HIGH VOLTAGE ELECTRON COOLER*

M. Bryzgunov, A. Bubley, A. Goncharov, V. Panasyuk, V. Parkhomchuk, V. Reva,
D. Skorobogatov, BINP SB RAS, Novosibirsk, Russia
J. Dietrich, TU Dortmund and Helmholtz Instituit Mainz, Germany
V. Kamerdzhiev, FZJ, Jülich, Germany

Abstract

Discussions on physical requirements and technical design of the 2 MeV electron cooler for the synchrotron COSY began in 2002.

In 2009 contract for cooler production was signed. In this report results of cooler commissioning with electron beam at BINP are 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 momentum spread in antiproton beam, which must be better than 10^{-4}. To obtain such a momentum spread cooling time in the range of 0.1- 10 s is needed. The 4 MeV electron cooler at the RECYCLER ring (FNAL) [1] achieves cooling time about 30 min. The new cooler for COSY should provide a few orders of magnitude more powerful longitudinal and transverse cooling that requires new technical solutions. [2] 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 [3].

The basic parameters of the COSY cooler are listed in Table 1. The length of the cooling section is given by the space available in the COSY ring.

Table 1: Basic Parameters of the 2 MeV electron cooler.

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

The calculation of cooling of a 2GeV proton beam with high density electron beam is shown in fig.1 The beam on each turn passes hydrogen target with density 10^{15} 1/cm^2. Magnetic field in the cooling section was taken as B=2 kGs.

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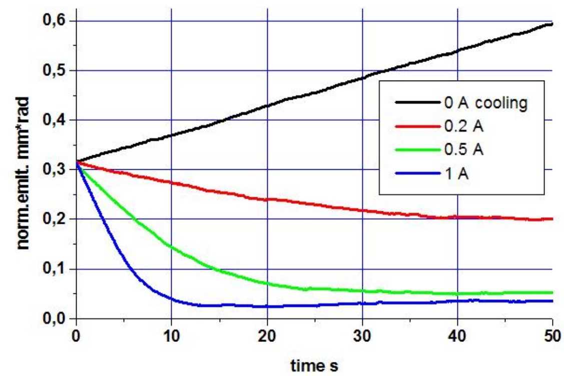

Figure 1: Cooling of 2 GeV proton beam .

From fig.1 one can clearly see that cooling shrinks the proton beam to small emitance and just 0.2 A suppressed the scattering on target. The equilibrium emittance decreases with increasing electron current by the more powerful cooling.

MAIN COMPONENTS OF COOLER

. The main features of the cooler are [2]:

1. The design of the cooling section solenoid is similar to the ones of CSR (IMP) and LEIR (CERN) coolers designed by BINP [3]. However, for the 2 MeV cooler the requirement on 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) is complemented by a Wien filter to suppress return electron flux.
3. Both acceleration and deceleration tubes are placed in the common high voltage tank.
4. The high power cascade transformer is installed around high voltage column for powering solenoids for generation of magnetic field along electron beam trajectory(Fig.2).

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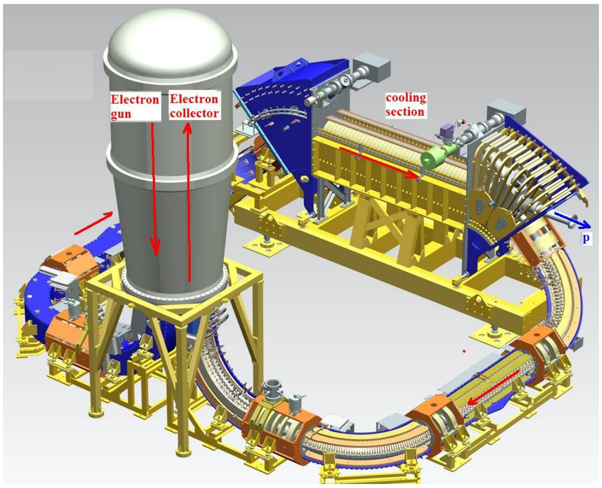

Figure 2:Sketch of 2 MV cooer for COSY.

The high voltage tank is shown in fig 3.

