Abstract
The magnetic system for the COSY cooler is presented. Electron beam energy range is wide (24keV–2MeV), typical bend’s radii of electrons track are near to 1 m, typical magnetic fields are 0.5 – 2kG. Transport channels with guiding magnetic fields for motion of electrons from high voltage terminal of cascade transformer into cooling section and their return for recuperation under such conditions are discussed. Results of Hall sensors measurements are compared with corresponding computations. Also some steps were taken for improvement of the magnetic field lines straightness in the cooling section.

DESCRIPTION
Solenoid consists of 40 pancake movele coils [1]. Half the coils have right-handed winding, the rest – left-handed winding. Interleaving of such coils minimize field inhomogeneities which arise at commutation of coils. Since cooling by magnetized electrons is used, high straightness of the magnetic field line is required: \( \Delta B / B = \theta < 10^{-5} \). Coils are installed on ball bearings for adequate correction of position. Magnetic field is aligned by tilting or slewing the coils. Necessary displacements of control screws were found by mathematical treatment of previous compass measurements [2]. Displacements of \( \sim 0.01 \text{mm} \) were needed in final stage. In addition magnetized electron beam may be tilted by horizontal and vertical correctors.
of cooling section \( (B_X=BY\leq\pm 15G) \). The values of longitudinal magnetic fields of solenoid \( B_{Zsol} \) and guiding magnetic fields of toroids \( B_{Stor} \) amount to 2kG. Usually \( B_{Zsol}=B_{Stor} \).

High-voltage tank magnetic system includes two solenoids around accelerating and decelerating tubes[1]. The nominal value of the magnetic field is 0.5kG. Electron beam moves from tank to cooling section and comes back for recuperation by identical transport channels. Each channel consists of three 90° bends, two short and one long transition sections and a solenoid with transverse correctors. Guiding magnetic field of channels \( B_Z \) amounts to 1kG. Two matching sections are situated at the ends of each channel. These sections ensure passage of electrons through longitudinal gradient of field without heating [3].

Transverse bending field is created by bending coils of bends and toroids. Field index \((\sim 0.5)\) is ensured by coils positioned on the walls of magnetic conductors.

Functionally five power supplies are used for water-cooled coils.

Table 1: Fields and Supplies parameters

<table>
<thead>
<tr>
<th>Series connection coils</th>
<th>Fields kG</th>
<th>Current A</th>
<th>Power kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coils of cooling solenoid</td>
<td>2</td>
<td>330</td>
<td>110</td>
</tr>
<tr>
<td>Toroidal coils of 45° toroids</td>
<td>2</td>
<td>1040</td>
<td>180</td>
</tr>
<tr>
<td>Toroidal coils of 90° bends</td>
<td>1</td>
<td>320</td>
<td>130</td>
</tr>
<tr>
<td>Coils of transition sections</td>
<td>1</td>
<td>300</td>
<td>70</td>
</tr>
<tr>
<td>All bending coils</td>
<td>0.1</td>
<td>350</td>
<td>45</td>
</tr>
</tbody>
</table>

Two dipoles are situated on the axis of cooling solenoid outside of toroids. Their vertical field coils may be connected in series with coils of 45° toroids. Two coils of matching section (4) connected in series with coils of cooling solenoid and other three are connected in series with coils of 90° bends.

**HALL SENSORS MEASUREMENTS**

Calibrated set of Hall sensors was used for magnetic measurements. Twelve devices are placed on a precise Cross-support so that 3-d components of field are measured, where every component is measured in four points around cross axis. The Cross is installed on a Carriage.

The Carriage moved along rails in one-step operation. Special rigid rails installed in the magnetic system elements ensured movement of the Cross center along the axis in straight sections, or along the arc of 1m radius in bends and toroids. The position of the Cross center along the track was considered as longitudinal coordinate \( s \).

General assembly consisted of cooling section, toroid, dipole and matching section \((1-2-3-4\) in Fig. 1). Other eight elements were measured in triads. Each triad consisted of one bend (one of the six 90° bends (5)) in the center with two neighboring transition straight sections, or one of the two solenoids (6) in the center with corresponding straight sections on sides \((7-6-7, \ 7-5-8\) etc). Measurements were carried out with various combinations of four power supplies for the triads’ elements.

