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THE NEW COLLECTOR FOR THE ELECTRON COOLING DEVICE AT LEAR

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ABSTRACT

An important aspect of the low-energy physics programme at LEAR is the use of electron cooling for phase-space compression of the circulating ion beam. In order to improve the reliability of the cooling device, a new electron beam collector has been developed in a collaboration between CERN and CAPT (Centre of Applied Physics and Technology) Lipetsk. The collector is designed to recuperate 3.3 A of 35 keV electrons with an efficiency better than 99.99%. It was constructed at the INP (Institute of Nuclear Physics) Novosibirsk workshop in accordance with a design produced by CAPT and the electron cooling team at CERN. The vacuum and electrical tests of the collector were performed at Lipetsk. The device is now installed at LEAR and has undergone first reception tests in the machine.

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An important aspect of the low-energy physics programme at LEAR is the use of electron cooling for phase-space compression of the circulating ion beam [1-3]. In order to improve the reliability of the cooling device, a new electron beam collector has been developed in a collaboration between CERN and CAPT (Centre of Applied Physics and Technology) Lipetsk. The collector is designed to recuperate 3.3 A of 35 keV electrons with an efficiency better than 99.99%. It was constructed at the INP (Institute of Nuclear Physics) Novosibirsk workshop in accordance with a design produced by CAPT and the electron cooling team at CERN. The vacuum and electrical tests of the collector were performed at Lipetsk. The device is now installed at LEAR and has undergone first reception tests in the machine.

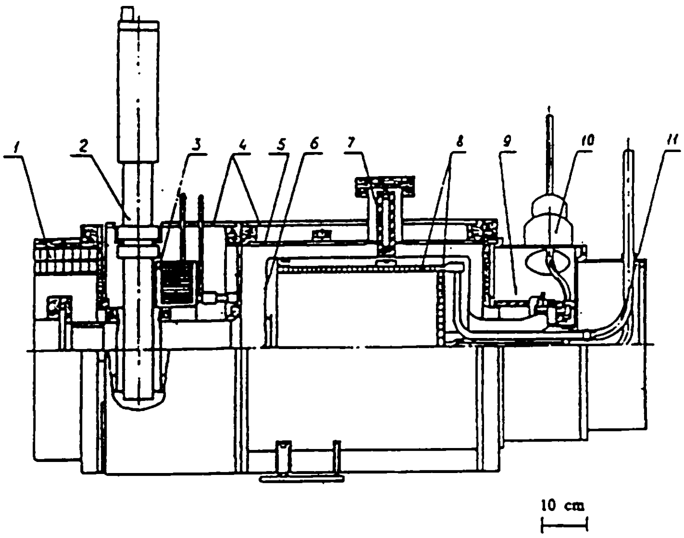
1. The design parameters

The object of the collaboration was to produce a highly reliable collector based on a simple concept providing the lowest possible level of current losses ΔI. The collection inefficiency of the old collector is $\Delta I/I > 10^{-3}$ and is suspected to be the main reason for the unstable operation of the electron cooling device at LEAR. The flux of secondary electrons deteriorate the vacuum conditions in LEAR due to gas desorption by bombardment of the vacuum chamber walls. Moreover, the collector ensemble was very unreliable at electron energies greater than 15 keV due to frequent high-voltage breakdowns between the different components. With the new collector, which has the parameters shown in Table 1, these difficulties should be set aside.

TABLE 1 - Main parameters of the LEAR Electron Cooler.
(The collector and repeller potentials are relative to the cathode)

Parameter	Present system	New System
lectron energy (keV)	27	35 (40)
Beam diameter (cm)	5	5
Beam current (I)	2.4	3.3 (4)
Collector potential (kV)	1.5 - 2.5	3.2
Repeller potential (kV)	0.8 - 1.5	3
Current losses (mA)	7.5	0.3
Average pressure (pTorr)	50	10

The principle of the new collector (Fig. 1) is simple enough; it is a Faraday cup with a suppressor (repeller) electrode at the collector entrance. The collector is connected to the electron cooling device via a vacuum valve which will allow repairs on the collector without disturbing the LEAR vacuum system. A differential pumping system of the collector chamber imposes that an additional ion pump be installed to one side of the device.



