# DEVELOPMENT OF ELECTRON COOLER COMPONENTS FOR COSY

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*Abstract*

The 2 MeV electron cooling system for COSY-Juelich was proposed to further boost the luminosity even in presence of strong heating effects of high-density internal targets. The project is funded since mid 2009. Manufacturing of the cooler components has already begun with collaboration efforts of two institutes BINP(Novosibirsk) and FZJ(Juelich). The high cooling rate requires using of the high intensity electron beam with strong magnetization at the cooling section. The 2 MeV cooler also well suits in the start up phase of the High Energy Storage Ring (HESR) at FAIR in Darmstadt. At the report experimental testing results of the prototypes of the cooler elements will be discussed.

## INTRODUCTION

The new generation of particle accelerators operating in the energy range of 1-8 GeV/u for nuclear physics experiments requires very powerful beam cooling to obtain high luminosity. For example the investigation of meson resonances with PANDA detector requires an internal hydrogen target with effective thickness $4\times10^{15}$ atoms per $cm^2$ and $10^{10}$ – $10^{11}$ antiprotons at 15 GeV circulating in the HESR. In this case the peak luminosities ranging from $2\times10^{31}$ to $2\times10^{32}$ $cm^{-2}s^{-1}$ are achievable. These experiments allow observe meson resonances in proton-antiproton annihilations. Resolution of the experiments is limited only by momentum spread in antiproton beam, which must be better than $10^{-4}$.

The average momentum losses $(dp/dt)/p$ of ion on such a target (for 4 GeV antiprotons ) will be about $4\cdot10^{-6}s^{-1}$ and the heating rate of momentum spread by fluctuation of ionization losses will be near $\frac{dp^2}{p^2dt} = 2\cdot10^{-9}s^{-1}$. To obtain momentum spread of $10^{-5}$ – $10^{-4}$ cooling time in the range $\tau_{cool} = 2(dp/p)^2/(dp^2/dt/p^2) = 0.1 \div 10s$ is needed. The 4 MeV electron cooler at the RECYCLER ring (FNAL) achieves cooling time about 1 hour. The new cooler for COSY [1] should provide a few orders of magnitude more powerful longitudinal and transverse cooling that requires new technical solutions. The basic idea of this cooler is to use high magnetic field along the orbit of the electron beam from the electron gun to the electron collector. In this case high enough electron beam density at low effective temperature can be achieved in the cooling section. For example the electron beam density of $2\cdot10^8$ $cm^{-3}$ (6 mm beam diameter and 1.5 A of current) magnetized with longitudinal magnetic field of 2 kG will have $2.7\cdot10^6$ cm/s drift velocity in the beam reference frame. This velocity corresponds to a cooling time about 0.1 s for the low angular spread ($\Delta p_\perp / p = 10^{-5}$) beam.

## BASIC DESIGN FEATURES

The basic parameters for the COSY cooler are listed in Table 1. The restrictions are given by the space available in the COSY ring. The height is limited to 7 m by the building.

Table 1: Basic Parameters and Requirements.

| COSY 2 MeV Electron Cooler | Parameter |
|---|---|
| Energy Range | 0.025 ... 2 MeV |
| High Voltage Stability | $< 10^{-4}$ |
| Electron Current | 0.1 ... 3 A |
| Electron Beam Diameter | 10 ... 30 mm |
| Length of Cooling Section | 2.69 m |
| Toroid Radius | 1.00 m |
| Magnetic Field (cooling section) | 0.5 ... 2 kG |
| Vacuum at Cooler | $10^{-9}$ ... $10^{-10}$ mbar |
| Available Overall Length | 6.39 m |
| Maximum Height | 5.7 m |
| COSY Beam Axis above Ground | 1.8 m |

In Fig. 1 the layout of the COSY 2 MeV cooler is shown. The cooler HV terminal is installed inside the pressure vessel filled with $SF_6$ gas. The main features of the cooler are:

1. The design of the cooling section solenoid is similar to the ones of CSR (IMP) and LEIR (CERN) coolers designed by BINP [2,3]. However, for the 2 MeV cooler the requirement on the straightness of magnetic field lines is so high ($\Delta\theta < 10^{-5}$) that a system for control of magnetic field lines in vacuum becomes necessary.
2. For suppression of high energy electron beam losses at IMP and LEIR coolers, electrostatic bending was used [4]. The shape of the 2 MeV transport lines, however, dictates a different approach. The collector (inside the HV terminal) will be completed by a Wien filter to suppress return the electrons flux.

