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ELECTROPHYSICS, ELECTRON AND ION BEAMS, PHYSICS OF ACCELERATORS

Efficiency Improvement of an Electron Collector Intended for Electron Cooling Systems Using a Wien Filter

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Abstract—An efficient collector for high-voltage systems of electron cooling is presented. Its efficiency (ratio of the reflected electron current to the current of the main beam) is greatly improved by suppressing the reflected particle flux in the Wien filter. Secondary electrons deflect in crossed transverse electric and magnetic fields and are absorbed by a special receiver plate (secondary collector). The filter is designed so that the whole backward flow of electrons deflects even if the trajectory and main beam profile are distorted insignificantly. Experiments carried out on a special-purpose test bench show that such a filter raises the efficiency of the collector hundredfold (up to 10^{-6}).

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INTRODUCTION

Electron cooling is widely used in advanced accumulators of heavy charged particles [1, 2]. Cooling improves the beam quality, decreasing the momentum spread; suppresses scattering from the target and intrabeam scattering; and makes it possible to accumulate ion beams. The maximal electron energy in most electron cooling systems varies from several tens to several hundred kiloelectronvolts. Designing high-voltage electron coolers (intended for energies of up to several megaelectronvolts) is a great technical challenge. To date, only one such system, intended for 4.3 MeV and used in the Tevatron complex, has been installed in the Fermi National Accelerator Laboratory (Batavia, United States) [3].

In the Budker Institute of Nuclear Physics (Novosibirsk, Russia), works on designing an electron cooling system for the COoler SYnchrotron (COSY) accelerator (Julich, Germany) are under way. It is expected that the electron energy in this cooler will be varied from 25 keV to 2 MeV. It is required in experiments that the cooling time be as short as several tens of seconds. This time is much shorter than the cooling time in the Tevatron, where it is several tens of minutes [3]. An important variation of the cooler for the COSY is the presence of a strong (to 2 kG) longitudinal magnetic field in the cooling section. This field is present throughout the electron trajectory from the gun to the collector, thereby providing fast cooling [1] and beam focusing and eliminating problems associated with the introduction of the beam into and extraction of it from the magnetic field.

In the presence of an electron cooling system, the total energy of the electron beam having interacted with ions remains almost unchanged; therefore, all electron coolers are based on the method of electron beam energy recuperation. In this method, the beam accelerated in an electrostatic tube (after interaction with the ion beam) is first retarded and only then directed toward a special collector, where it is absorbed. Such an approach makes it possible to considerably reduce the power consumed by the high-voltage power source. To minimize the load on high-voltage rectifiers and the radiation background, it is necessary to provide a high recuperation efficiency (in other words, the secondary electron flow to the grounded walls of the vacuum chamber should be minimized). In this work, we suggest a collector suppressing the backward electron flow using a Wien filter, which is an effective electron absorber, and hence, provides a high recuperation efficiency.

DEMANDS ON THE MAIN PARAMETERS OF THE COLLECTOR

The main parameters of collectors designed for electron coolers are the perveance, maximal dissipated power, and efficiency. Perveance P is a proportionality coefficient between collector voltage U raised to the power of 3/2 and maximal current I that a given collector can withstand in the Child's law ($P = I/U^{3/2}$). In coolers, the perveance determines primarily the maximal current that can be taken up by the collector at a given collector voltage. The maximal voltage of the power source is limited by the design of the collector unit and its environment and by the thermal power being released in the collector upon beam absorption. This is because for a given design of the collector and its cooling system, there is a limit of the maximal dissipated power. The collector efficiency, defined as the ratio of the electron current reflected from the collector to the current of the main beam, characterizes first of all the power of a high-voltage generator feeding the accelerating tube.

As a rule, the electron beam current in electron coolers is determined from the maximal cooling efficiency. The typical value of the working current for low-energy coolers is on the order of 100 mA. A drift arising in crossed electric and magnetic fields (the electric field is generated by the electron beam's space charge and the magnetic field is directed in the longitudinal direction) is the main reason for the current limitation [4]. However, when cooling is accomplished by high-energy electrons (several megaelectronvolts), repulsion due to the electric field of the beam is prevented by using magnetic compression, so that the effective field drops by $1/\gamma^2$ times (γ is the relativistic factor). Therefore, the gun and collector of the given cooler are intended for a current of no higher than 3 A.