1 - solenoid
2 - vacuum valve
3 - compensation coil
4 - magnetic shielding
5 - vacuum chamber
6 - repeller
7 - supporting insulator
8 - collector
9 - vacuum insulator
10 - feed through
11 - water cooling tubes

Fig. 1. The new collector scheme

An important constraint on the collector design was the use of the existing power supplies. This means that the maximum collector potential (relative to the cathode) cannot exceed 3.2 kV for a beam current of 3.3 A. The total power that has to be extracted from the collector is nearly 10 kW which imposes an efficient cooling of the collector walls and base. To maintain the collector inside the vacuum chamber, a ceramic insulator from a standard industrial electronic tube is used along with two additional purpose built insulators which support the collector walls inside the vacuum chamber.

The need to install a vacuum valve has resulted in the displacement of the collector from the main solenoid. To compensate for this "gap" in the magnetic field, a special coil has been added just after the valve. It produces an axial field of up to 0.1 T which also creates a magnetic trap at the collector entrance. The electron deceleration and expansion occur in this area of decreasing magnetic field. The outer magnetic screen provides a homogeneous distribution of electrons along the collector surface. The repeller electrode has a lower voltage relative to the collector and with the electron beam space charge produces an electrostatic barrier which keeps the secondary electrons inside the collector volume. Electrostatic and magnetic traps determine the efficiency of the collector [5].

2. Computer simulations and collector geometry determination

Computer simulations of the electron trajectories from the entrance to the collector walls were done with the POISSON/EGUN package at CERN [6] and with SAM [7] at INP. Trajectories of electrons with energies of 20 keV and 27 keV, with a perveance of 0.52 $\mu AV^{-3/2}$ are shown in Figs. 2 and 3. The plot of the equipotential lines shows that an electrostatic barrier for secondary electrons is located near to the collector entrance. Its amplitude is 650 V for a current of 1.45 A of primary electrons having an energy of 20 keV. The energy spectrum of the secondary electrons has two maxima - the first one is broad near 0.1 eΔU (ΔU being the collector potential with respect to the cathode) and the second one a very sharp peak near the kinetic energy of the primary electrons. The electrostatic barrier will only trap low energy electrons while a magnetic trap will trap secondaries with relatively high energies if the angle θ between the velocity and magnetic field vectors (at the secondary electron origin) is greater than an angle θ_{min} given by

$$\sin^2\theta_{min} \approx \min\left\{\begin{array}{c} \dfrac{H_0}{H_e}\dfrac{\Delta U_e}{\Delta U} \\ \\ \dfrac{H_0}{H_{max}} \end{array}\right\}$$

where H_0, H_e, H_{max} are the magnetic field strengths on the collector wall, inside the electrostatic barrier, and at the center of the collector coil respectively, ΔU_e is the potential of the electrostatic barrier relative to the cathode.

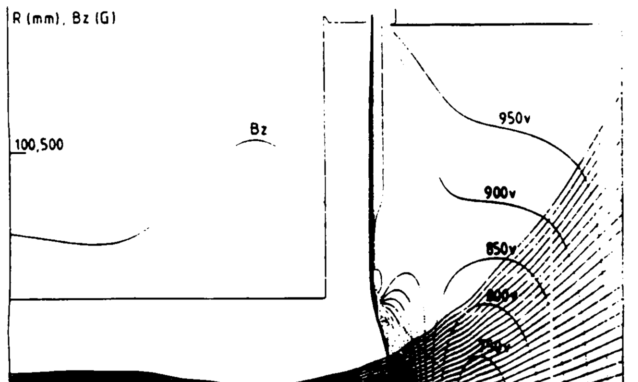


Fig. 2. Computed electron trajectories with the collector and repeller settings respectively at 1 kV and 200 V. The electron beam energy is 20 keV and the magnetic field strength is 500 G.