## MAGNETIC SYSTEM

The magnetic system has the cooling section (1) (see fig.1), where electrons and protons move at common orbit and parallel to each other. At the $45^0$ toroid magnets this beams are joined and separated (2). Magnetic dipoles (3) are installed along the proton orbit for compensation of the vertical field action on protons at toroids. There are two transport cannels for electron beam: to inlet it to cooling section and to return it at the high voltage vessel for recuperation of the electros energy. Each system has matching section (4), three 90° bending parts (5), solenoids (6), two short (7) and one long (8) transition sections and matching section (9) at entry to acceleration tube.

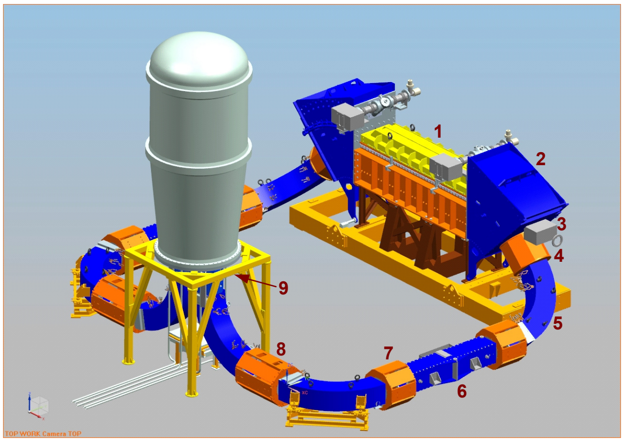


Fig.1 Schematic view of the 2 MeV COSY cooler.

The requirement on the parallelism for motion of the proton and electron beams inside cooling section is very high ($\Delta B / B = \theta < 10^{-5}$). To satisfy these requirements cooling solenoids will be made from the pancake coils with possibility to incline each on the down support points. For better compensation of transverse components of magnetic field generated by communication lines, two types of coils with opposite direction of winding are used at this cooler (in contrast to previous cooler EC-35, EX-300, LEIR). At this case neighboring coils can compensate transverse magnet components.

The toroid radius and the bending solenoid radius is 1 m (at central axis of electron beam). The value of longitudinal magnet field in toroid ($B_{tor}$) is up to 2*kG,* and in bending solenoid ($B_{turn}$) is up to 1*kG*. The transverse magnetic field gradient is generated by special position of the bending magnetic coils. The profile of electron trajectory and the profile of magnetic lines can be adjusted at average but at the entry and exit of a magnet the electrons will have kick by transverse component of magnetic field. The transverse magnetic field should be changed according to electron beam energy as $B_{\perp} \propto \gamma\beta$. We can use self compensation scheme if electron will made integer number of Larmor turns along the orbit. To keep the phase of Larmor rotation constant it is also necessary to change longitudinal component of magnetic field along electron orbit as $B_s \propto \gamma\beta$. At next figures (fig. 2, 3) an example of calculation of electron motion at the transport channel is shown. Start point is located at center of long section (8), then electrons passes bending solenoid (5), short section (7), and then enters at solenoid (6). Calculations were made using Tiunov M.A. code MAG3D at geometry which is very close to real and magnetic parameters of iron correspond to steel 10 ( Russian name type of steel)

