

Features of magnetized motion of electrons in electron cooling devices

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In electron coolers devices, at low energies the electron beam is immersed in a continuous solenoid, which provides a cold and tightly focused beam in the cooling and transport sections. At low energies, the electron motion satisfies the adiabatic criterion when the typical length of the magnetic field variation is much larger than the Larmor spiral length. At relativistic energies, this condition generally cannot be fulfilled, so a special method of transporting the electron beam is required. This article describes one such method, which involves the use of special “resonant” elements to guide the electron beam along the desired trajectory.

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I. INTRODUCTION

Electron cooling is a highly effective technique for producing high-quality ion beams with high intensity and low momentum spread [1–4]. In this method, the phase-space density of the ion beam is increased due to the Coulomb interaction between the “hot” ion beam and a “cold” electron beam. The ion beam repeatedly transfers its thermal energy to the electron beam, which is moving at the same velocity. A significant number of ion accelerator rings were equipped with electron cooling systems for various energies (SIS-18, Fermilab’s Recycler, RHIC, CSRm, CSRe, LEIR, ESR, e.t.c). The energy of the electron beam ranges from a few eV to several MeV at current up to 1 A. The electron beam operates in energy recovery mode, so special attention should be paid to minimizing current losses.

These devices may be divided into two types: in the first case, the electron motion occurs in the presence of a strong longitudinal magnetic field, and in the second, without it. The operation of an electron cooler with an energy of 4.3 MeV and a dc current of 0.1–0.5 A in the Recycler storage ring at Fermilab [5] demonstrated the feasibility of using a small longitudinal magnetic field in the cooling section (approximately 100 G). Also, in this project, nonmagnetized electron beam optics was used to transport the electron beam to the cooling section. The rf-based electron cooler at BNL [6–10] both employed a nonmagnetized electron beam and used nonmagnetized optics.

However, in most electron cooling devices, a strong longitudinal magnetic field is used to transport the electron beam. The main advantage of a longitudinal magnetic field is its ability to operate in a wide range of energies. At low energies, the transverse motion of the electron beam is not a significant parameter, since the motion of electrons is adiabatic and generally, there is no significant increase in transverse momentum. However, at high energies, the longitudinal Larmor length increases. Thus, the electron motion is not adiabatic, and a significant increase in transverse momentum is possible. This can lead to a decrease in friction force at high energies [11] and make it difficult to transport the electron beam.

The transverse momentum can occur for various reasons. The main reasons are the presence of transverse magnetic and electric fields as well as the irregularity of the longitudinal magnetic field along the trajectory. Thus, reducing the electron’s transverse momentum becomes a significant challenge. It leads to special solutions for electron beam optics, which are described in this article. The paper is organized as follows: In Sec. II, the authors explain the main features of excitation of transverse motion in systems with a longitudinal magnetic field. In next sections, the authors describe the features of the motion in low- and high-energy electron coolers. Section III is focused on the description of the case where there is an experimental experience, and Section IV is focused on the future projects.

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II. MOTION IN LONGITUDINAL MAGNETIC FIELD

The equation of motion for a charged particle in a longitudinal magnetic field with a fixed orbital curvature $K = 1/R$ can be written as follows:

$$\begin{aligned}
\frac{dp_x}{dt} &= \frac{p_s^2}{\gamma m_e (R+x)} + \frac{e}{\gamma m_e c} (p_y B_s - p_s B_y) \\
\frac{dp_y}{dt} &= \frac{e}{\gamma m_e c} (p_s B_x - p_x B_s) \\
\frac{dx}{dt} &= \frac{p_x}{\gamma m_e} \\
\frac{dy}{dt} &= \frac{p_y}{\gamma m_e} \\
\frac{ds}{dt} &= \frac{p_s}{\gamma m_e (1+x/R)}.
\end{aligned} \quad (1)$$

For motion near the axis of the magnetic element, this equation can be rewritten as

$$\begin{aligned}
\frac{d\sigma_x}{ds} &= \frac{eB_s}{\gamma\beta m_e c^2} \sigma_y + \left(\frac{1}{R} - \frac{eB_y}{\gamma\beta m_e c^2} \right) \\
\frac{d\sigma_y}{ds} &= -\frac{eB_s}{\gamma\beta m_e c^2} \sigma_x + \frac{eB_x}{\gamma\beta m_e c^2}
\end{aligned} \quad (2)$$

or, in a complex form,

$$\frac{d\sigma}{ds} = -i\Omega\sigma + \frac{i\Omega}{B_s} \left(B_x + i \left(B_y - \frac{\gamma\beta m_e c^2}{eR} \right) \right), \quad (3)$$

where $\sigma = (\sigma_x + i\sigma_y)$ is the complex combination of electron's transverse momenta $\sigma_x = p_x/\gamma\beta m_e c$ and $\sigma_y = p_y/\gamma\beta m_e c$, $\Omega = eB_s/(\gamma\beta m_e c^2)$ is a quantity inversely proportional to the Larmor spiral length, E is the kinetic energy of electrons, B_s is the longitudinal magnetic field, and B_x , B_y are the transverse magnetic fields.

The solution to Eq. (3) is

$$\begin{aligned}
\sigma(s) &= \sigma_0 \exp(-i\Omega s) \\
&+ i\Omega \exp(-i\Omega s) \int_0^s g(s_1) \exp(i\Omega s_1) ds_1,
\end{aligned} \quad (4)$$

where σ_0 is the initial momentum at $s = 0$, and

$$g(s) = \frac{1}{B_s} \left(B_x + i \left(B_y - \frac{\gamma\beta m_e c^2}{eR} \right) \right). \quad (5)$$

In the case of a finite-length disturbance, the second term of Eq. (4) can be rewritten as

$$\begin{aligned}
\Delta\sigma &= i\Omega \exp(-i\Omega s) \int_{-\infty}^{\infty} g(s_1) \exp(i\Omega s_1) ds_1 \\
&= i\Omega \exp(-i\Omega s) G(\Omega(E)),
\end{aligned} \quad (6)$$

which describes the increase in transverse momentum resulting from the combined action of all the magnetic elements. If the function $g(s)$ can be represented as a set

of localized disturbances, then this solution can be rewritten as

$$\begin{aligned}
\Delta\sigma &\approx i\Omega \exp(-i\Omega s) \sum_{p=1}^N G_p \cdot \exp(i\Omega s_p) \\
&= i\Omega \sum_{p=1}^N G_p \cdot \exp(-\Delta\theta),
\end{aligned} \quad (7)$$

where s_p is the location of each disturbance, G_p is its complex amplitude, and $\Delta\theta$ is the phase change of the cyclotron motion between the disturbance and observation points. Equations (1)–(7) describe all features of the electron trajectory in the presence of a longitudinal magnetic field.

