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THE MAGNETIC SYSTEM OF ELECTRON COOLERS OF COLLIDER NICA

V. Panasyuk, M. Bryzgunov, A. Bubley, V. Parkhomchuk, V. Reva,V. Konstantinov, V. Korchagin, N. Kremnev, S. Pospolita, S. Ruvinskii, BINP SB RAS, Novosibirsk, Russia

Abstract

The complex of electron cooling is created in the BINP SB RAS. Complex is duplex of electron coolers. According to technical specifications total power consumption of the complex should not exceed 500 kW, electron energy from 0.2 to 2.5 MeV, magnetic field in solenoids of cooling up to 2kG, and distance between the centers of solenoids should be 320mm. In general, the layout of this complex is similar to the layout of the cooler created in BINP for COSY [1], but its production due to the above specifications is much more complicated.

LAYOUT OF MAGNETIC SYSTEM. POWER SUPPLIES.

Magnetic system of coolers complex is shown on Fig. 1. The units of upper cooler of this system marked counterclockwise from gun to collector: **1**–gun, **2**–accelerating tube, **3**–match-1, **4**–bend-1, **5**–line08-1, **6**–bend-2, **7**–insert-1, **8**–transport channel-1, **9**–insert-2, **10**–tor90-1, **11**–ion dipole-1, **12**–ins&match-1, **13**–solenoid, **14**–ins&match-2, **15**–ion dipole-2, **16**–tor90-2, **17**–insert-3, **18**–transport channel-2, **19**–insert-4, **20**–bend-3, **21**–insert-5, **22**–transport channel-3, **23**–line08-2, **24**–bend-4, **25**–match-2, **26**–decelerating tube, **27**–collector.

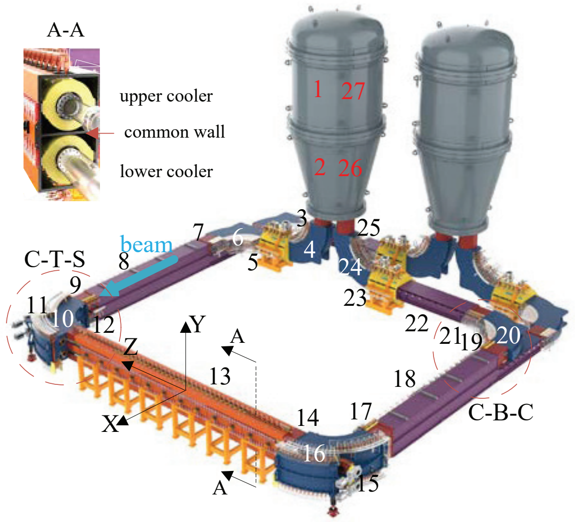

Figure 1: Layout of magnetic system. C-B-C – reference segment, C-T-S – multifunctional segment.

The same units of the lower cooler are placed clockwise from gun to collector (on direction of electron beam). Total length of transport channels here is 1.4 times greater.

The power consumption is determined by the specified value of longitudinal field B_s in units of system and permissible winding height in their coils. The radial or vertical dimensions of the vacuum elements determine inner radius r_{in} of the round coils or inner size on Y of the toroidal coils: ≥87 mm. The common wall of the magnetic shields of electron coolers with a thickness of 15mm and the distance between the beams (320 mm) limit the outer radius of round coils: r_{out}=150mm. To minimize the power loss, it was necessary to implement the maximum possible winding height in round coils: r_{out} - r_{in} = 63mm. In this case, the losses per 1 m in the solenoid (at 2 kG) are equal to 10 kW/m. Coils of bending field (B_b) are locates above and below coils of longitudinal field (B_s) in toroids and bends. Minimal thickness of the bending coil is 17mm. As a result, winding height of these coils is reduced by 17 mm. Such restrictions on the winding height determine the value of the B_s field in these and other units of the magnetic system: no more than 1kG. For this reason, short units of field matching (ins&match **12**, **14**) are inserted into each gap between the solenoid (**13**, 2 kG) and the toroids (**10**, **16**, 1 kG).