When designing a collector for the COSY cooler, we based it on the design used in EKh-35, EKh-40, and EKh-300 accelerators. The collector perveance in them is varied in the range 14–18 $\mu A/V^{1.5}$ as may be required [5]. When a rated current of 3 A is achieved, the necessary voltage across the collector is about 5 kV, which corresponds to a 15-kW power of the source.

The electron energy in electron cooling systems is specified by a high-voltage generator, which controls the cathode voltage relative to the earth. If coolers are intended for low and medium energies (several hundred kiloelectronvolts), the current of high-voltage generators is usually limited at a level of several milliamperes. In high-energy coolers, the current of the generator is still lower (several hundred microamperes). For example, in the 8-MeV electron cooler being designed for the high-energy storage ring (HESR project), the maximal current of the Pelletron power source is limited by a value of 300 μA [6]. In this case, the collector efficiency must be no worse than 3×10^{-4} at a maximal current of 1 A. A high loss current causes problems of another sort. For example, electrons accelerated to a maximal energy cause intense gas liberation when striking the walls of the vacuum chamber. In addition, such electrons are sources of radiation.

However, limitations imposed on the maximal loss current in high-voltage coolers are more stringent because of the dielectric strength of accelerating tubes. Experience on the electron accelerator for the Tevatron complex suggests that a loss current of 1–3 μA toward the accelerating tube far exceeds the breakdown rate at total voltage [3, 6]. However, it is difficult to directly relate the loss current and the current reaching the accelerating tube, since, first, this relationship depends on the geometry of the collector and tube and, second, magnetization of the electron flow in the tube (in contrast to the Tevatron cooler) considerably decreases the electron flow in the transverse direction (toward the tube).

With the aforesaid in mind, it was adopted that the loss current in the COSY cooler must not be higher than several tens of microamperes, which corresponds to the recuperation efficiency on the order of 10^{-5}.

WAYS TO IMPROVE THE COLLECTOR EFFICIENCY

Most collectors in electron cooling systems represent a Faraday cup with additional input electrodes producing a confining potential preventing the escape of secondary electrons. Confinement within the collector is complemented by a magnetic plug, which reflects secondary electrons moving at a large angle to magnetic lines of force. Having appropriately configured magnetic lines of force using coils and magnetic iron, one can create a magnetic plug and distribute the electron flow over the inner surface of the collector for more efficient cooling. In practice, however, the efficiency of such collectors is on the order of 10^{-4}–10^{-3}. This is because a particle in this symmetric collector may reflect and escape from it (this is especially true for central beam particles). The ultimate efficiency of such collectors was estimated by the formula [7]

$$\frac{I_{\text{loss}}}{I_{\text{beam}}} = k\left(\frac{U_{\min}}{U_{\text{coll}}}\right)^2 \frac{B_c}{B_0}. \qquad (1)$$

Here, U_{coll} is the collector voltage; $U_{\min}$ is the input voltage of the collector; B_c and B_0 are the magnetic fields on the surface of the collector and at the input to it, respectively; and k is the coefficient of reflection from the collector. Ratio $U_{\min}/U_{\text{coll}}$ depending on the space charge distribution was set equal to 0.3 (for current $I = 1$ A and $U_{\text{coll}} = 2.5$ kV), and ratio B_c/B_0 is roughly equal to the ratio of the cross-sectional area of the beam at the input to the surface area of the collector (it is usually equal to 0.01 or more). Coefficient k was taken to be 0.1. Then, the ultimate efficiency is $\sim 10^{-4}$.

In most electron coolers, the recuperation efficiency equals the efficiency of the collector, because a transverse magnetic field is used to compensate for centrifugal drift. When an electron beam is introduced into and extracted from the cooling section, it is rotated in the attendant magnetic field. This causes a centrifugal drift the influence of which must be suppressed. When magnetic compensation for this drift is applied, backward secondary electrons when rotated are doubly shifted and fall on the wall of the vacuum chamber.