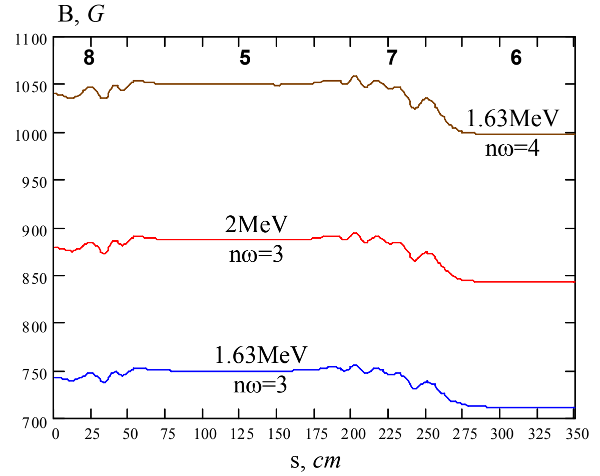


Fig. 2. The longitudinal field in the transport cannel. For this field the electron passes transport system without heating.

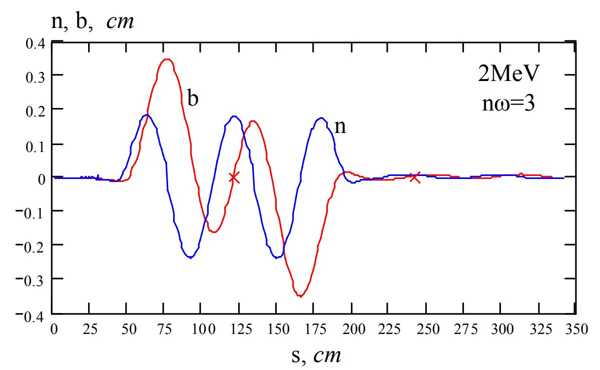


Fig. 3 The electron deflections from the axis line: **n** – at radial direction, and **b** – at perpendicular direction (drift).

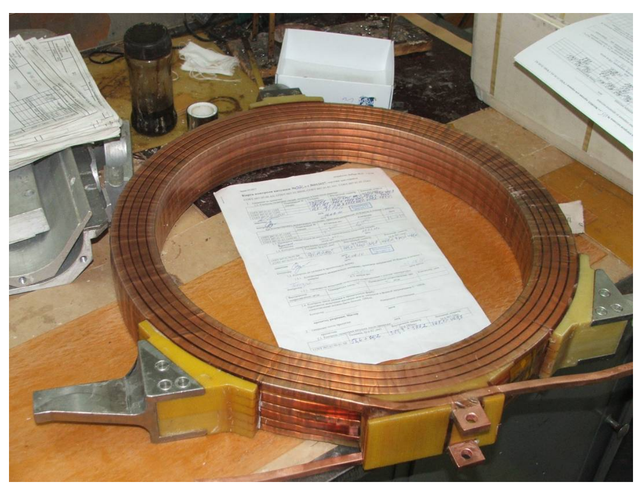

Fig. 4 Coils for the cooling section

## MAGNETIC LINE STRIGTHNESS

For high voltage cooler key role at cooling efficiency belongs to the quality of magnetic field at cooling section. Deviation of magnetic lines to angle θ produces motion of electrons $\Delta V = \theta\gamma\beta c$ at the electron beam rest system and, as results, decreases cooling rate. For measuring of angle of magnetic line a sensitive compass with mirror is used which reflects the laser beam along axis of the cooling section (Fig. 5). The feedback system measures back scattered laser beam and returns it to center of the system using currents at correction coils. The currents are proportional to the perpendicular components of magnetic field. Using inclining of the pancake coils the perpendicular components of magnetic field can be compensated.