There are several methods for reducing transverse momentum.

The first is a reduction in the amplitude of the impact at each perturbation (for example of edge of bending magnet). Since the integral on the right-hand side is the Fourier harmonic with a fixed wavelength, the following simple rule can be applied. The more concentrated $g(s)$ is, the more spread out its Fourier transform $G(\Omega)$ must be, and vice versa. Therefore, the function $G(\Omega)$ decreases with increase of Ω (i.e., with increase of magnetic field and decrease of electron energy). Thus, if the perturbation is sufficiently smooth, then the spectrum of function $g(s)$ will contain mainly harmonics with large wavelength $\lambda_{\parallel} = 1/\Omega$ (or small Ω) and the amplitude of short-wavelength harmonics for specific large value $\Omega(E)$ will be small. This corresponds to the adiabatic approximation in the theory of particle motion. Another way to reduce kick amplitude induced by edge of bending magnet is to ensure that the particle's trajectory aligns more precisely with the magnetic field line when

$$B_x \rightarrow 0 \quad \text{and} \quad B_y - \gamma\beta m_e c^2 / eR \rightarrow 0.$$

In that case, the absolute value of the amplitude of the function $g(s)$ will be small. This can be achieved through computer modeling of magnetic elements. Here, the radius of a coil creating the longitudinal field plays a significant role. A larger radius allows for a smoother field change, whereas smaller coils allow for a more precise match between the bending field profile and the magnetic field line.

The second method involves compensating for the influence of edge fields at the entrance and exit of the magnetic element. For example, if the entrance and exit fields are antisymmetrical and $|G_1(\Omega)| = |G_2(\Omega)|$ in Eq. (7), then

$$\Delta\sigma \sim G(\Omega) \cdot (1 - \exp(i\Omega L)). \quad (8)$$

If the phase shift of the cyclotron motion is $\Omega L = 2\pi$, then $\Delta\sigma \approx 0$. For this method to be successful, it is

recommended to minimize $G_p(\Omega)$ at both the entrance and exit, since it is difficult to achieve an identical design for the edges of the magnetic elements from practical point of view.

If there are a large number of magnetic elements in the transport channel, a third method can be used to reduce the amplitude of the transverse Larmor rotation. This involves adjusting the Larmor phase using any straight magnetic solenoid. There is a possibility that the sum of all local perturbations will be close to zero. Another option is to implement a special single kick with the correct relation B_x and B_y in order to compensate for transverse motion at a specific location of the transport channel.

A real strategy for finding the optimal solution may involve using all of the methods listed above.

III. LOW-ENERGY ELECTRON COOLERS

Figure 1 shows scheme of the EC-300 device as example of electron cooler for low and medium energy. The electron beam is generated in an electron gun and accelerated in an electrostatic tube. The toroidal section merges the electron and ion beams together. In the cooling section, the electron beam interacts with the ion beam. After the interaction, the electron beam leaves the ion orbit, after which it decelerated and is absorbed by the collector.

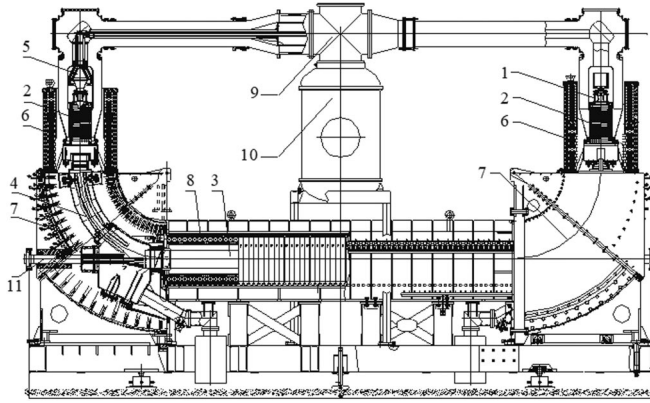


FIG. 1. Scheme of the EC-300 cooling device. The electron beam is generated by an electron gun (1). After being accelerated in the electrostatic tube (2), it enters the cooling section (3). Centrifugal force is compensated by electrostatic plates (4). After deceleration in another electrostatic tube (2), the electron beam is dumped in the collector (5). The longitudinal magnetic field is generated by the solenoid coils of the gun/collector (6), the toroid (7), and the cooling section (8). The gun and collector are connected by a high-voltage feeder (9) to enable energy recovery. The high-voltage power supply is located in the vessel (10). The ion beam vacuum chamber is (11). The length of the cooling device from flange to flange is 720 cm. The average diameters of the coils in the gun/collector and the cooling sections are 66 and 45 cm, respectively. The toroid coils are rectangular in shape with dimensions 65×110 and 65×69 cm.

The strong magnetic field at small electron energy leads to small length $\lambda_{\parallel}$ ($\lambda_{\parallel} = 1$ cm at energy 100 keV and magnetic field 1 kG). The typical sizes of the coils in the gun/collector, toroid and cooling section are in range 45–110 cm. Thus, the motion of particles in a magnetic field is approximately adiabatic. In this case, the magnetic flux through Larmor circle is a transverse adiabatic invariant and remains constant with high precision. Therefore, the electron's transverse velocity remains constant if the longitudinal magnetic field does not change. Thus, low-energy electrons do not need to pay particular attention to the problem of maintaining a low transverse velocity. However, achieving low transverse momentum in low-energy coolers can be crucial in electron-target experiments, as well as for cooling highly charged ions [12]. The high precision measurement in recombination experiments requires the interaction with the electron beam at low transverse momentum and magnetic adiabatic expansion is used in order to obtain a transverse temperature a few meV or less [13,14].