Each cooler will use twelve high-current power sources (PS). PS of upper cooler are show in Table 1. IST-9up and IST-5up are PS of bending field B_b. IST-10up and IST-11up are PS of ion dipoles. Others IST-s are PS of longitudinal field B_s of the rest units.

Table 1: PS of Upper Cooler

PS	Magnetic system units	I(A)	P(kW)
IST-1up	solenoid (**13**)	221	61
IST-2up	tor90-1 (**10**)	710	19.8
IST-12up	tor90-2 (**16**)	710	19.8
IST-9up	∑Btor90 (**10**,**16**)	295	3.72
IST-3up	∑bend (**4**,**6**,**20**,**24**)	195	31.5
IST-5up	∑Bbend (**4**,**6**,**20**,**24**)	295	7.45
IST-4up	∑line08 (**5**,**23**)	250	19.3
IST-7up	∑channel(**8**,**18**,**22**)	135	30.1
IST-6up	∑ins(**7**,**9**,**12**,**14**,**17**,**19**,**21**)	320	21.9
IST-8up	∑ins&match (**12**,**14**)	440	7.56
IST-10up	ion dipole-1 (**11**)	440	4.93
IST-11up	ion dipole-2 (**15**)	440	4.93

Full power of upper cooler is 232kW. Power of lower cooler is 244kW (more due to the length of channels).

REFERENCE SEGMENT: CHANNEL– BEND – CHANNEL

Properties of turn of electrons by 90° in the case, when centrifugal force compensates by Lorentz force only on average, studied when creating a COSY cooler [1]. Let's consider the a similar variant adapted to NICA cooling complex. Calculations performed using proven MAG3D code [1]. Sizes of coils and ferromagnets as close to real as possible. Radius of turn is R=1m. The longitudinal field B_s=1kG. The electron passage of the bend is resonant in

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energy. At resonant energy, electrons entering a bend without transverse energy leave it without “heating”. Some of these energies are equal to 4.865, 2.5, 1.65, 1.185 and 0.905 MeV. The oscillations of electrons $y_i(s)$ across bending plane (y=0) at these energies are shown on Fig. 2.

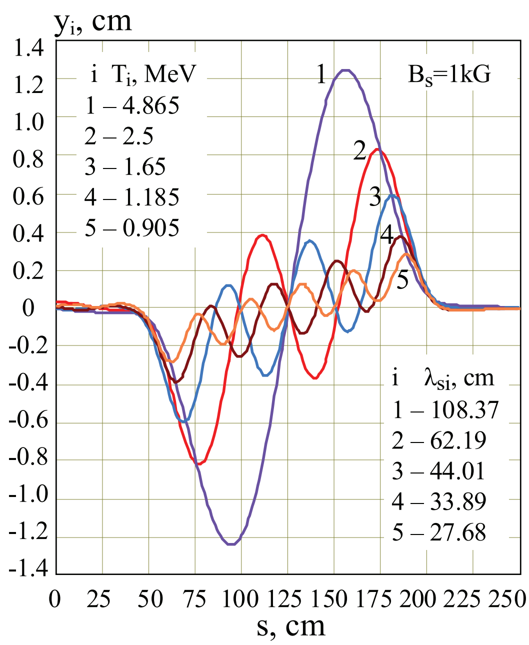

Figure 2: Reference oscillations of electrons yi(s).

The characteristic longitudinal size in this calculation is pitch of Larmor spiral $\lambda_s=2\pi\rho_s$, where $\rho_s = \beta c/\omega_H$ - Larmor radius, $\omega_H = (eB_s)/(\gamma mc)$ - Larmor frequency. Further, K(s) is the curvature of axial force line of longitudinal field B_s. Width at half maximum of K(s) equal $\Lambda \approx (\pi/2)\cdot R$ = 157cm. Note that the ratios Λ/λ_{si} are not integers: 1.45, 2.52, 3.57, 4.63 and 5.67.