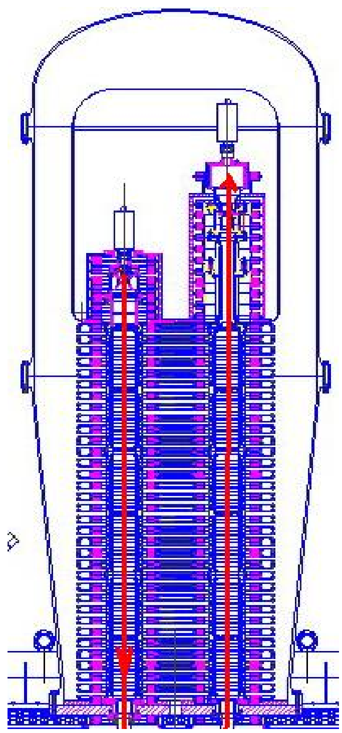

Figure 3:The high voltage tank of the cooler.

High Voltage Experiments

The high voltage tank was filled with SF_6 gas. Fig.3 shows the corona current versus high voltage for different pressures. Most of the time the cooler was operated at 6 bar (+5 atm). This pressure allows for electron beam with energy up to 1.5 MeV. The corona current decreased with time but once happened jump with increasing corona from nominal value 15 mkA on 1 MV to 100 mkA by destroy the aluminium scotch used for smoothing inner rough surface of tank. Small pane of aluminium rise perpendicular of surface. For stable operation cooler (without sparking) the pressure 7-8 bar (6-7 atm) can be used.

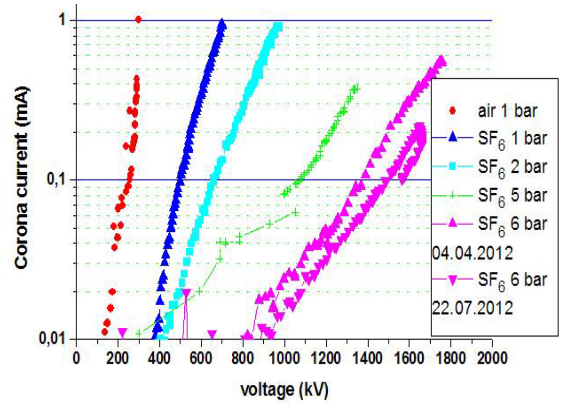

Figure 4: Corona current versus voltage for different SF_6 pressures.

Electron Gun

The electron gun design is based on the concept of the "hollow" electron gun [4]. It uses a ring-shaped near-cathode electrode (grid electrode) for changing the profile of the electron beam. The new feature is splitting the ring in 4 sectors. This allows generating four AC beams with different position relative to the centre.

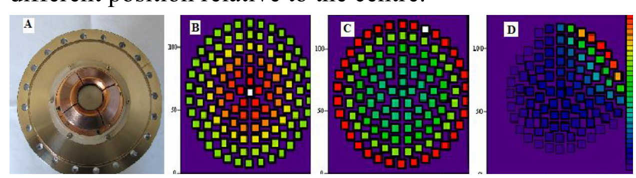

Figure 5: A is a photo of the cathode with four sector gridelectrodes, B is parabolic shape beam with maximum at centre C is "hollow" beam with minimum at the centre, D is AC component of beam with RF voltage applied to a single sector.

This design can be used as diagnostic tool for space charge of electron beam along the cooler. The pick-up monitors can detect position of this AC fractions(components?) (4 sectors and centre when the same AC voltage is applied to all 4 sectors) of the electron beam. The space charge (including ions accumulated in the electron beam) generate rotation of AC fractions around the beam axis. The experiments with clearing ions from the main electron beam demonstrated changing of this rotation.

Electron Collector with Wien Filter

The high voltage cooler produces high level of radiation in case of high electron current to ground. In order to avoid this, efficiency of recuperation (which is equal to the efficiency of collector) should be as high as possible.

Efficiency of the collector in the cooler is improved by suppression of the secondary electron flux by crossed transverse electric and magnetic fields (Wien filter). For primary beam influence of electric field is compensated by magnetic field, but for secondary beam, which moves

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in opposite direction, electrostatic and Lorenz forces act in one direction and the beam is shifted (deflected away ..?) from primary beam and absorbed by special electrode (secondary collector).