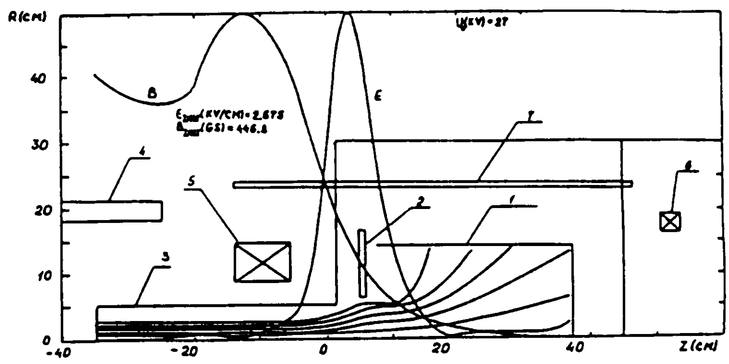


Fig. 3. Electron trajectories for magnetic and electric field strengths on the axis U_0 = 27 kV, I = 2.5 A, ΔU = 3 kV, U_r = 1 kV and B_{coll} = 446 G. 1) collector, 2) repeller, 3) drift tube, 4) solenoid, 5) collector coil, 6) coil having opposite magnetic field, 7) magnetic shielding.

If the electron energy is 27 keV and the beam current 2.3 A, the space charge forms on the beam axis an area of lower potential. In this regime all primary electrons arrive on the collector wall but all secondary electrons are trapped. Computer simulations show that after passing through this area the beam has an inhomogeneous density distribution; the density decreases near the beam axis and increases at the boundary (Fig. 4). The current on the bottom wall of the collector is only about 0.2 A.

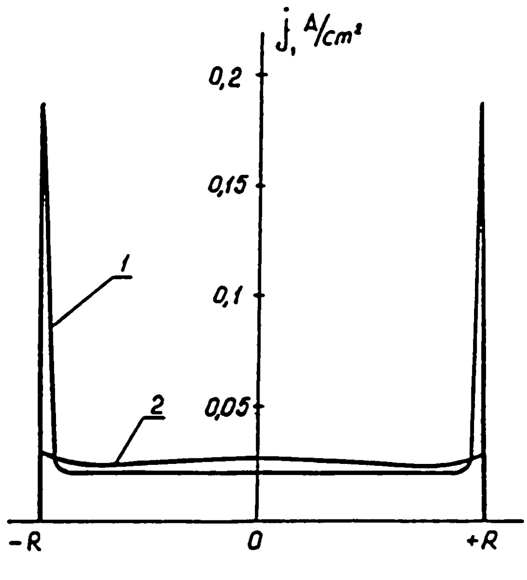


Figure 4. Variation of the current density along the beam radius.
1 : at the collector entrance,
2 : in the area of reduced potential (see section 4).

It should be mentioned that these computer programs do not take into account the influence of space charge due to the secondary electrons and ions generated by residual gas ionization.

The collector geometry is determined by two important conditions. Firstly, if the beam intensity is low, and hence space-charge effects are negligible, a high-collection efficiency is obtained if the collector is long. This is due to the fact that the number of secondary electrons that can escape from the collector is proportional to the solid angle $\Omega = S/L$ where S is the surface area of the entrance hole and L the collector length. This can be easily understood as in the absence of space charge forces and a magnetic field inside the collector, secondary electrons experience electric forces due to the potential inside the collector. Therefore, for a long collector, most of the secondary electrons will be captured by the walls of the collector. Secondly, when the beam intensity is high, so that the beam perveance inside the collector

$$P_c = \frac{I}{(\Delta U)^{3/2}} \approx 10 \mu A V^{-3/2}$$

the collector length is limited by the formation of a virtual cathode which can reflect the primary electrons. In this case the minimum potential at the collector entrance will limit the maximum current I that can enter the collector. This minimum potential can be increased if the collector length is decreased. The collector length must therefore be of the order of its entrance diameter. The optimal collector will have dimensions such that there are no back-scattered electrons from a virtual cathode and a trap is created for secondary electrons.