For the intermediate energy T_n, we can choose the appropriate y_i (s) (see Fig. 2). For T_{n1}=1.0 and T_{n2}=1.5MeV oscillations $y_3(s)$ are suitable (T_3=1.65MeV).

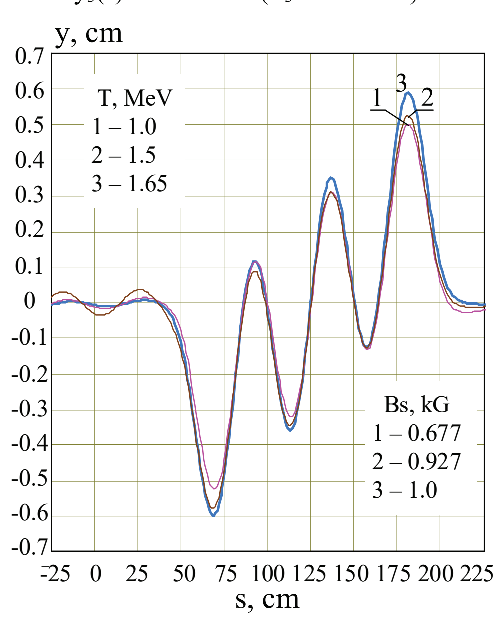

Figure 3: oscillations $y_3(s)$, $y_{n1}(s)$ and $y_{n2}(s)$.

Oscillations $y_{n1}(s)$ and $y_{n2}(s)$ are obtained using verified program for $y_3(s)$. For this, the coils currents in this program were multiplied by corresponding ratio $(\gamma_n\beta_n/\gamma_3\beta_3)$. Such a procedure follows from $\lambda_{s3}= \lambda_{sn1}=\lambda_{sn2}$ and bending fields $B_{b3}(s) \sim \gamma_3\beta_3$, $B_{bn1}(s) \sim \gamma_{n1}\beta_{n1}$, $B_{bn2}(s) \sim \gamma_{n2}\beta_{n2}$. Results of such calculations are given in Fig. 3.

Calculations performed for ferromagnetic shields with nonlinear magnetic permeability from ST-10. This causes some discrepancies in oscillations.

Profiles of the centrifugal force Fc(s) and the Lorentz force FL(s) are shown on Fig. 4. Here $Fc(s) = \gamma\beta^2\mathcal{E}_0K(s)$, where $\mathcal{E}_0$=512keV, K(s) in cm^{-1}, and $FL(s) = -0.3\beta\cdot B_b(s)$, where $B_b(s)$ in G.

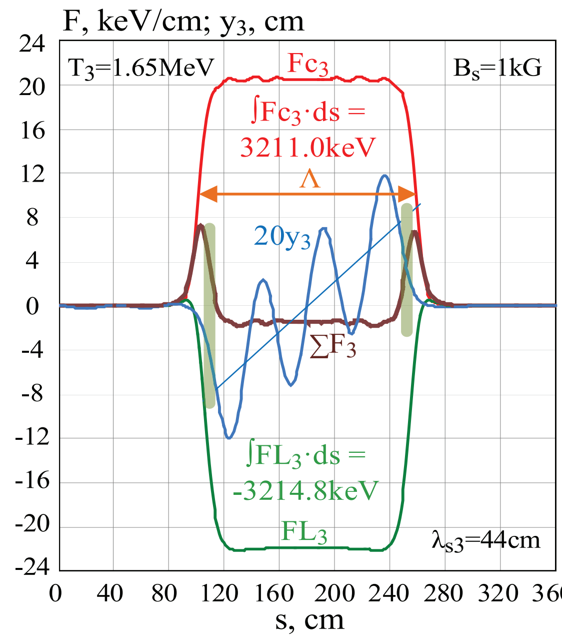

Figure 4: Profiles of $Fc_3(s)$, $FL_3(s)$ and $\sum F_3(s) = Fc_3(s) + FL_3(s)$ along axial force line.

Note that integrals of these forces along the longitudinal coordinate quite well compensate each other.