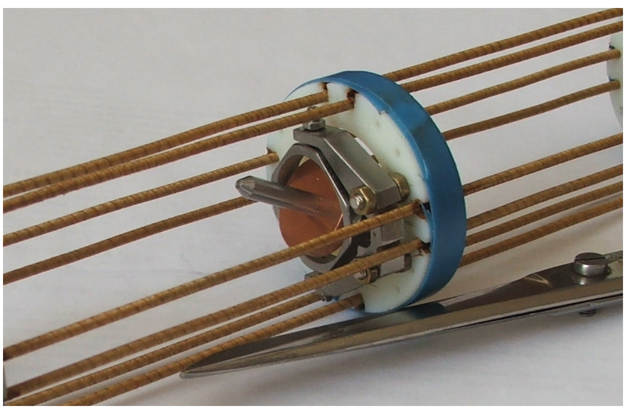

Fig.5 The compass with mirror for measuring direction of magnetic line at cooling section.

The experience of using of this system for regular control [6] demonstrated that after some period of time the deformation of line increases and procedure should be repeated. At 3 m cooling section this period for accuracy $<10^{-5}$ was about 1 week. FNAL cooler required new alignment procedure for elements of cooling solenoid after 2 months of operation [7].

## HIGH VOLTAGE COLUMN

Testing of the high voltage section prototypes demonstrated that for $SF_6$ with 1.6 bar pressure the voltage between section achieved the project value 60 kV (Fig.6). For pressure 1.4 bar sparking events were detected. The higher pressure of $SF_6$ is required for suppression of sparking between the high voltage terminal and the ground potential vessel. Calculations show that the electric field on the high voltage terminal will be near 160 kV and for suppression of discharge we need more then 3 bar pressure. The really existing roughness of the high voltage terminal surface requires increasing of gas pressure to 5 bar.

Projecting high voltage vessel and column, we took the main parameters of industrial accelerator ELV-8 that works on 2.5 MV.

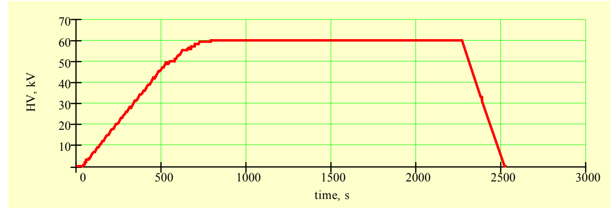


Fig. 6 Testing of the high voltage stability

The first experiments with high voltage were made with using of own BINP produced ±30 kV power supply. But later, for serial production, high voltage power supply of Japanese company MATSUSADA Precision Ink model RB30-30N will be used.

## THE CASCADE TRANSFORMER

For core of the cascade transformer we will use the amorphous iron of Russian plant (http://www.amet.ru/) with small power losses for 20 kHz (at iron and winding 180 Wt/cascade). The 33 cascades will be installed at vertical column so that each core will correspond to high voltage section. Transformer oil circulated along transformer will be used for cooling and isolation (Fig. 6).

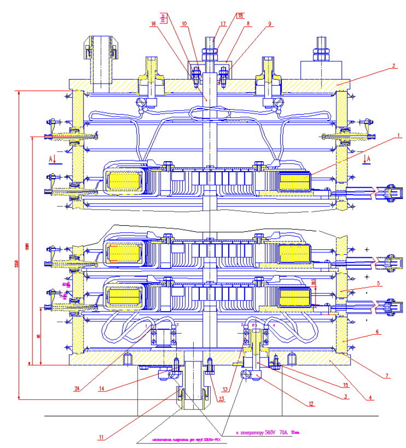

Fig. 7. The high power cascade transformer

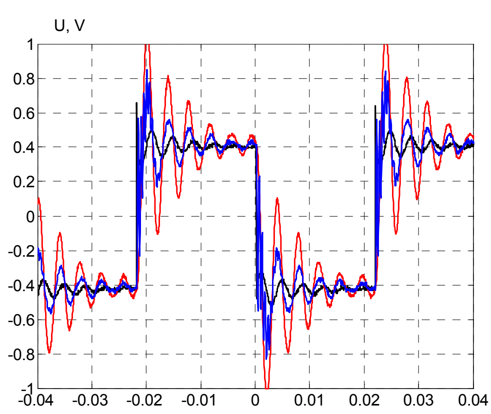


Fig 8. The voltage oscillation on 3 sections transformer if input voltage is taken from rectangular wave form generator. Measurements without resistor loading.