The centrifugal force acting on electrons in the bending sections (toroids) of an electron coolers manufactured by BINP [15–17] can be counteracted either by electrostatic plates (see Fig. 1), magnetic correction coils, or a combination of both. The magnetic bending field corrects the electron with forward velocity only. The backward electron, which is reflected from the collector, has double shift in the toroid section. During several oscillations from the gun to the collector and back, the electron escapes from the beam and is lost. Another option is to fully compensate for the centrifugal force using an electric field in the bending section. Thus, for both electron flows, there is no electron drift in the transverse direction relative to the longitudinal magnetic field, which makes it possible to achieve very low leakage current and a high recovery factor. This method was first realized in the EC-300 at energy up to 300 keV.

Figures 2 and 3 show the variations in the curvature of the magnetic field line $K(s)$, the transverse electric field

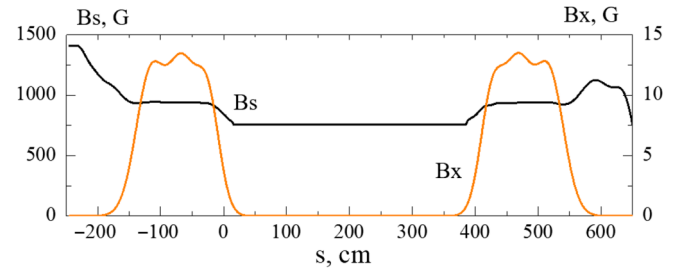


FIG. 2. Longitudinal and transverse magnetic fields $B_s(s)$ and $B_x(s)$ versus the longitudinal coordinate of the magnetic field line of the longitudinal magnetic field. The interval $s = 0$ –400 cm corresponds to the cooling section; the coordinates of the gun and collector are $s = -242$ cm and $z = 648$ cm, respectively.

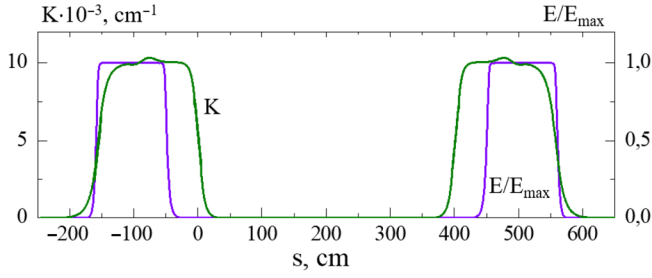


FIG. 3. Curvature $K(s)$ and the normalized electric field $E(s)/E_{\max}$ versus longitudinal coordinate of magnetic field line of the longitudinal magnetic field.

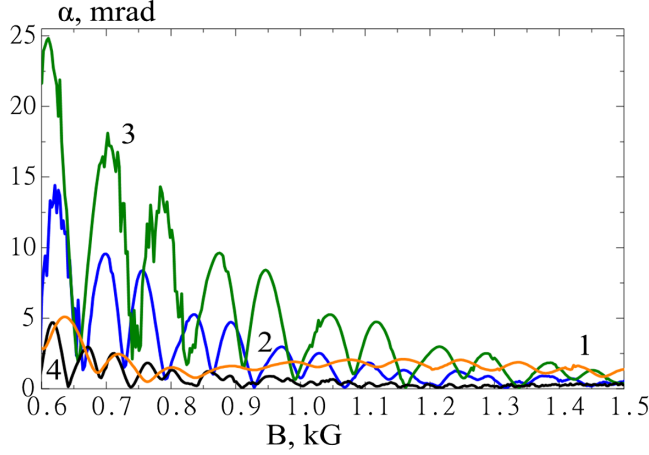


FIG. 4. Computer calculated transverse angle of electron after passing 90° bend with radius 100 cm versus longitudinal magnetic field. Curves 1–3 correspond to electrostatic bend with energies 50, 100, and 150 keV, while curve 4 corresponds to magnetic bending at energy 300 keV.

$E(s)$, the longitudinal magnetic field $B_s(s)$, and the transverse magnetic field $B_x(s)$ along a magnetic field line exiting from the center of the cathode. It is clear that the profiles $K(s)$, $E(s)$, and $B_x(s)$ do not match completely (Fig. 3). Figure 4 shows the results of the calculation of transverse oscillation excitation in such a system. The transverse-field coils are large and are located outside the longitudinal-field coils. Thus, the length of the magnetic field inhomogeneity is quite large, and the excitation of the transverse momentum is small. On the contrary, the profile of the electric field is close to the step function because the distance between plates is 7 cm and the transverse heating effect may be essential (see first method in Part II). The length of the electric field along the electron beam path corresponds to an angular dimension of $\pi/3$ (rather than $\pi/2$) and is shorter than the length of the transverse magnetic field, since there must be a gap in the electrostatic plate to allow the ion beam to pass into the cooling section. So, the electrostatic bend is realized in an integral way only.

The excitation of transverse oscillations in an electrostatic bending structure has a resonant character with

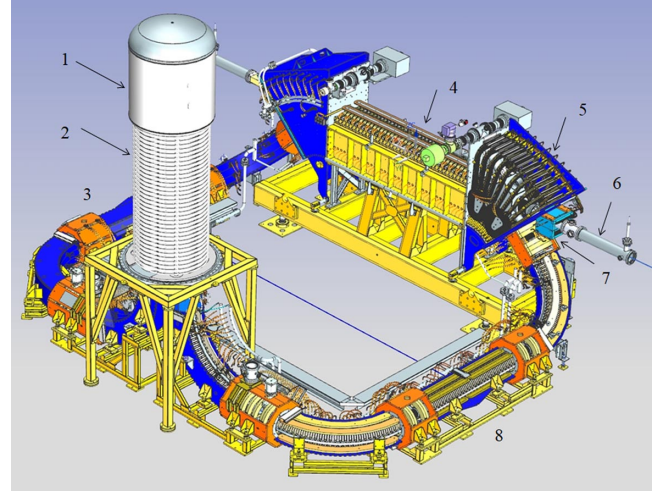


FIG. 5. Design of a high-energy cooler device. Electrons are emitted by an electron gun located in the high-voltage terminal (1). After acceleration in the accelerating column (2), the electrons pass through the transport channel (3) into the cooling (interaction) section (4). A toroidal section (5) merges the electrons with the ion beam, which moves inside the vacuum chamber (6). The dipole magnet (7) compensates transverse kick for the ion because of the toroid magnetic field. After cooling section at length 270 cm, the beams are separated by another toroid and the electron beam moves to the electrostatic accelerator along transport channel (8). After deceleration, the electrons are dumped into a special collector located inside the high-voltage terminal (1).

respect to the magnitude of the longitudinal magnetic field. As can be seen (Fig. 4), there are situations in which the edge perturbations at the entrance and exit cancel each other out over a whole number of Larmor cycles along the bend. At a half-integer number of Larmor revolutions, the transverse momentum is doubled. The range of magnetic field values in which compensation occurs is quite narrow. For the electron energy $E_e = 100$ keV, the range, where the minimum heating values are observed, is about $\Delta B \sim 60$ G and $\Delta B \sim 80$ G for $E_e = 150$ keV.