Dependencies of bending fields B_b in the center of the bend on y and on radius ΔR=r-R are shown on Fig. 5.

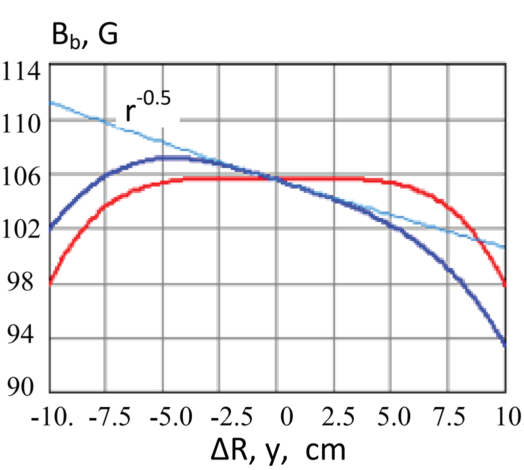

Figure 5: Profiles of bending fields $B_b(y)$ and $B_b(\Delta R)$.

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The field index (~0.5) is provided by the shape of bending coils located on the side walls of magnetic shields. Note that correct profile of $B_b(\Delta R)$ is limited by interval -2.5cm <ΔR <2.5cm.

Electrons moving in the channel after passing through the bend are shown on Fig. 6. View of the trajectories from the end of the channel is presented.

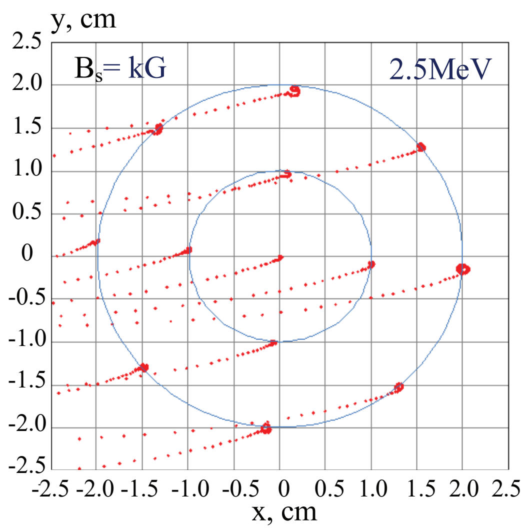

Figure 6: View on trajectories from the end of channel.

Coordinates of the axial electrons x=0 and y=0. A noticeable transverse Larmor radius arises at periphery of considered electrons ensemble.

Bends and toroids are units with similar properties. Considered algorithm for changing fields (coils currents) with a change in electron energy is also suitable for toroids. In addition, there is a sufficient number of tools to configure the field: additional PSU, various correctors etc.

MULTIFUNCTIONAL SEGMENT: CHANNEL – TOROID – SOLENOID

Layout of this segment is shown on Fig. 7. Inserts and ins&matches are multifunctional units that provide the possibility of mounting and repairing of the whole complex.

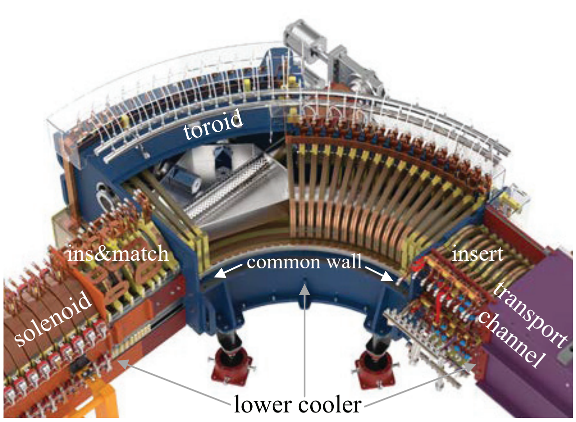

Figure 7: Layout of segment **C**–**T**–**S**.

The inner radius of the insert coils of these units is 2 cm larger than the radius of the coils of adjacent units. Field inhomogeneity occurs at the junction of coils of different inner radius. Inhomogeneity is minimized by order of insert coils location.