3. The test bench

For the collector tests a new test bench was set up at CAPT Lipetsk. This test bench (Fig. 5) consists of a vacuum chamber of 2 m length, the electron gun and a system of coils forming the longitudinal magnetic field. The fields in the gun, collector and drift tube can be adjusted independently. The gun has a Ba-Ni oxide cathode of 3 cm diameter and a 5 cm beam is obtained by decreasing the magnetic field in the drift section. The magnetic field H_g in the gun is simply determined from the drift field from the relation $H_g = (5/3)^2 H_d$ where H_d can be varied from 300 to 530 G.

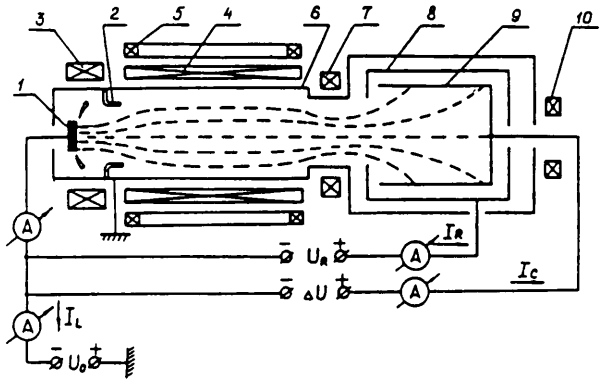


Fig. 5. Layout of the Lipetsk test bench. 1) cathode with Pierce shield, 2 : anode, 3) gun coil, 4) drift section coil, 5) correction coils, 6) vacuum chamber, 7) collector coil, 8) repeller, 9) collector, 10) coil with reverse field.

To steer the beam position, correction coils with transverse magnetic field are used. In addition a small coil was installed at the back of the collector with a magnetic field opposite to the main field. This enabled a 10 to 15% gain in collection efficiency.

The gun perveance is identical to that of the LEAR gun, namely 0.52 $\mu AV^{-3/2}$ which generates a 4.1 A beam at 40 keV. The gun geometry (Fig. 6) is similar to a Pierce gun and computer simulations show that at the exit to the gun the angular spread is less than 10^{-2} rad for a 30 keV beam working in the space charge limitation regime (2.6 A of current are generated). Such a large angular spread does not hinder the tests of the collector, but are obviously unacceptable for electron cooling as such.

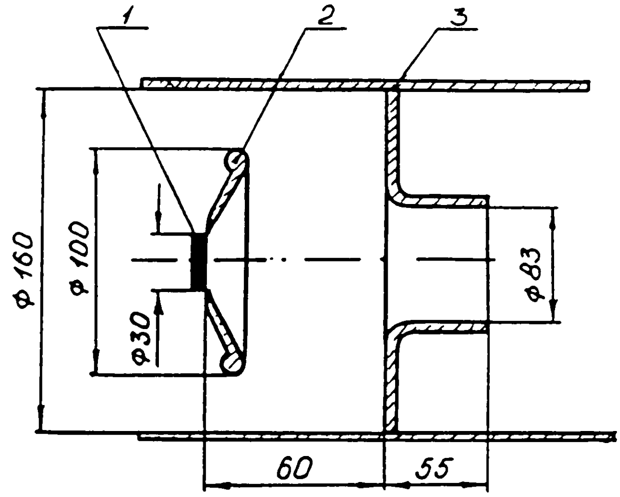


Fig. 6. Gun scheme. 1)cathode, 2)Pierce shield, 3) anode. (The dimensions are in mm.)

The vacuum in the test bench chamber was measured to be of the order of 2n Torr after baking to 300°C without an electron beam (see part 5). The experiments and long term electrical tests were performed with a vacuum 10^{-6} to 10^{-8} Torr.

4. Experiments on electron beam recuperation

The first experiments were made with the electron gun running in the space-charge limit mode with a perveance of 1.1 $\mu AV^{-3/2}$. The current generated was found to be twice the theoretically required intensity and leads to a very bad collection efficiency. In order to reduce the emitted current the gun was then run in a temperature limited mode. However, due to the inhomogeneity of the emission of electrons along the cathode surface and their large angular spread because of the non-colinearity of the electric and magnetic fields in the cathode, this mode had to be abandoned.