Thus, electrostatic bending can generate a transverse electron momentum; however, at low energies this value is not very large, and practical experience shows that it does not play a significant role in the cooling rate. In [18], the decrease in the recombination rate is described as a characteristic of transverse motion caused by the influence of special electrostatic plates; however, the measured cooling rate did not change significantly. At high energies, this effect must be taken into account [11,19].

IV. ELECTRON COOLERS AT ENERGY UP TO 2 MEV

The 2 MeV electron cooler for COSY [20,21] has the highest energy of any cooler that were made with the idea of magnetized cooling and transport of the electron beam.

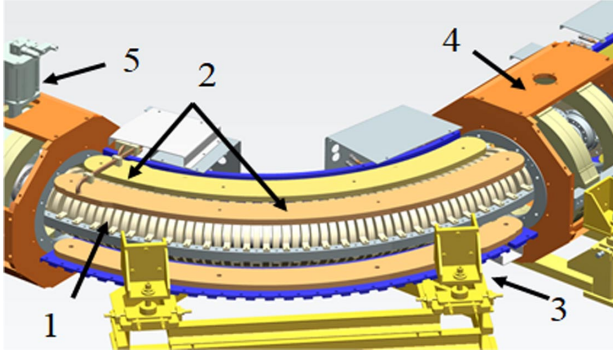


FIG. 6. Design of coils inside the magnetic yoke of 90° bending magnet. The longitudinal magnetic field is produced by the coils (1), and the transverse (bending) magnetic field is produced by coils (2). Bending coils (2) are powered from two power supplies in order to regulate field index of bending magnetic field. The magnetic element is installed on support (3) that is connected to magnetic yoke (not shown). The magnetic yoke of adjacent element (4) may be used for location diagnostics or vacuum elements such as vacuum gate (5). Bending radius is 100 cm, the average diameter of coils in the bend is 20 cm and in the adjacent elements is 42.3 cm.

The magnetic field strength is 500 G in the electrostatic column, 1 kG in the transport channel, and 2 kG in the cooling section. The COSY cooler is designed with beamoptics based on the strong longitudinal magnetic field (Fig. 5). At high energies, it is difficult to ensure that the motion of electrons is adiabatic; therefore, other approaches must be used to minimize the transverse momentum. The edge effect results in a significant transverse component of the magnetic field along the desired path of the electron beam, which induces Larmor rotation.

In an ideal bending magnet with a longitudinal magnetic field, the longitudinal momentum of the electrons is parallel to the longitudinal components of the field, and the corresponding Lorentz force is zero. In real designs, the geometric dimensions of the bend and the solenoid coils differ, and it is generally impossible to achieve a perfect alignment of the electron trajectory with the field line of the longitudinal magnetic field.

An example of a practical design is shown in Fig. 6, where the bend field profiles are aligned as closely as possible with the desired electron trajectory. Characteristic functions of the bending magnet

$$K_x = \frac{e B_y}{p_s c}, \quad K_y = \frac{e B_x}{p_s c}, \quad (9)$$

with longitudinal magnetic field are shown in Fig. 7. Here, $p_s = \gamma\beta mc$ denotes the longitudinal momentum, while (B_x, B_y, B_s) represent the vertical, horizontal, and longitudinal components of the magnetic field, γ is the relativistic factor, and K is the curvature of the baseline.

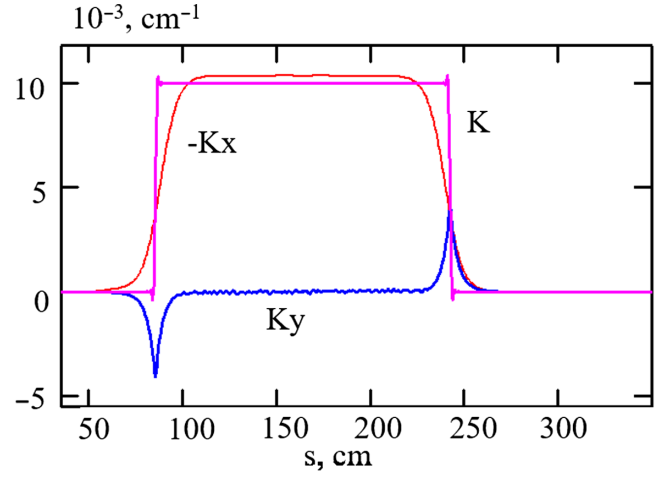


FIG. 7. Optic functions of 90° bending magnet with longitudinal magnetic field. Here, the base line is used for the calculation of optic function and the curvature looks like step function.

All values are specified relative to the geometric baseline, which consists of two lines and a 90° arc with a radius of $R = 100$ cm corresponding to the centerlines of the magnetic elements. From a physical standpoint, the magnetic field line of the longitudinal field is considered the preferred baseline for calculating the magnetic function; however, from a practical standpoint, a combination of lines and arcs proves to be more convenient.

The contribution of various components of the magnetic field may differ between the entrance and exit (see Fig. 7). The $K_x - K$ function has alternating signs, and its effect on cyclotron motion can self-compensate independently at the entrance and exit, since the integral of this function is close to zero. However, a kick K_y at the entrance can only be compensated for by a corresponding change at the exit. Thus, the number of cyclotron rotation cycles required to fully compensate for the deviation approaches an integer; however, its exact value can only be determined through precise computer modeling of electron motion in the bending magnet.