**MEASUREMENT RESULTS**

Results of measurements (dot curves) and results of corresponding computations (solid curves) are presented in next figures.

Measurements on the assembly \( 1-2-3-4 \) along straight axis are represented below in Fig. 3 (i.e. measurements in the path of ion beam). The \( z \) origin is fixed in the centre of the cooling solenoid.

![Figure 2: The Cross with Hall sensors on the Carriage.](image)

![Figure 3: Longitudinal component \( B_Z \) and its constituents \( B_{Zsol}B_{Ztor} \) and vertical component \( B_Y \) along the axis. Dot – measured curves, solid – computed curves.](image)
Here and farther each constituent is powered by its own supply.

Measurements of assembly 1–2–3–4 along travel line (axis–45°arc–straight line) are represented below (i.e. measurements on the path of electron beam). The s origin is fixed also in centre of cooling solenoid.

- This allows constructing of field by variation of the constituent currents, for example, constructing the optimal field for electron transit without ‘heating’.

**COMPUTATION OF ELECTRON TRANSIT THROUGH TOROIDS AND BENDS**

Profiles of guiding field curvature (cur(s)) and bending field $B_B(s)$ do not coincide. So, the Lorentz force $F_L(s) = e \beta_B B_B(s)$ counteracts with centrifugal force $F_C(s) = mc^2 \gamma^2 \beta^2 s \text{cur}(s)$ only on average [4]. Normalized profiles are shown in Fig. 6.

Electron beam energy range is wide (24keV- 2MeV). Non-adiabatic electrons of major energies are ‘heating’ in such bends and toroids. If electrons make integer number of turns ($n_\omega$) around magnetic field $B_S$ during transit, they leave bend or toroid without ‘heating’.

Since diverging profiles are present, fitting of coils current for $B_S$ and $B_B$ is needed. For the beginning we can choose $B_S$ corresponding to integer number of Larmor's turns on the bend transit and $B_B = 17 \gamma \beta$ (from $F_L = F_C$).

Computations of electron transit through channel fragment 8–5–7–6 are presented on the Fig.7, 8 and 9.
Electron oscillations relative to central force line are shown below. Here $\delta r$ is radial displacement in the bend and $x$ is displacement across bend plane.

![Graphs showing electron oscillations](image)

Figure 8: Electron oscillation in optimal fields – 1, 2 and electrons with $T_e=2\text{MeV}$ in field for $T_e=1.63\text{MeV}$ – 3.

Larmor’s turns of $2\text{MeV}$ electrons into solenoid 6 (i.e. after bend transit) are shown below for different cases.

![Graphs showing Larmor’s turns](image)

Figure 9: Left graph – Larmor’s turns in optimal $B_S$, $\pm 2\%$ varying relative to optimal $B_S$ and non-optimal ($n_\omega=2.5$). Right graph – Larmor’s turns in optimal $B_B$ and $\pm 2\%$ varying relative to optimal $B_B$.

Optimal fields $B_S$ at $T_e=2\text{MeV}$, $n_\omega=3$ and at $T_e=1.63\text{MeV}$, $n_\omega=4$ got by fitting. At fixed $n_\omega$ optimal $B_S$ value varies on energy as $\gamma\beta$. At $T_e=1.63\text{MeV}$ conversion $n_\omega$ from 4 to 3 decreases optimal field by 0.71 instead of 0.75. At electron energy $T_e=2\text{MeV}$ max($B_{Bbend}$)=84G (max($B_{Btor}$)=104.6G) and varies on energy as $\gamma\beta$.

Variation of optimal guiding field $B_S$ on $\pm 2\%$ increase ‘heating’ slightly. Variation of optimal bending field $B_B$ on $\pm 2\%$ substantially shifts the beam axis across bend plane on $\pm 2\text{mm}$.

Computations were done by MAG3D code [5] in maximal approximation to real design. Steel grade of magnetic conductors is ST10.

**CONCLUSION**

The magnet measurement of magnetic elements: cooling section, toroid, bending solenoid and matching section shows good agreement with calculated magnet fields. Beginning of the electron beam orbit optimization for different energy will made according results of $B_S$ and $B_B$ computations.

Naturally final positioning of electron beam orbit will made according results of diagnostic measurement. Tools for optimisation exist: system of pick-up and set of the correctors.

**REFERENCES**