A high recuperation efficiency (10^{-6}–10^{-5}) at a collector efficiency of 10^{-4}–10^{-3} can be achieved by compensating the centrifugal drift with an electric field. This method was first tried at the Indiana University Cyclotron Facility (United States) [8]. In the cooling section of this facility, a transverse electric field was produced to compensate for the centrifugal-drift-induced shift of the rotating beam. Since the direction of the drift in crossed electric and magnetic fields does not depend on the direction and velocity of particles, the electron flow can be rendered completely reversible; that is, secondary electrons having escaped from the collector may travel through the cooler to the gun and then fall into the collector again, where they may be absorbed. However, since the electric field is produced within the cooling section, this method is inapplicable for cooling ion beams.

The method of centrifugal drift compensation by the electric field was elaborated upon in coolers designed in the Budker Institute of Nuclear Physics for LEIR, CSR-E, and CSR-M coolers, where electrostatic deflecting plates were mounted immediately at turns [5, 9]. In these coolers, a recuperation efficiency of 10^{-7} at a collector efficiency of about 5×10^{-4} was achieved. Such an approach can be applied immediately during cooling, since the electric field in the cooling section itself is absent.

Unfortunately, the method of electrostatic compensation fails in the case of high-voltage coolers, in which the electric field at turns, and consequently, the voltage on the electrostatic deflecting plates are too high and a transverse field is difficult to produce. Therefore, it is necessary to increase the efficiency of the collector in high-voltage coolers.

A collector with a transverse magnetic field was suggested for the electron cooling system of the Tevatron complex [10]. The essence of this approach is that magnetic lines of force rotate unidirectionally instead of being axisymmetric. In this way, a turn is provided inside the collector, which deflects the beam. The beam shifts normally to the plane of rotation due to centrifugal drift. Reflected electrons also shift relative to the input to the collector for the same reason. If the total shift of secondary electrons is such that some of the electrons do not fall into the input aperture of the collector, the efficiency of the collector is greatly improved. In experiments carried out on the test bench and with the cooler itself, the efficiency of the collector was $(5–10) \times 10^{-6}$ at a beam current of up to 2 A. However, the rated current of this collector is lower, 0.5 A, and is limited by the performance of its cooling system. Since the beam in this structure produces a small spot on the collector's inner surface, a strong overheating may arise at high currents. Therefore, another solution for our cooler with a current of 3 A was selected.

COLLECTOR WITH A WIEN FILTER

In the COSY cooler being designed, the backward flow of electrons reflected from the collector is suppressed with a Wien filter—the method suggested in [11]. Figure 1 shows the package drawing of the collector unit. Electrons passing through accelerating tube *1* are slowed down to an energy of 20 keV and fall into Wien filter *2*. After the Wien filter, the electrons pass through collector electrode *3* and suppressor *4* and fall into collector *5*. The shape of magnetic screen *6* and the current configuration in solenoids *7* are such that the electron flow is uniformly distributed over the inner surface of collector *5* to avoid local overheating. Vacuum pumping is accomplished through window *8*.