To reduce the motion disturbances that occurs after passing through the magnetic element, the principle of “resonant” optics can be used, similar to low-energy coolers [22,23]. It requires the same design for the entrance and exit of bending magnets then the perturbation at the entrance to the element may be maximally compensated at the exit from it. In addition, for “resonant” optics, it is necessary to select the correct longitudinal magnetic field to ensure the desired Larmor phase, as shown in Fig. 8. As can be seen, the minimum values of the Larmor radius are observed within a narrow range of longitudinal magnetic field values.

If the conditions are not ideal and the previous solution does not fully resolve the problem, it is necessary to use special compensating coils with a transverse magnetic

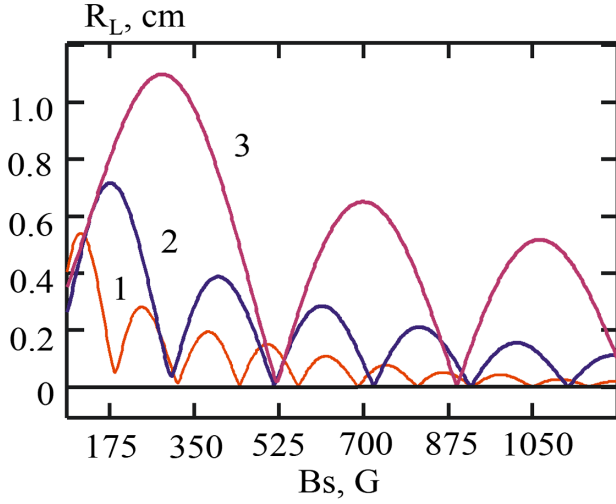


FIG. 8. Transverse Larmor radius after 90° bend passing versus longitudinal magnetic field. Curves 1–3 correspond to electron energy 0.5, 1, and 2 MeV.

field, which reduce the amplitude of the Larmor motion of electrons (see the third method in Part 2). The most convenient place to install it is a straight section of the trajectory.

The equation of motion for an electron in a straight line is given by Eq. (3) when $R \rightarrow \infty$. An example of the $|G(E)|$ function for the saddle-shaped coil type is shown in Fig. 9. The impact force increases at high energies because the coil's behavior becomes more similar to that of a thin (lump) element, and the effect of the longitudinal magnetic field becomes negligible. At low energies, the motion is adiabatic, and transverse disturbances are suppressed by the longitudinal magnetic field. This is not a problem, since disturbances arising in other magnetic elements are also suppressed. To avoid a sharp drop in the dipole kick at an energy of approximately 200 kV (local resonance), an appropriate value for the longitudinal magnetic field is used. In this case, the length of the Larmor spiral is short, so resonant passage through the bends can occur over a wide range of longitudinal magnetic field values.

The quality of an electron beam's optics can be experimentally evaluated in various ways. One method involves estimating the friction force [11], while another involves performing a special diagnostic test using a phase shift in the longitudinal magnetic field and measuring the BPM signal [24]. But there is another way to assess the quality of the optics. For each operating mode, there is a range of longitudinal magnetic field values in straight solenoids within which the electron beam recovery efficiency is sufficiently high. This corresponds to the Larmor phase shift in the Eq. (7). If this range is wide, it means that the Larmor oscillations in each magnetic element are negligible and do not affect the passing of the electron beam. Figure 10 shows the dependence of the loss current during scanning with a longitudinal magnetic field in the

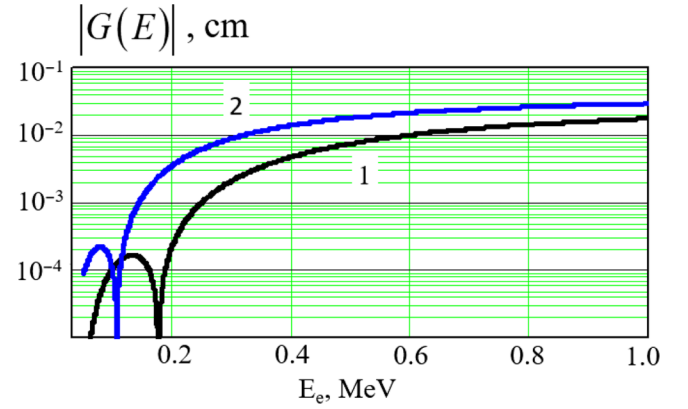


FIG. 9. Absolute value of $|G(E)|$ versus electron energy for saddle-shaped coil type. The radius of arc of dipole corrector is 10 cm; the length is 12 cm. The integral of transverse magnetic field $\int B_y(s)ds = 20 \text{ G} \cdot \text{cm}$, $B_x = 0$. The longitudinal magnetic field is 800 G (curve 1) and 600 G (curve 2).