As is known [7] the problem in design of a cascade transformer is its own resonance mode. The high mode oscillations exiting at process of operation of high power voltage converter can limit the power transport along cascade [7]. Fig 8 shows response signals of 3 cascade transformer without resistive loading on input rectangular signal from generator. We see that own mode oscillations have frequency about 250 kHz that far from working frequency 20-25 kHz.

Table 2. Basic parameters of transformer

| | |
|---|---|
| Size Fe (ØD1-ØD2) | 28 cm–20 cm |
| Thickness (2 Fe rings) | 2 cm |
| Mass | 4.8kg |
| Magnet conductivity | 26000 |
| Cross section Fe | 8*2 $cm^2$ |
| Number winding | 2*28 |
| Coupling inductance | 29.8 mH |
| Leakage inductance | 160 uH |
| Working frequency | 20kHz |
| Capacitance C0 | 1.8nF*900V |
| Capacitance C1 | 0.4 uF*280V |
| Voltage single winding | 280 V r.m.s. |
| Magnet field at Fe core | 2kGauss r.m.s. |
| Type of Fe core | 5BDSR type B |

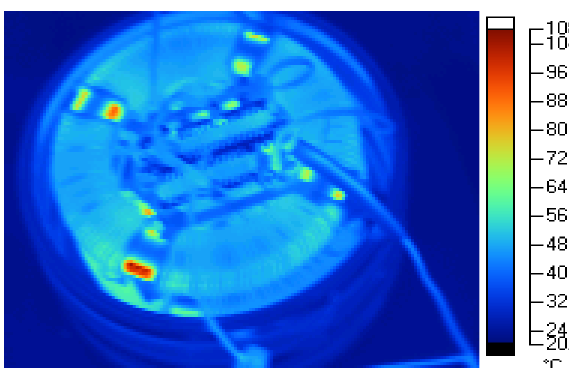


Fig 9. Thermo distribution after testing with power 15 kWt (thermo sensor photo).

After 5-10 minutes of operation of the transformer with high power 15 kWt, the photo of thermo distribution was made (Fig.9.). This measuring was made without oil cooling and we think that cooling will decrease temperature for normal value.

## HIGH VOLTAGE TERMINAL

The high voltage terminal is supported by column from the 33 identical high voltage sections (fig. 10). The column with high voltage terminal is placed in special tank which can be filled with $SF_6$ under pressure up to 10 bar. The section contains two magnetic coils producing guiding magnetic field for acceleration and deceleration tubes and the high voltage power supply producing up to 60 kV. Each section is supplied with power from separate winding of the cascade transformer. Total power consumption of one section is about 300 W. The coils and the electronic components are cooled with flowing transformer oil.