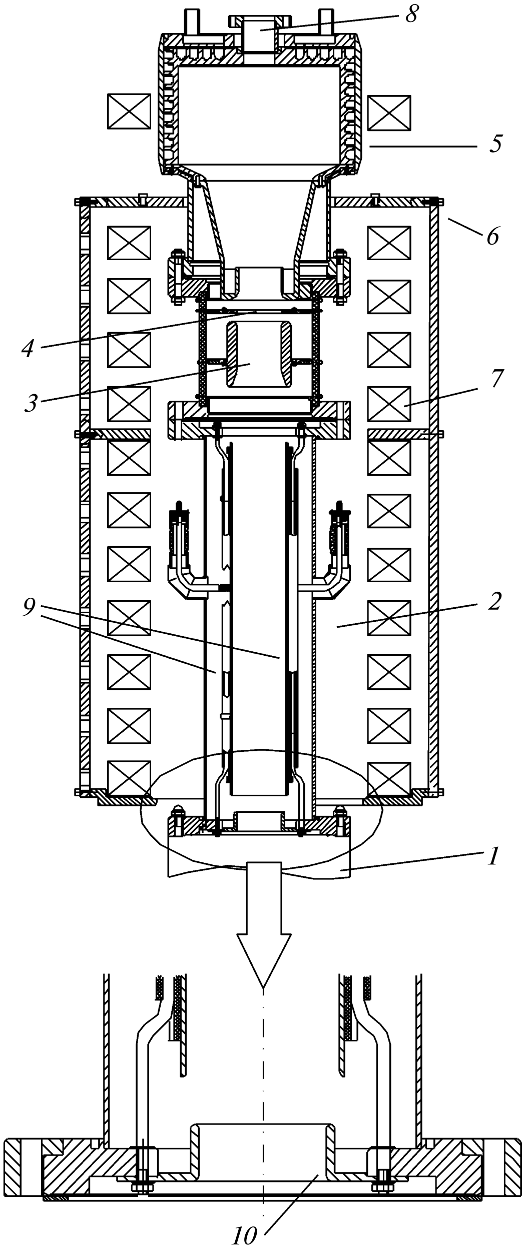

Fig. 1. Collector unit (collector and Wien filter).

The idea of using a Wien filter to raise the recuperation efficiency is to generate crossed electric and magnetic fields for suppressing the backward flow of electrons reflected from the collector (Fig. 2). In the case of the main beam, transverse forces are compensated for and the beam moves undeflected,

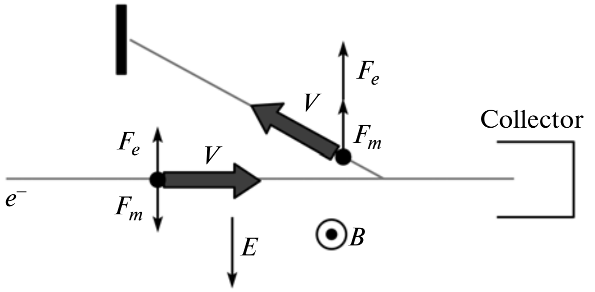

Fig. 2. Operating principle of the Wien filter.

$$F_\perp = \frac{e}{c}V_\parallel B_\perp - eE_\perp = 0. \tag{2}$$

Here, $F_\perp$ is the transverse force; e is the electron charge; c is the velocity of light; $V_\parallel$ is the electron velocity in the filter; and $B_\perp$ and $E_\perp$ are the transverse magnetic and electric fields, respectively.

For reflected electrons, the Lorentz force is oppositely directed and enhances, rather than reduces, the action of the electric field. Therefore, the backward electron flow deflects and can be absorbed by a special receiver plate,

$$F'_\perp = \frac{e}{c}V_\parallel B_\perp + eE_\perp = 2\frac{e}{c}V_\parallel B_\perp. \tag{3}$$

Longitudinal magnetic field $B_\parallel$ in the Wien filter prevents electrons reflected from the collector from falling on the electrostatic deflecting plates generating an electric field, since the shift of the secondary beam is due to drift, which is parallel to the plates. Drift velocity $\mathbf{V}_\perp$ in the filter and transverse deflection Δy are given by

$$\mathbf{V}_\perp = c\frac{[\mathbf{F}_\perp \times \mathbf{B}_\parallel]}{eB_\parallel^2}, \quad \Delta y = V_\perp \tau = 2L\frac{B_\perp}{B_\parallel}, \tag{4}$$

where L is the length of the Wien filter, $\tau = L/V_\parallel$ is the time it takes for an electron to propagate through the filter.

A transverse electric field in the Wien filter is produced by means of electrostatic plates. Having entered into a region with the transverse electric field, electrons are accelerated or decelerated by the edge fields of the plates. As a result, the longitudinal velocity of the electrons in the beam depends on which plate the electron was closer to. If the transverse magnetic field is uniform, this difference in velocities will result in that the Lorentz force will not be equal to the electrostatic force for most particles in the main beam. Eventually, the main beam will be curved. Such a curved beam may decrease the perveance and efficiency of the collector. To avoid this, the transverse magnetic field may be made gradient, rather than uniform,

$$B_x(y) = B_\perp \frac{n}{R}y, \quad B_y(x) = B_\perp\left(1 - \frac{n}{R}x\right), \tag{5}$$

where $R = \dfrac{p_0 c}{eB_\perp}$, x and y are the transverse coordinates with the origin on the axis of the system, and p_0 is the electron momentum at the input to the filter.

