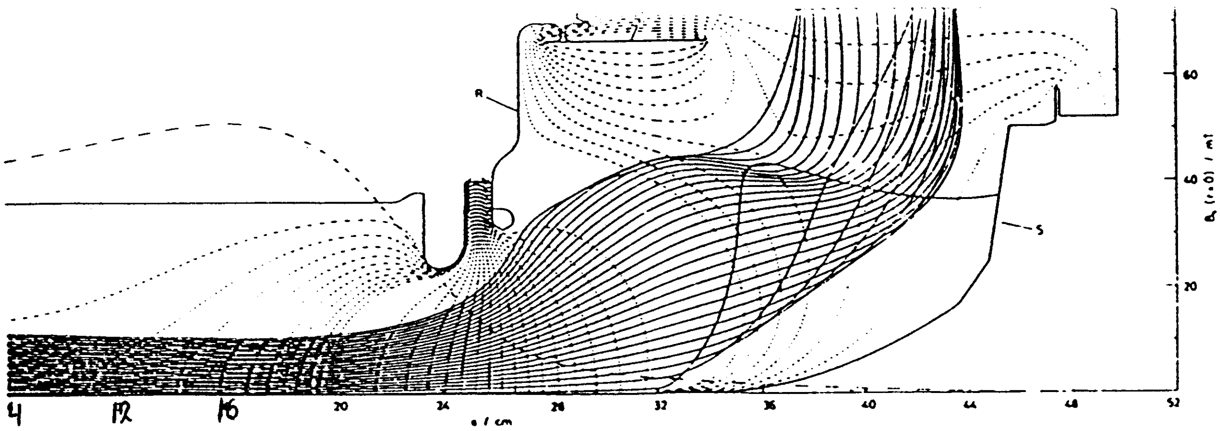


Fig. 4

Secondly, this collector is "open" enough, i.e. the potential inside the collector cavity depends strongly on the potential of the collector anode. As a result, the potential minimum is "shallow". For the simulation $U_{MIN} \sim 0.3$ kV, $U_{MIN}/U_C \sim 0.4$.

Thirdly, such a collector has no effective "magnetic mirror", because in the region with strong magnetic field the potential (correspondingly the energy of secondary electrons) is large.

The best results reported for an energy of the electrons $U_0 = 28$ kV and $H_0 = 500$ gauss are:

$$I = 2.6\ \text{A},\quad U_C = 3\ \text{uV},\quad (P_C \sim 15\ \mu\text{A/V}^{3/2}),\quad \Delta I/I \geq 1.5 \cdot 10^{-3}.$$

In recent measurements, with $U_0 = 11.7$ kV, $H_0 = 300$ gauss, $I \sim 0.7$ A, the results are:

$$U_C \sim 1.1\ \text{kV},\quad (P_C \sim 18\ \mu\text{A/V}^{3/2}),\quad \Delta I/I \sim 4.0 \cdot 10^{-3}\ \text{by}\ U_{REP} = U_C$$

$$U_C \sim 2.4\ \text{kV},\quad (P_C \sim 6\ \mu\text{A/V}^{3/2}),\quad \Delta I/I \sim 1.0 \cdot 10^{-3}\ \text{by}\ U_{REP} = -300\ \text{V}.$$

There is a smooth dependence of losses on collector and repeller potentials and no dependence in the wide range of variation on the mesh potential. Losses increase with the spike potential increase.

The optimal field in the correcting coils around the collector has the same direction as the main magnetic field. This means that the optimal place of the beam is near the spike surface. The probable reason for this is the small value of the minimal potential across the beam. Therefore, to improve the results it is necessary to decrease the reflections in the transformation region and to make deeper the potential barrier in front of the collector surface. Most probably, it is impossible to decrease the losses down to the 10^{-4} level in this construction.