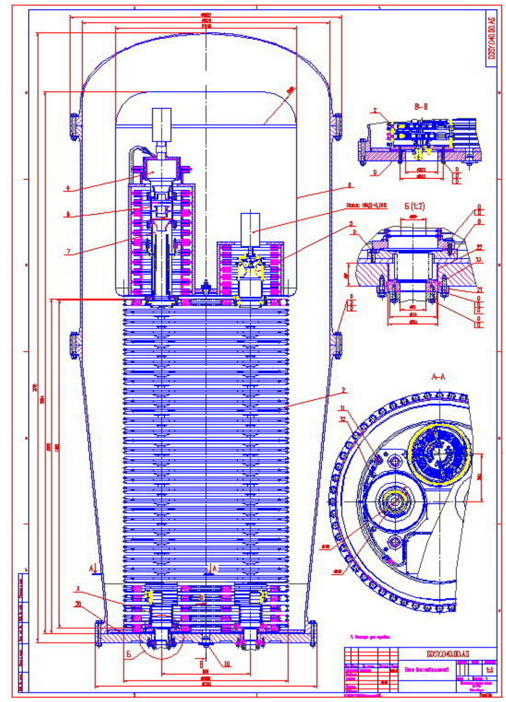

Fig. 10 The high voltage terminal with electron gun and collector

Construction of electron gun with variable beam profile is close to one which is used in previous electron cooling systems. Innovation of the gun is a controlling electrode which is split to 4 parts for independent modulation in 4 sectors of electron beam. It provides to have time modulated part of electron beam which is shifted from main beam axis. Using such modulation it is possible to control beam size and rotation with the help of pickup electrodes.

Electron collector is added with system of suppression of secondary electron flux based on Wien filter, where beam moves in crossed transverse electric and magnetic fields. In previous coolers (EC-35 CSRm, EC-300 CSRe, EC-40 LEIR) in order to achieve high recuperation special electrostatic plates, installed in bends, were used. The plates make motion of the electrons reversible. It means that electrons, reflected from the collector, move back in direction of the gun and then go to collector again where they can be absorbed by the collector. Such scheme improved efficiency of the recuperation ($I_{loss}/I_{total}$) from $10^{-3}$ to $10^{-6}$.

In high energy cooler for COSY, production of such electrostatic bending plates is related with some problems. The voltage on the plates becomes too high and geometry of the cooler is too complicated: there are 6 bend with 90º and 2 bends with 45º.

Another method, based on Wien filter, was proposed for the cooler to improve efficiency of the recuperation. The idea is to collect electrons, reflected from the collector, before they are accelerated in electrostatic tube (Fig.9).

The principle of the Wien filter is based on motion in crossed transverse electric and magnetic fields. For primary beam the electrostatic and Lorenz forces are compensated, but for secondary beam they are summed and the secondary beam drifts from the primary beam to the wall of vacuum chamber with low kinetic energy 10-20 keV.

Depending on the initial displacement of electron of the primary beam, it can be accelerated or decelerated by the edge fields of the plates. It means that in homogeneous magnetic field resulting transverse force will be equal to 0 only for central particles. Consequently shape of primary beam will be changed. To avoid this, transverse magnetic field should have gradient

$$B_x = B_\perp \frac{n}{R} y, \quad B_y = B_\perp (1 + \frac{n}{R} x),$$

where $R = \frac{pc}{eB_\perp}$, $n = \frac{1}{2\gamma_0^2}$. For low energy (20 keV) $n=0.5$.

Electrostatic field is produced with special plates. There are special shims on the plates to make distribution of electrostatic field in region of main beam more homogeneous.

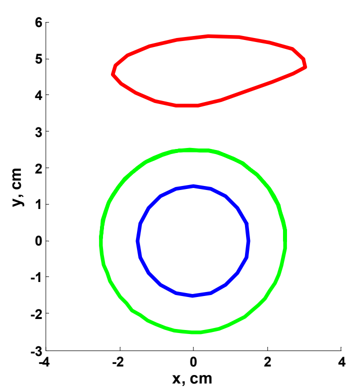


Fig. 11. Displacement of the secondary beam in Wien filter. Blue – secondary beam before filter, red – secondary beam after filter, green – internal size of diaphragm.

Transverse magnetic field in the filter is produced by permanent magnets. The magnets size and position provide average transverse magnetic field 35 G and gradient 0.5. Length of electrostatic plates is 39 cm, integral of transverse magnetic field in center 1400 G·cm, voltage on electrostatic plates ±8 kV relative to vacuum chamber. Potential of the chamber is 20 kV relative to cathode. In fig 11 displacement of the secondary beam with energy 20 keV in Wien filter is shown. As easy to see, reflected electron beam have strong deflection and can not pass limiting diaphragm.

## ACKNOWLLEDGMENTS

The cooler design and production is a results of active work of big BINP team of designers and engineers. We like to thank of this team for help at cooler construction.

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