To find n, we will first determine the drift velocity components for a particle with transverse coordinates x and y ($E_\perp$ is aligned with the x axis),

$$\begin{cases} V_{\perp x} = \dfrac{1}{B_\parallel}(V_0 + \Delta V)B_x(y) \\ V_{\perp y} = -\dfrac{c}{B_\parallel}\left[E_\perp - \dfrac{1}{c}(V_0 + \Delta V)B_y(x)\right]. \end{cases} \tag{6}$$

Here, V_0 is the longitudinal velocity at the input to the filter and ΔV is the longitudinal velocity increment due to acceleration in the edge fields of the electrostatic plates. Assuming that acceleration-induced change ΔE in the particle energy is much smaller than the particle energy ($\Delta E \ll E$), we can find the longitudinal velocity increment,

$$\Delta V = \frac{\Delta E}{\gamma_0^3 m V_0}. \tag{7}$$

Substituting expression (7) into Eqs. (6) for the drift velocity, expanding the result in powers of x and y, and retaining only first-order terms, we obtain

$$\begin{cases} V_{\perp x} = -\dfrac{V_0 B_\perp n y}{R B_\perp} \\ V_{\perp y} = \left[-\dfrac{V_0 B_\perp n}{R} + \dfrac{eB_\perp^2}{mc\gamma_0^3}\right]\dfrac{x}{B_\parallel}. \end{cases} \tag{8}$$

It is seen that the particle will stay near the center of the beam only if it describes a circular orbit about it. The condition for circular rotation has the form

$$\frac{V_{\perp x}}{y} = -\frac{V_{\perp x}}{x}. \tag{9}$$

Whence it follows that n can be found from the expression

$$n = \frac{1}{2}\frac{eB_\perp R}{mc\gamma_0^3 V_0} = \frac{1}{2\gamma_0^2}. \tag{10}$$

The energy of electrons in the given filter is 20 keV; therefore, they can be considered nonrelativistic and accordingly $n = 0.5$.

MAGNETIC SYSTEM FOR THE WIEN FILTER

When designing the filter, we considered two ways of producing a transverse magnetic field: by means of special coils or permanent magnets. The former way causes technical difficulties. To make coils uncooled, we had to increase their size, as a result of which they went beyond the design limits. Their shrinkage owing

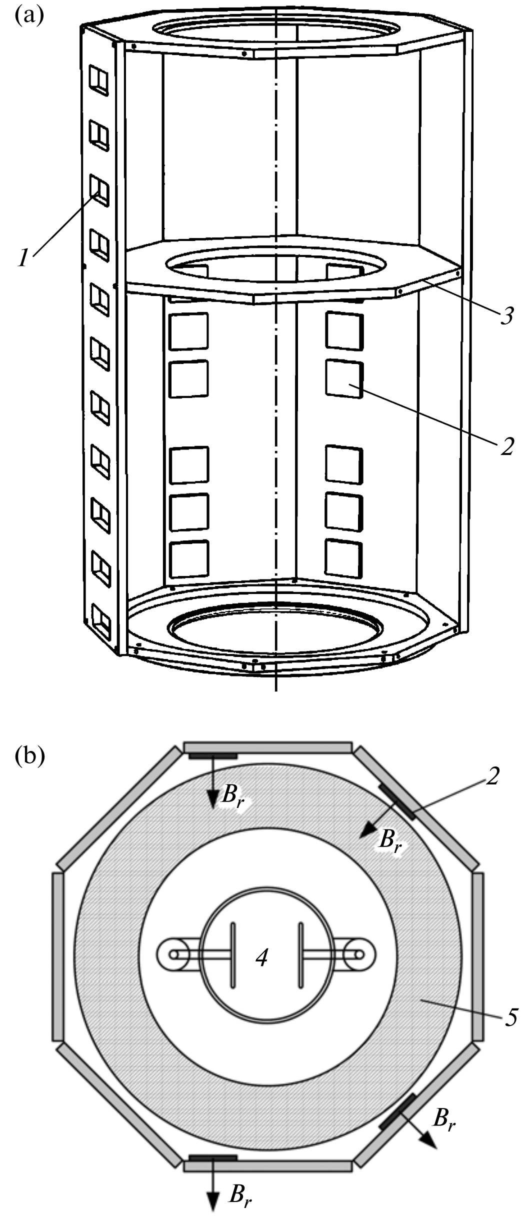

Fig. 3. Magnetic system of the Wien filter: (a) magnetic screen of the filter with permanent magnets (three side plates are omitted) and (b) top view of the filter.