Dipoles of the transverse fields (see Fig. 8) are located in obtained radial gap of insert. Radius of uniform field region is ~ 3cm. These dipoles are tools to reduce "heating" of electrons.

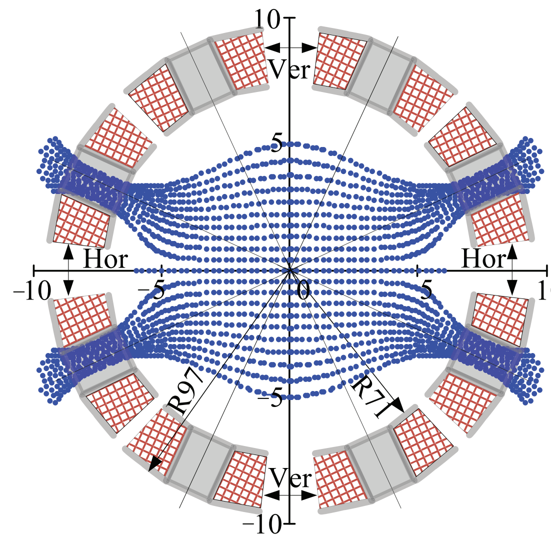

Figure 8: Dipoles of transverse fields. Force lines of horizontal field.

The pancake coils of the solenoids almost touch the common wall of the magnetic shields. Because of this, the magnetic fluxes of the solenoids axially symmetrical in the center of the solenoids to their edges lose symmetry, shifting to a common wall. In addition, about half of the flux of each solenoid is closed on magnetic shields of units ins&matchs (**12**, **14**) and again asymmetrically. Accordingly, vertical field $B_y(z)$ appears along the axis of each solenoid, changing the sign in its center. In principle, this field can be compensated by correctors of ins&match unit and by means of precise turns of solenoid coils around horizontal axis X and vertical axis Y [2]. But the strength of these compensation tools is limited, and additional steps are needed to reduce the value of this BY(z) field.

Field matching units of segment are shown on Fig. 9.

According to the calculations, the end plates at the joints of the solenoids with units **12** and **14** (ins&matcht) redistribute the fluxes so that the vertical field decreases to $B_{Y0}(z)$. Then above tools compensate the field to $B_{Y1}(z)$ (see Fig. 10). Plates 15mm thick have holes coaxial with coils. The calculation made with a shortened solenoid: only 34 pancake coils (whole solenoid has 84 coils).

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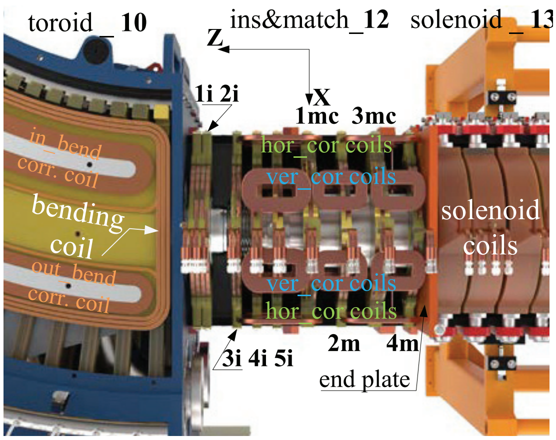

Figure 9: Magnetic elements of units **10**, **12** and **13**.

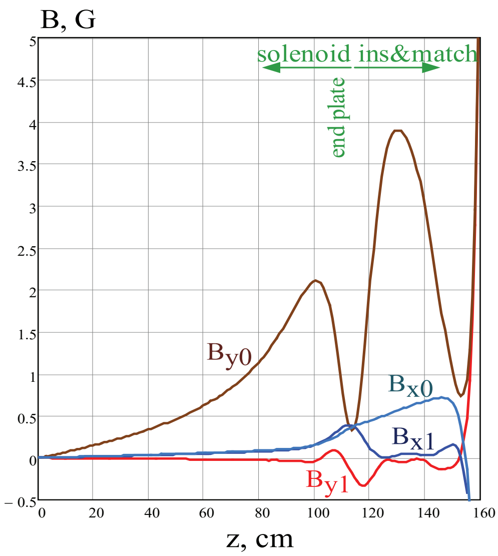

Figure 10: Transverse fields along solenoid axis before (B_{x0}, B_{y0}) and after (B_{x1}, B_{y1}) compensation.