If the collector and gun parameters follow the relation

$$I = P_g U_0^{3/2} \leq P_c \Delta U^{3/2}$$

where P_g, P_c are the gun and collector perveances, and U_0 the gun voltage all primary electrons will enter the collector. If the gun perveance is high such that $P_g > P_c(\Delta U/U_0)^{3/2}$ then primary electrons are reflected at the collector entrance creating important current losses. This is shown in Fig. 7 where the dependence of relative current losses on gun perveance for stable U_0 and ΔU is shown. This means that the gun perveance cannot exceed a critical value P_{cr} given by

$$P_g \le P_{cr} = P_c\left(\frac{\Delta U_{max}}{U_{0\,max}}\right)^{3/2}$$

where ΔU_{max} is the maximum possible value of the collector potential, and U_{0max} the maximum gun voltage. In our case the gun perveance is fixed as are the values of ΔU_{max} (3.2 kV) and U_{0max} (35 kV) (see Table 1). This means that the minimum collector perveance is given by $P_c \ge 18.2\ \mu AV^{-3/2}$.

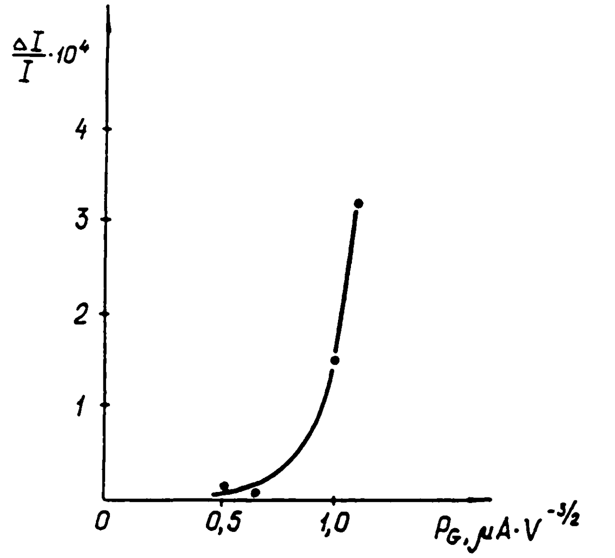


Fig. 7. Dependence of the current losses on gun perveance measured for U_0 = 20 kV, ΔU = 2.6 kV, U_R = 0.1 kV.

The dependence of current losses on electron energy for a gun perveance of 0.5 $\mu AV^{-3/2}$ is shown in Fig. 8 for different pressure levels and magnetic field strengths. If the gun and collector parameters are carefully adjusted [4] and the angular spread of the beam is low, the relative current losses for electron energies between 10 and 35 keV are equal to 2×10^{-6} to 3×10^{-5}. The current losses for energies less than 20 keV are apparently determined by residual gas ionization [5]. If ions, generated by the electron beam, are kept within the transverse electric field of the beam they travel to the gun or the collector, but in a stable regime create a flux of low-energy electrons to the vacuum walls. As a result, ionizing current losses are given by

$$\frac{\Delta I_{ion}}{I} \approx \sigma n L \approx 3.6\times10^{16} P_{Torr}\sigma L$$

where σ is the ionization cross section, n the residual gas density, P the vacuum chamber pressure and L the cooling section length. For an electron energy of 25 keV, $\sigma = 10^{-17}$ cm^2, and for $P = 2 \times 10^{-8}$ Torr, $\Delta I_{ion}/I = 1 \times 10^{-6}$. These estimations are in good agreement with the experimental results shown in Fig. 8.