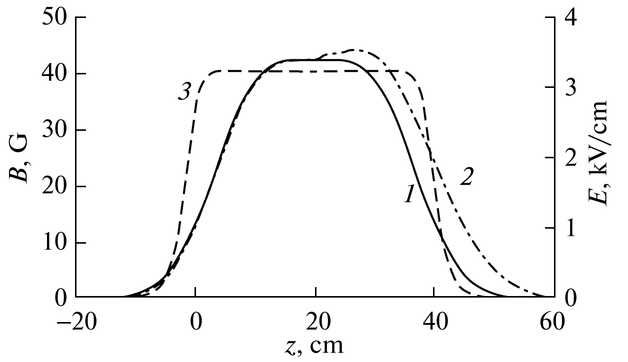

Fig. 4. Distributions of the transverse fields along the axis of the Wien filter: (*1*) magnetic field in the presence of the diaphragm, (*2*) magnetic field without the diaphragm, and (*3*) electric field.

to cooling required a considerable redesign of the terminal.

Permanent magnets posed no difficulties. They were well within the clearance limits. Moreover, permanent magnets do not require additional power sources unlike coils. However, such a solution narrows down the flexibility of the system: it becomes necessary to dismount the system and manually reconfigure it to change the value or gradient of the magnetic field.

Figure 3a shows the magnetic screen of the Wien filter. The screen consists of eight rectangular plates connected to three octagonal diaphragms. In one of the plates, holes *1* are made to pass tubes through which oil cooling electromagnetic coils generating a longitudinal magnetic field is supplied. Another four plates contained six permanent magnets *2* each. The magnets are 40 × 44 × 4-mm parallelepipeds with a remanent magnetization of 13 kG, the magnetization vector being directed normally to the large face. The sizes and arrangement of the magnets are selected so that the integral of the transverse magnetic field at the axis of the filter is equal to 1400 G cm and parameter n specifying the magnetic field gradient is $n = 0.5$ for 20-keV electrons. Computation was carried out with the Mermaid program package [12].

Central diaphragm *3* forms a sharp edge of the transverse magnetic field for the profiles of the magnetic and electric fields to be as close as possible to each other. Figure 4 shows the distribution of the transverse magnetic field along the axis of the filter for systems with and without the diaphragm. In Fig. 3a, the z coordinate is directed upward, $z = 0$ being the lower edge of the magnetic screen. It is seen in Fig. 4 that the diaphragm makes both edges symmetric. In addition, the fall of the field in the presence of the diaphragm is sharper.

A longitudinal field in the filter (Fig. 3b) is generated by placing its vacuum chamber *4* in a solenoid consisting of coils *5*.

ELECTROSTATIC SYSTEM OF THE WIEN FILTER

The electrostatic system of the Wien filter (Fig. 1) consists of two plates *9*, placed inside the vacuum chamber, and secondary collector *10*, on which secondary electrons deflected in the filter are lost. The spacing between the plates, 6 cm, equals their width. The diameter of the hole in the secondary collector is 5 cm. Electrons having reflected from the main collector and having fallen on the secondary collector serve, in their turn, as sources of secondary electrons. They may fly into the accelerating tube, accelerate, and set-

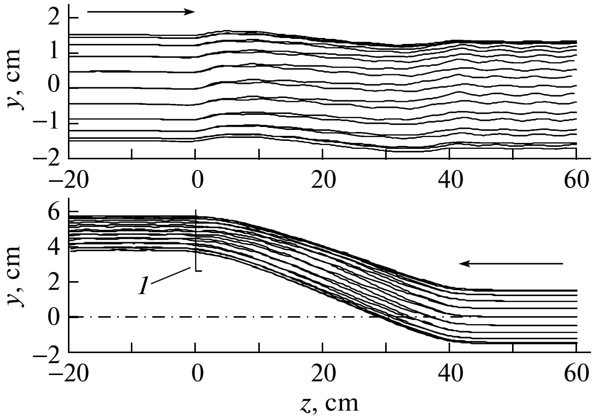

Fig. 5. Trajectories of the main (upper panel) and secondary (lower panel) beams in the filter.