3. *THE PROPOSAL FOR A NEW COLLECTOR FOR THE LEAR ELECTRON COOLING DEVICE*

The simplest solution for a new LEAR collector is probably an ordinary Faraday cup without additional electrodes inside (Fig. 5). To make the collector more "closed", it is useful to remove the collector anode. In the present collector configuration, this collector anode is simultaneously used as a magnetic shunt. Without such a shunt, the divergence of the magnetic field lines is very slow, but it is possible to have a magnetic shunt electrode near the entrance.

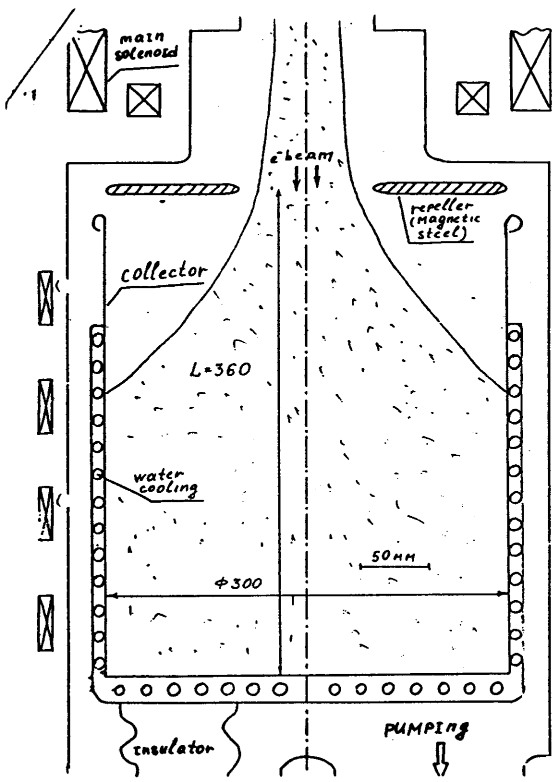


Fig. 5

In this case, the boundary magnetic field lines will behave as shown in Fig. 5. In the optimal regime, a deep closed potential minimum will be formed in the cavity. For this purpose, it is necessary to displace the bottom of the collector by more than the collector diameter away from the entrance. The potential minimum is located in the region with a strong enough magnetic field, so that the "magnetic mirror" effect becomes efficient.

To predict the performance of this collector, we can compare its geometry with other known collectors. The ratio of the beam radius R_B, diameter D and length L of the collector is r_B:D:L = 1:12:15. This is similar to the NAP-M collector (1:12:24) and to another collector, which was used in model experiment at INP (1:12:20). The repeller in the NAP-M collector was also made of magnetic steel to work as a magnetic shunt. In both cases, magnetic shields were used around the collector (in this example there is a shield around the vacuum chamber, with a diameter almost equal to that of the collector). The distance between the collector entrance and the collector anode (the last electrode with high potential) was in both cases approximately equal to the effective gap l_{EFF} in the gun. $\mu P_{GUN} \equiv 2.3\pi r_B^2/l_{EFF}^2$, like in the present proposal.

The collector which was used in the Test Bench experiments at CERN (Seligmann et al.) has larger relative dimensions (r_B:D:L = 1:32:32), a conical repeller and no magnetic shunt. The beam shape inside this collector cavity was changed by additional coils. Correspondingly, perveance and minimal losses (see Fig. 3) were changed. Apparently, the shape of the repeller is not very important. The computer simulations show that also in this case of a long repeller the potential minimum is created inside the collector. This observation also concerns the FNAL collector.

Space charge effects depend on the relative dimensions. For this reason we expect the same results for the proposed collector as for the NAP-M or the INP model collectors: as the relative sizes are approximately the same as the magnetic field lines will have a similar shape. The slightly smaller relative length which we propose cannot change the situation strongly because the space charge density near the bottom of the collector is low. By comparison with Fig. 3 we can expect minimal losses for this collector of $\Delta I/I \sim 10^{-4}$ for $P_C \sim 30\ \mu A/V^{3/2}$ (U_C = 2 kV for I = 2.6 A).

This seems to be a valuable improvement compared to the present collector which was designed to fit into the space-limited environment of the ICE machine.

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