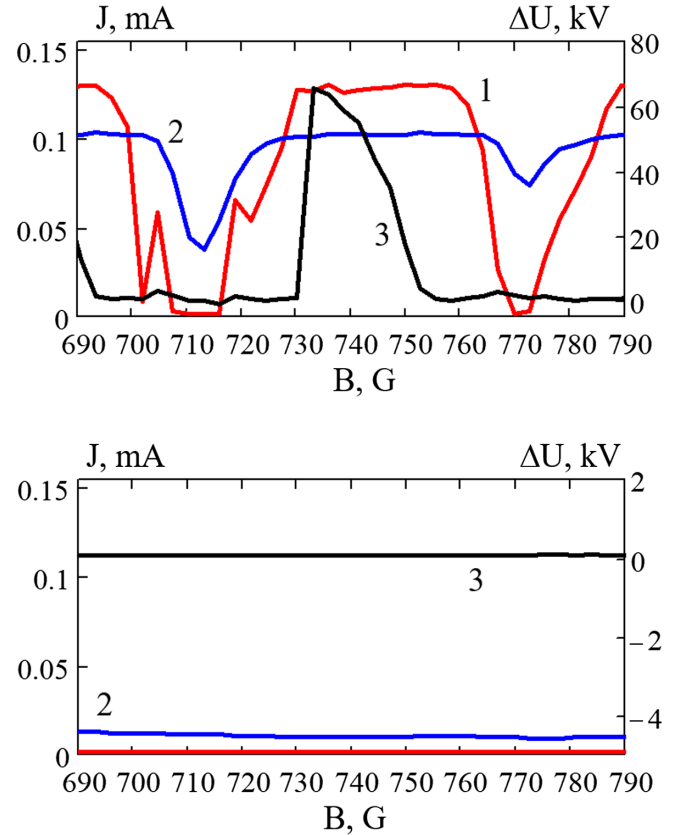


FIG. 10. Dependence of the loss current (1, left axis), the x-ray radiation intensity (2, left axis and arbitrary units) and the voltage difference on the dividers of the accelerator tubes (3, right axis) versus the magnetic field in the cooling section. The electron energy is 500 kV; the electron beam current is 130 μA . The bottom picture corresponds to the resonance value of the magnetic field in the bend ($B_s = 565 \text{ G}$), and the top picture corresponds to the case when the magnetic field has no optimum value ($B_s = 544 \text{ G}$).

cooling section of the COSY 2 MeV cooler. Here, the cooling solenoid is used only to change the phase of the cyclotron motion between two symmetrical sections of the transport channel (before and after the cooling section).

It is evident that this significantly affects beam recovery due to changes in the Larmor precession phase as the beam passes through the transport channels, when the magnetic field in the bending magnet is not at its optimal value $B_s = 544$ G. When the longitudinal magnetic field has a resonance value of $B_s = 565$ G, the Larmor phase does not produce a significant effect (see Fig. 10). Thus, the phase shift produces the intervals in which the optical error is optimally canceled out by resonance. In this case, “windows” of effective transmission are formed where the leakage currents and x-ray radiation have a minimum values. If the magnetic field in the bending magnet has optimal value, then the minimal leakage currents and x-ray radiation are achieved at any phase change of Larmor motion between two sections of the transport channel (before and after cooling section). This adjustment of the electron beam pass is optimal because it allows for a stable recovery of the beam over a wide range of various parameters of the electron cooler.

Leakage current and radiation indicate electron beam losses in the vacuum chamber. There is usually a correlation between these parameters; however, the x-ray detector is more sensitive at high electron beam energies. A thallium-enriched NaI crystal was used as the x-ray detector. When exposed to a gamma-ray beam, this crystal emits photons with a wavelength of approximately 415 nm. The electrons emitted by the photocathode and amplified in the secondary electron multiplier generated a

signal that triggered the comparator. The registered frequency of the comparator’s triggering allowed for an assessment of the radiation level. This method was sensitive enough to detect leakage current at a very early stage, but it did not provide an accurate quantitative value.

The voltage difference between the resistive dividers of the electrostatic tubes (the accelerating and decelerating tubes) indicates that electrons have fallen onto one of the tubes (usually the decelerating tube). The leakage current was measured with the special resistor connected with ground potential of electrostatic accelerator.

This experiment (Fig. 10) can only be carried out with low current and low electron energy. Adjustment at an operating current of approximately 1 A is difficult due to the risk of the recovery mode failing and high-voltage breakdown.

Evidence that passing through the resonance reduces the Larmor oscillation can be observed in the BPM located downstream of the cooling section. Changes in the magnetic field in the cooling section lead to observation of beam displacement related to the transverse kicks accumulated before this element. The transverse positions of the electron beam in this case are shown in Fig. 11.

V. MAGNETIZED ELECTRON MOTION IN PROJECT WITH ENERGY 1–8 MEV

The methods described above can be used in higher-energy electron coolers in future projects [25–28]. Figure 12 shows an example of such a design for a 180° bend with a radius of 100 cm, made by combining two 90° bends. In this case, the bending design is similar to the one that has already been tested. In addition, this type of bend design significantly simplifies assembly compared to a design that uses a single 180° element. A special

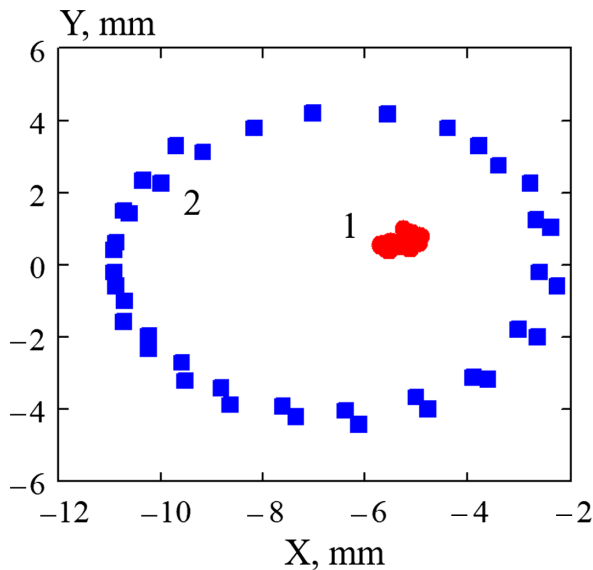


FIG. 11. Transverse position of the electron beam during change phase of Larmor oscillation induced by the variation of the magnetic field in the cooling section. The resonance value of the magnetic field is curve 1, and no optimum value is curve 2.

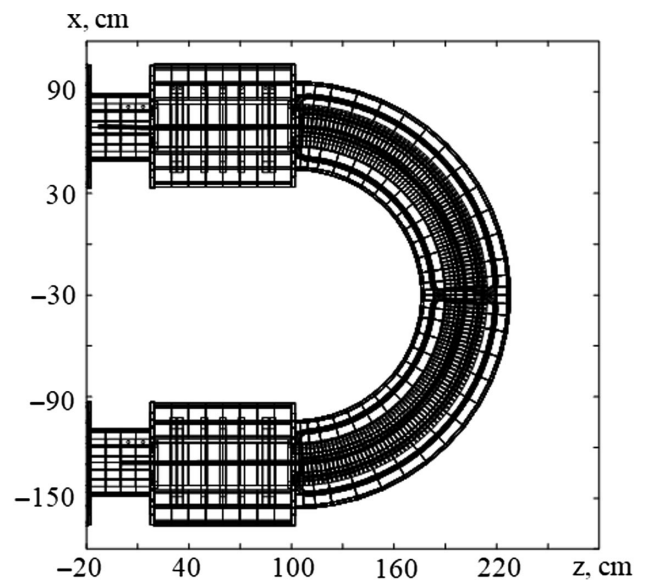


FIG. 12. Construction of the 180° COSY-type bending magnet.