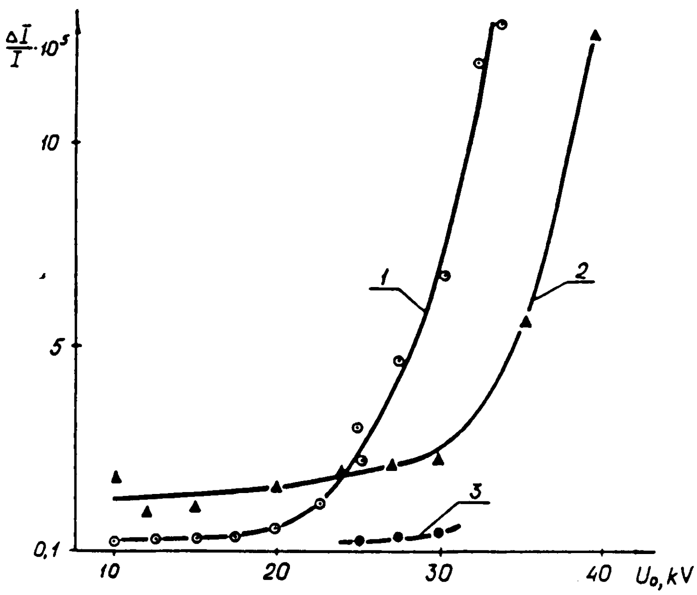


Fig. 8. Current losses as a function of gun voltage measured for a beam with perveance 0.53 $\mu AV^{-3/2}$. Values of B_{sol}, B_{coll}, and P are respectively :
1) 420 G, 828 G, 2.4×10^{-8} - 1.5×10^{-7} Torr,
2) 516 G, 1050 G, 5×10^{-8} - 6.7×10^{-7} Torr,
3) 516 G, 1050 G, 1.5×10^{-8} Torr.

When the electron energy exceeds 25 keV, the increase in current losses can be explained by a number of reasons. If the gun perveance is greater than or equal to 0.5 $\mu AV^{-3/2}$, the generated current is more than 2 A and hence space-charge effects in the collector become important. In this regime a potential barrier is formed at the collector entrance (Figs. 2, 3) and it is necessary to increase the repeller potential (relative to the cathode) in order not to reflect primary electrons with high-transverse velocities. However, this results in a less effective potential barrier for secondary electrons which can escape and travel back up to the gun. The optimal repeller potential exists when the energy of the electrons and the collector potential are fixed. However, the collector potential needs to be modified in order to reduce current losses which means that the optimum values of each potential is determined in an iterative process.

It should be mentioned that for beam currents greater than 3 A, it would be more effective to simply increase the collector potential (higher than 3.2 kV) instead of increasing the repeller potential. However, due to the fact that the LEAR collector power supply is limited at 3.2 kV, all the collector tests were done with this limitation.

It is interesting to note that the collector perveance increases with energy and increasing repeller potential (Fig. 9). For electron energies between 30 and 40 keV it is approximately 20 $\mu AV^{-3/2}$ which is almost the perveance limit for an electron beam with radius 2.5 cm in a cylindrical chamber of radius 7.5 cm:

$$P_c = (4\pi\varepsilon_0)\sqrt{\frac{2e}{m_e}}\frac{1}{1+2\ell n(b/a)} \approx 20\mu AV^{-3/2}$$

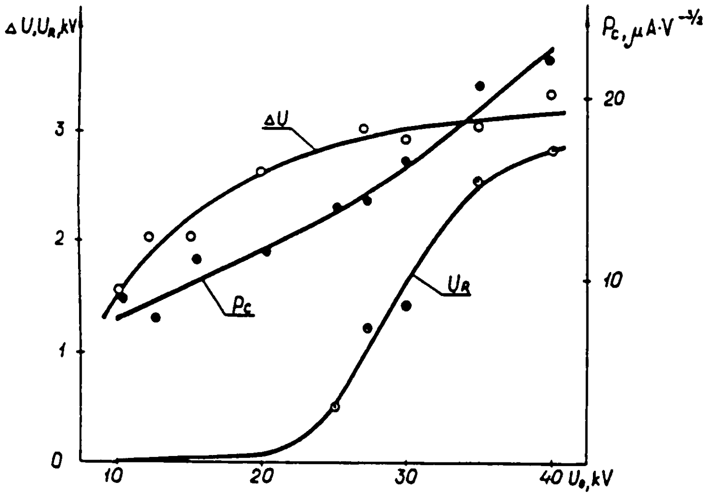


Fig. 9. Plot of the collector (ΔU) and repeller (U_R) potentials and the collector perveance P_c computed for different acceleration voltages for an electron beam with perveance 0.52 $\mu A V^{-3/2}$.