In units **12** and **14** (ins&match), the field $B_z(z)$ should be not only axisymmetric but also have a certain profile along Z axis: B_{z1}(z, T, B1, B2) [3]. The basic profile $B_{z2}(z)$ is given by the arrangement of round coils 1mc – 4m. Adjustment of profile $B_{z3}(z)$ for selected parameters T, B1, B2 is carried out using the correcting turns of the coils 1mc and 3mc. Profiles for the following parameters: T=2.5MeV, B1=1kG, B2=2kG, are shown in Fig. 11.

Calculation of electrons passage through segment **C–T–S** is considered. The electrons start in the channel **(8)** along magnetic field B1=1kG. They must enter the field B2=2kG of the solenoid **13** without "heating". Field B2 itself must be uniform with an accuracy of 10^{-5}. View of trajectories from the end of solenoid (**13**) is shown on Fig. 12.

Coordinates of the axial electrons x=0.14cm and y=0. After passing ins&match-1 (**12**), the electron radius $\sqrt{x^2+y^2}$ decreases by $\sqrt{2}$ times.

To obtain an acceptable result, we used:

- Six PS, four of them with individually adjustable currents: in solenoid (**13**), in 1mc - 4m coils of ins&match (**12**), in coils of longitudinal field of toroid (**10**) and in coils of bending field of toroid (**10**).
- Three correctors of vertical and two horizontal fields in ins&match (**12**).
- Precise turns of solenoid coils around a horizontal axis X
- Adjustment of $B_{z3}(z)$ profile using correcting turns of the 1mc and 3mc coils.
- Dipoles of the transverse fields in insert-2 (**9**).

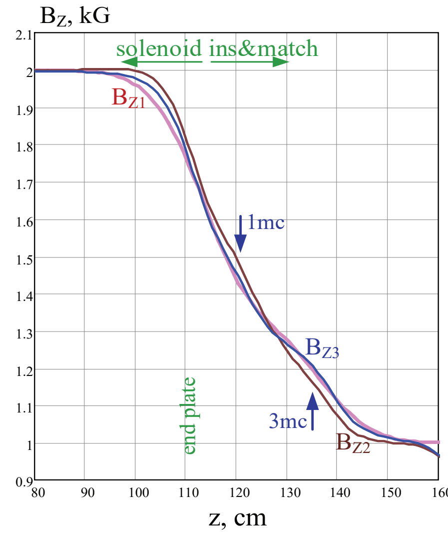

Figure 11: Profiles $B_{z1}(z)$ – theoretical, $B_{z2}(z)$ – basic, $B_{z3}(z)$ – adjusted by coils 1mc and 3mc.

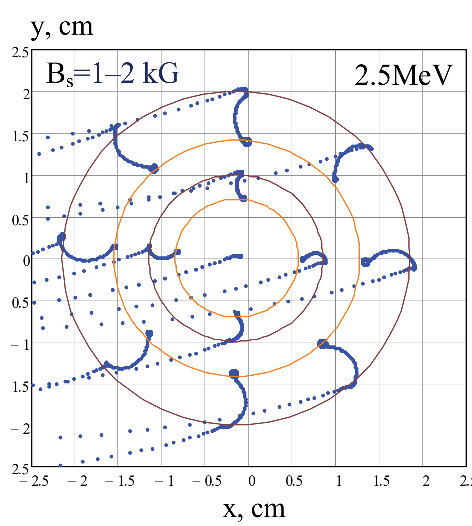

Figure 12: View on trajectories from the end of solenoid.

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