TABLE I. Magnetization parameter of electron passing 90° ($m = 1$) bending magnet with radius 100 cm.

Energy, MeV	B_s , G	N
1.2	220	1
1.2	870	4
4.5	670	1
4.5	1330	2
8	1130	1
8	2300	2

solenoids at the entrance and exit of the bend are required to install additional equipment, such as a vacuum pumps, diagnostic equipment, etc. Let

$$N = m \frac{R}{4} \frac{eB_s}{\gamma\beta m_e c^2}, \quad (10)$$

is the magnetization parameter, which characterizes the number of Larmor oscillations along the length of the bend. The parameters $m = 1$ and 2 correspond to 90° and 180°, respectively.

Table I lists the magnetization parameters for various energy values under typical parameters for future electron cooler devices. For an arbitrary energy, the magnetic field must be changed proportional to $\gamma\beta$ in order to keep parameter N constant [see Eq. (10)]. At low energies, the value of N can range from 2 to 4 when the longitudinal magnetic field is low. But for energy in the range from 4 to 8 MeV, with a bending radius 100 cm and a typical longitudinal magnetic field of about 1 kG, the magnetization parameter is only 1. To increase this parameter, you must increase either the magnetic field strength or the bending radius. This leads to increased power consumption by transport channels, and from a technical standpoint, a value of $N = 1$ may be optimal.

Figure 13 shows calculated trajectories of an electron passing through a COSY-type bending magnet with a bending angle of 180° and radius of 100 cm at energies 1.2 and 4.5 MeV. It is clear that the transverse movement at the entrance and exit locations is well compensated. The range of the transverse electron displacement at an energy of 4.5 MeV is approximately 2.5 cm peak-to-peak. It is magnetization regime $N = 2$ for 180° bend ($m = 2$) in Fig. 12. So, in the right figure, two Larmor oscillations are observed in a bending magnet with an angle of 180°. The resonance value of longitudinal magnetic field is 870 G, which exceeds the value listed in Table I (for $N = 1$). This can be explained by the fact that the effective length of the bending magnetic field and the distance between the edges of the magnetic field distribution are not exactly equal to $\pi R/2$. At an energy of 8 MeV, the magnetization regime $N = 1$ will correspond to a longitudinal field value of 1.5 kG recalculated with $\gamma\beta$ coefficient from case 4.5 MeV.

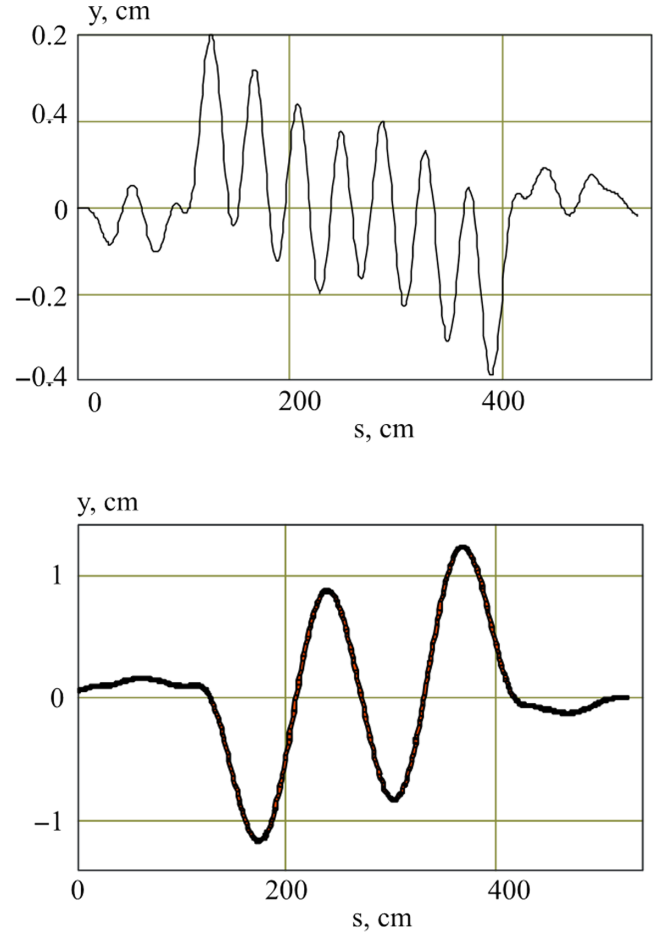


FIG. 13. Trajectories of electron with energies 1.2 (left) and 4.5 MeV (right) in the 180° bend. The magnetization parameter of electron motion is $N = 8$ ($B_s = 836$ G) and $N = 2$ ($B_s = 870$ G).

Another example of use of magnetization transport is the electron cooler for the NICA collider [27,28]. The design of a bend magnet with a radius of $R = 1$ m and a maximum longitudinal field $B_s = 1$ kG is shown in Fig. 14. The electron passage of the bend has resonant character. To improve the resonance transport, the bending magnets are designed so that the entrance and exit are as identical as possible. The magnetic calculations are performed using the MAGEL program [29]. The match between the profiles of the curvature of the magnetic field lines and the bending field is shown in Fig. 15. It is clear that, despite the small size of all the coils, there is a difference between the magnetic field lines and the bending field profile. However, in this case, the principle of resonance allows electrons to move with minimal excitation of transverse motion.