The amplitude of the magnetic field also has a noticeable influence on current losses if the electron energy is between 30 and 40 keV. Figure 8 shows this for two different values of the magnetic field. The decrease in losses for the magnetic field in curve 2 can be explained by the reduction in the angular spread of the electron beam. This spread in the transverse direction Φ is caused by the inhomogeneous magnetic field and the beam transverse electric field $E_\perp$

$$\Phi \approx \max\left\{\begin{matrix}\dfrac{E_\perp}{\beta c B}\\[2mm] \dfrac{\rho_L}{L}\end{matrix}\right\}$$

where L is the length of the inhomogeneous magnetic field and ρ_L the Larmor radius. Because of this strong dependence of the collector potential on the beam angular spread Φ at the collector entrance [5], we have:

$$\Delta U \approx U_0\Phi^2 + \left(\frac{P_c}{I}\right)^{2/3}.$$

Another reason for the decrease in current losses with increasing magnetic field for intense electron beams is due to the beam structure inside the collector. The primary electrons are decelerated at the collector entrance to almost zero velocity and it is in this area that space-charge effects are important. The electron beam is transformed from a cylindrical form to a tube shape (Fig. 4) where the electron density is greatest on the edges of the beam. The critical current I_{cr} for such a beam is greater than in the case of a cylindrical distribution and a higher current is able to pass through this area of lowered potential. The minimal thickness at the edge of such a beam is approximately the Larmor radius ρ_L and the beam current limit is given by

$$I_{cr} \approx (4\pi\varepsilon_0)\sqrt{\frac{2e}{m_e}}\frac{a}{\rho_L}\Delta U^{3/2}$$

where a is the beam radius. It follows from the above relationship that a reduction in the magnetic field causes a decrease of the beam current limit for the central part of the beam which can be reflected by the potential barrier. Keeping these limitations in mind, the new collector was designed to have a recuperation efficiency of 0.9995 for the nominal working conditions with I = 2.5 A at 27 keV energy. These performances were well obtained in the tests.

5. Vacuum and electrical tests

In order to test the vacuum capabilities of the new collector, long term tests were performed for the conditions shown in Table 2. The total time was 160 hours divided into three cycles of 55 hours each. Figure 10 shows the dependence of current losses and vacuum during one complete cycle of 55 hours of tests. The decrease in current loss in the periods between the 18th and 23rd hour and between the 35th and 45th hour is related to night time operations when the mains voltage is slightly higher. This results in a net increase of 10% of the magnetic field.

TABLE 2
Main collector parameters during test experiments.
The collector and repeller potentials are relative to the cathode

Parameter	Value
Electron energy (keV)	27
Beam diameter (cm)	5
Beam current (I)	2.4
Collector potential (kV)	3.0
Repeller potential (kV)	2.0
Current losses ($\Delta I/I$)	0.6 - 0.9 × 10^{-4}
Magnetic field in drift (G)	285 - 305
Magnetic field in collector coil (G)	885 - 900
Vacuum (nTorr)	10 - 40
Power of cooling water (kW)	7
Cooling water temperature (°C)	75
Speed of water temperature (ℓ/min)	7
Water pressure (atmospheres)	0.8
Total operation time (h)	167
Maximum time of continuous operation (h)	55

During operation the vacuum in the collector gradually decreased from 10^{-7} Torr to 1.5×10^{-8} Torr at the end of the 160 hours test. After this long term test, additional tests at 35 keV (3.45 A) and 40 keV (4.1 A) were conducted. The collector potential in these tests was 3.2 kV with the repeller set between 2.5 - 2.8 kV. Magnetic field levels in the drift chamber and at the centre of the collector coil were respectively 516 G and 1050 G. The relative current losses were between 5×10^{-5} and 2×10^{-4}.