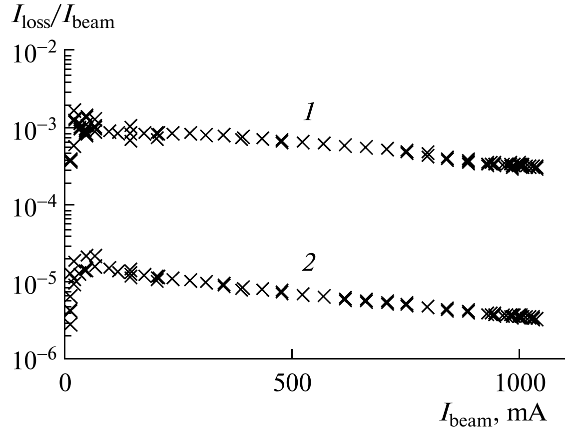

Fig. 6. Relative current losses vs. the beam current (*1*) from the normal collector and (*2*) from the collector with the Wien filter.

tle on its electrodes or on the walls of the vacuum chamber. To decrease the amount of such electrons, the secondary collector has a special wall that prevents the escape of the electrons from the filter.

Figure 4 shows the distribution of the transverse electric field along the axis of the filter. It is seen that the electric field of the filter decays at its edges much faster than the magnetic field. This is because the transverse dimensions of the electrostatic system are much smaller.

CALCULATION OF THE ELECTRON BEAM MOTION IN THE WIEN FILTER

Figure 5 shows the trajectories of the main and secondary electron beams in the filter. The radius of the beam is 1.5 cm, and the longitudinal magnetic field is 500 G. A small disturbance of the main beam motion is observed, which is related to incomplete coincidence between the magnetic and electric field profiles. However, the strengths of the field can be selected so as to compensate their influence. The secondary beam deflection in the filter is strong enough for it to fall on secondary collector *1* for certain. As follows from calculations, the diameter of the hole in the secondary collector, 5 cm, suffices, first, to avoid contacts with the main beam and, second, to provide that all electrons of the secondary beam fall on this collector.

MEASUREMENT OF THE COLLECTOR EFFICIENCY

The collector efficiency was measured on a modified gun–collector test bench [13]. The efficiencies of the normal collector and the collector with the Wien filter are plotted against the beam current in Fig. 6.

It is seen that the Wien filter raises the efficiency of the collector by about 100 times. In addition, the efficiency also rises with the beam current, because the intrinsic space charge induces an additional suppression. An efficiency of 3×10^{-6} was achieved at a main beam current of 1 A.

MODIFICATION OF THE ELECTROSTATIC SYSTEM

Tests of the Wien filter revealed some drawbacks. Below, we suggest a number of modifications for its electrostatic system, which are expected to improve the performance of the filter.

The first modification is aimed at improving the uniformity of the electric field in the filter. Since the spacing between the electrostatic plates equals their width, the electric field in the filter is highly nonuniform. Note that the field cannot be made uniform by increasing the size of the plates or decreasing their spacing, since (i) the system must be electrically strong to avoid breakdown to the wall of the vacuum chamber and (ii) the spacing between the plates must be large enough for electrons of the main and secondary beams not to fall on them. It is possible to achieve good uniformity of the electric field by changing the shape of the plates, namely, by making a shim at their edges, without changing the overall dimensions of the system (Fig. 7).

Figure 8 shows the electric field distributions in both designs. In the area ±2 cm containing the main beam, the field of the shimmed plates is seen to be more uniform.

Figure 9 demonstrates the main beam profile after passing through the Wien filter for flat plates and for plates with shims. When electrons move between the flat plates, the beam profile curves markedly and the effective size of the beam increases. Conversely, the profile of the beam remains almost unchanged in the presence of the shim.