At resonant energy, electrons entering to bend without transverse amplitude leave it without “heating.” Some of these energies (for 1 kG) are equal to 4.865, 2.5, 1.65, 1.185, and 0.905 MeV. The trajectories of electrons $y(s)$

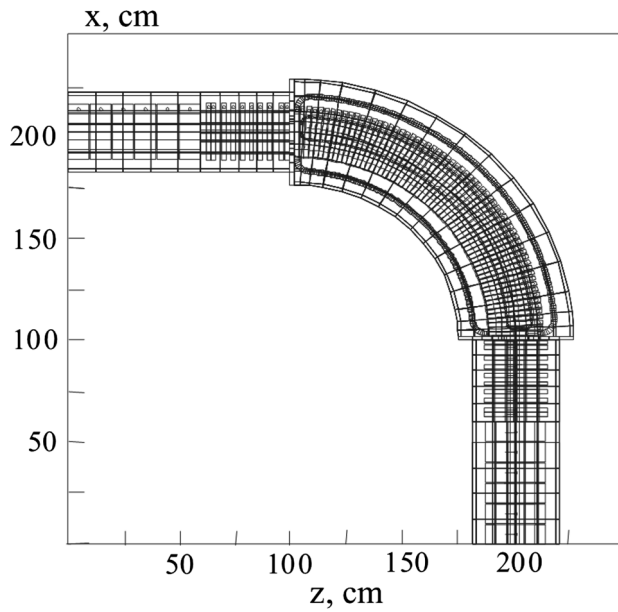


FIG. 14. Construction of the 90° bend for NICA collider. Bending radius is 100 cm, the average diameter of coils in the bend is 21 cm and in the adjacent elements is 24 cm.

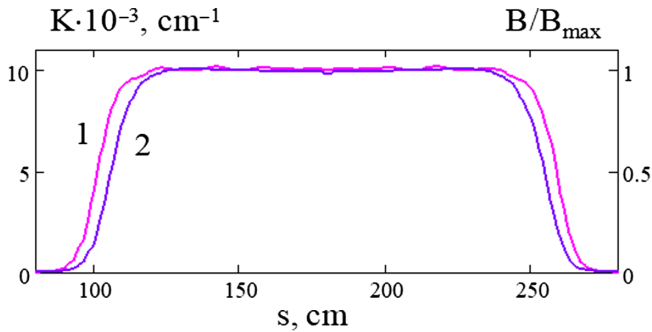


FIG. 15. Curvature $K(s)$ (curve 1) and transverse magnetic fields $B_x(s)$ (curve 2) versus the longitudinal coordinate.

relative to bending plane ($y = 0$) at these energies are shown in Fig. 16.

As can be seen, at high energies, the deviation of the electron beam from the geometric baseline inside the bending magnet becomes quite significant; therefore, it is necessary to investigate ways to reduce this deviation. For example, the increase of bending radius to 1.5–2 m or increase of the magnetic field strength could be appropriate decision for project of 8 MeV cooler. But it is clear that somewhere within this range lies the electron energy at which it is advisable to use magnetized motion with strong longitudinal magnetic field along whole trajectory.

Another approach involves eliminating the continuous longitudinal magnetic field and creating a transport channel consisting of a sequence of bending magnets and lumped axisymmetric solenoid-based lenses. In the simple

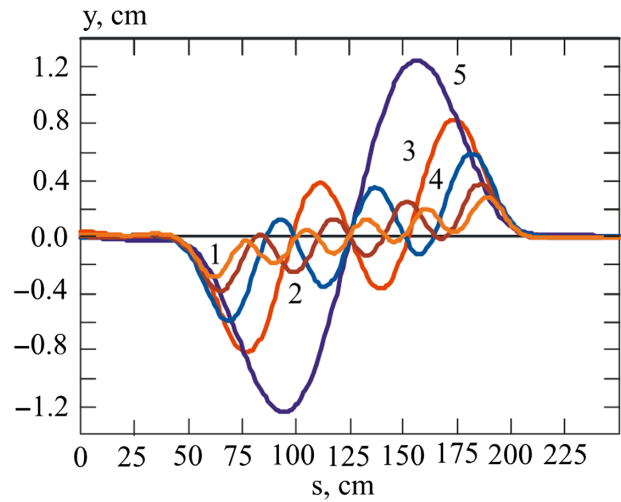


FIG. 16. Electron motion in the 90° bend with longitudinal magnetic field 1 kG in bending magnet of the NICA cooler. 1–905 keV, 2–1185 keV, 3–1650 keV, 4–2500 keV, 5–4870 keV.

case where the bending field index $n = 0.5$, the motion in a bending magnet with a longitudinal magnetic field has rotational symmetry; that is, the equations of motion for the vertical and horizontal oscillations of the particle are identical. In this case, it is possible to move the particle from one solenoid to another without causing axially asymmetric disturbances in its motion as it passes into the cooling solenoid. Articles [30,31] show that other solutions based on KAM theory are also possible.

The use of localized elements is most effective at high energies; however, at low and medium energies, a number of difficulties arise due to the high value of the “magnetic emittance” that occurs when an electron exits a longitudinal magnetic field. In this case, the need for additional focusing of the electron beam blurs the distinction between a continuous solenoid and localized elements. At the same time, it is necessary to take into account the challenges associated with minimizing the displacement of the electron beam relative to the center of the solenoid, as well as ensuring the azimuthal uniformity of the edge fields. Therefore, the realization of electron cooling up to energies of 8 MeV with strong longitudinal magnetic field remains a fairly good method especially when tuning over a wide energy range is required.

A discussion of the use of longitudinal magnetic fields for cooling process requires an analysis of a large number of arguments, parameters, and specific experimental requirements and is beyond the scope of this article. For example, LERec experiment [6–10,32], which is a rf-based (“bunched”) electron cooler, did not use a continuous solenoidal field in the cooling section. But probably, the cooling rate is likely far from its maximum value when extrapolated to the results of the Fermilab and COSY experiments. So, the question about use of the longitudinal

magnetic fields to increase the electron beam current and friction force remains open [33].

VI. CONCLUSIONS

The concept of resonant electron optics in electron cooling systems appeared at the very beginning of the development of the electron cooling method [24,25]. However, in low-energy coolers, this idea has generally not been very in demand. With the development of new high-voltage electron cooling systems using a magnetized electron beam, the concept of resonant transport has been given new life and, thanks to the experience acquired during cooling experiments in the COSY cooler, has come to play an important role in the commissioning of such systems. Another very important problem is the diagnostics of the electron beam for the purpose of optimizing resonant transport. Some of these ideas have been tested and improved in the COSY cooler; however, experience shows that this issue requires further study to develop effective methods for optimizing cooling in such systems. The potential of the classical approach has still not been exhausted, and it can be applied to high-energy electron coolers for NICA [25,26] and HESR [27,28].

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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