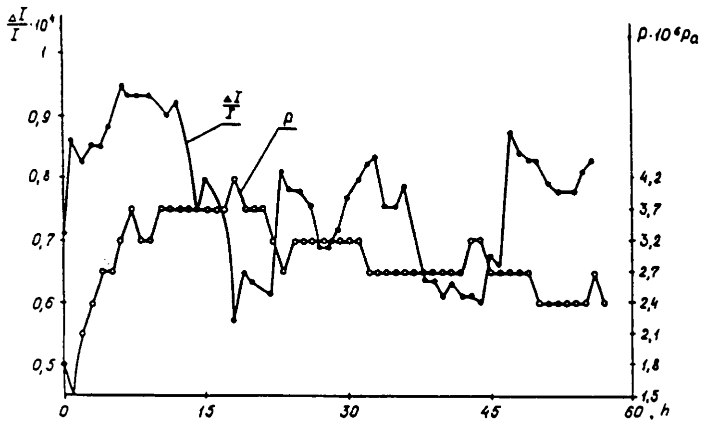


Fig. 10. Dependence of current losses and pressure as a function of time.

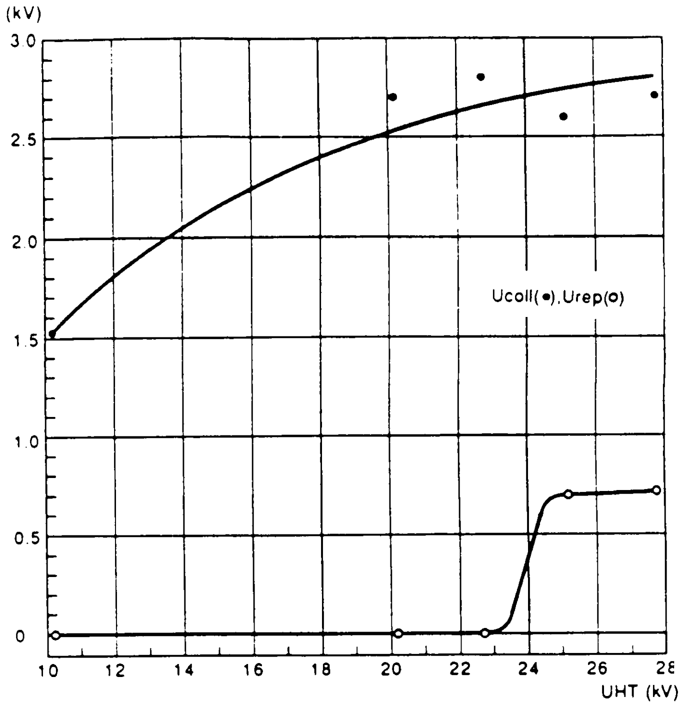


Fig. 11. Plot of the collector and repeller potentials obtained on the LEAR electron cooler for various acceleration voltages. For each measurement the electron losses were minimized.

In accordance with the standard CERN vacuum procedures, three baking cycles up to 300°C were performed. In each cycle the temperature was increased adiabatically during 12 hours, then kept stable during another 12 hours, and then decreased to room temperature in a final 12 hour period. After such a cycle, a vacuum pressure of 1.5×10^{-9} Torr was achieved with the use of three sputter ion pumps having each a pumping speed of 400 ℓ/s. Detection of vacuum leakages showed their absence down to the level of less than 1.5×10^{-11} ℓTorr/s.

6. Conclusions

A new collector has been developed for the LEAR electron cooling device for the efficient recuperation of electrons with energy up to 35 keV (3.3 A). The measured current losses were from 2×10^{-6} to 5×10^{-5} for energies between 10 keV and 35 keV of an electron beam generated by a Pierce type gun of perveance 0.52 $\mu AV^{-3/2}$. For an energy of 40 keV and 4.1 A of current, losses of 2×10^{-4} were achieved. Under these conditions the collector's perveance was 20 $\mu AV^{-3/2}$. This new collector is now connected to the present LEAR system via a newly installed vacuum valve which will facilitate any future interventions on this element. The first tests on the LEAR electron cooler were performed in July and have shown good agreement with the results obtained at Lipetsk (Fig. 11). Stable operation at 27 kV (2.5 A electron beam current) was obtained during the whole machine experiment period and enabled us to investigate the problems that can be encountered in a storage ring when strongly cooled beams are stored for a long period of time.

7. Acknowledgements

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