The second modification is aimed at preventing the Penning discharge in the filter. This discharge arises in

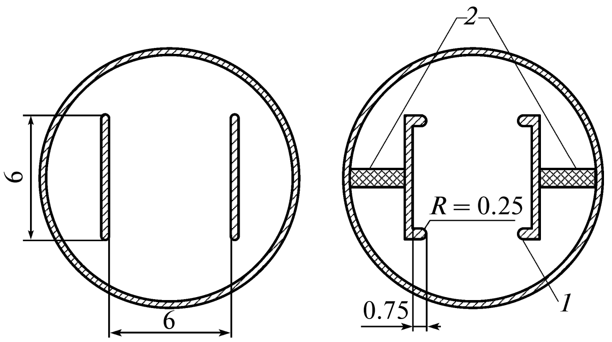

Fig. 7. Electrostatic plates of the Wien filter in the vacuum chamber. On the left: flat plates; on the right: plates with (*1*) shims and (*2*) insertions made of conducting glass.

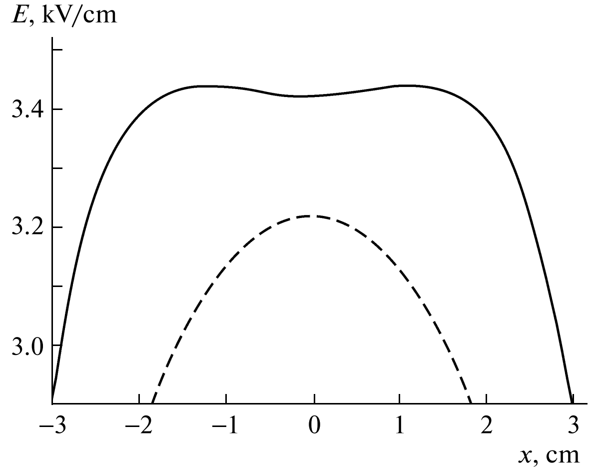

Fig. 8. Electric field distributions in the Wien filter for plates with (continuous line) and without (dashed line) shims.

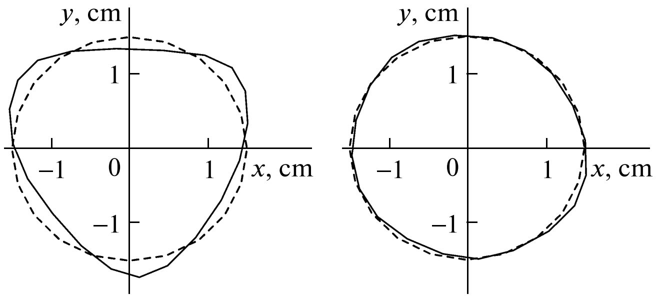

Fig. 9. Profiles of the electron beam having passed through the Wien filter for plates without (on the left) and with (on the right) shims at the input (dashed lines) to and at the output (continuous lines) from the filter.

poor vacuum, which is especially strong when the filter begins to operate immediately after evacuation of atmosphere gas. Under these conditions, electrons falling on the secondary collector knock out adsorbed molecules that had no time to escape under vacuum heating. Such a situation persists for as long as the surface of the secondary collector becomes clean and electrons striking it do not deteriorate vacuum. This process lasts several days.

To prevent the Penning discharge, it is suggested that elements made of special conducting glass be added (Fig. 7). These elements are expected to prevent the drift of charged particles around the plates, and hence, prevent the discharge [14]. Conducting glass makes it possible to avoid (in contrast to a normal insulator) local accumulation of the charge causing spontaneous discharges and deteriorating vacuum. At the same time, the conductivity of the glass is still poor and such insertions will insignificantly load the high-voltage power sources of the filter plates.

CONCLUSIONS

A collector unit combining a cooled collector and a Wien filter is developed and tested. The filter is used for suppressing the flow of electrons reflected from the collector. With this approach, the recuperation efficiency in electron cooling systems can be raised to a level of 10^{-6} without applying electrostatic turns. A high recuperation efficiency is necessary for creating high-voltage electron coolers, specifically, the 2-MeV cooler being designed for the COSY accelerator (Germany).

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