On fig. 6 scheme of the collector with filter and part of magnetic screen with permanent magnets are shown. Electron beam comes from the acceleration tube (1) to the vacuum chamber of Wien filter (2), which contains electrostatic plates (3) for production of transverse field in the filter. After the filter the beam goes to the collector (4), which is cooled by oil. Combination of magnetic screen shape (5) and current in coils of solenoid (6) distributes electrons across the internal surface of the collector. Solenoid is also cooled by oil through the holes in one plate of the solenoid screen (8). Transverse magnetic field in the filter is produced by a set of permanent magnets (9). Diaphragm (10) provides sharper edge of transverse magnetic field distribution.

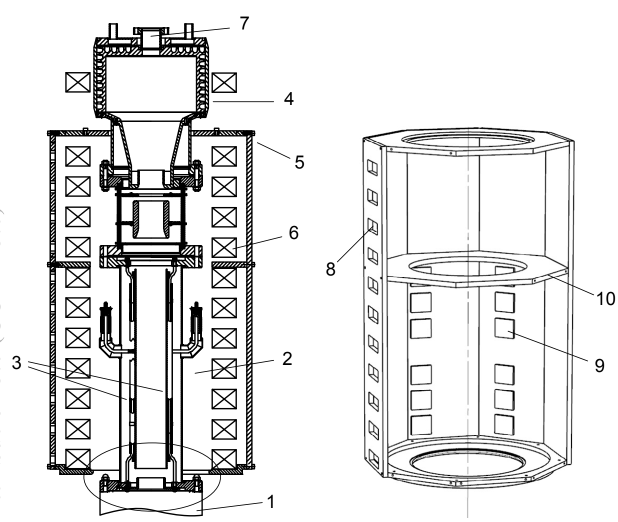

Figure 6: Collector with Wien filter inside solenoid magnet(s) (left) and magnetic screen of the solenoid with permanent magnets (right)

Clearing Electron Beam System

The BINP low voltage coolers used electrostatic bending electrodes that simultaneously remove secondary ions generated by ionization of residual gas from the electron beam . It is a good solution for low energy cooler. However for 2 MV the electric field for compact bending with 1 m radius requires electric field of 24 kV/cm resulting in +-100 kV on the bending plates . These values were considered impractical.

For COSY cooler clearing electrodes installed in toroid magnet are used. At strong magnetic field B the low energy electrons and ions move across magnetic and electric fields. Radius of drift oscillation in electric field E equal to: $R = \frac{E}{B^2}\frac{mc^2}{e}$ is very small.

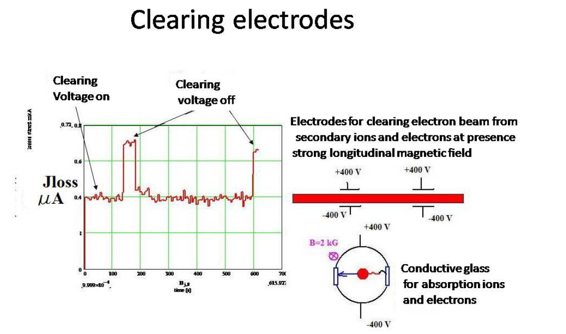

Figure 7: The principle of system for clearing the electrons and ions from main beam.

For electric field of 60 V/cm (+-300 V on electrodes) electron Larmor radius is only $8*10^{-5}$cm and proton Larmor radius is 0.15 cm. For easier clearing conductive glass is installed between electrodes so that equipotential lines cross the glass where electrons and ions are catches. Fig 7. shows that using clearing electrodes decreased losses of electron current by almost factor of 2 from 0.7 µA to 0.4 µA.

Magnetic System

The main component of the magnetic system is the cooling solenoid where electron and proton beams move at (on?) the same orbit. To satisfy the requirements on straightness of the magnetic field, the cooling solenoid is assembled from numerous short coils. The required field quality is achieved by mechanically adjusting the angles of individual coils. Dipole magnets are installed along the proton orbit for compensation of the vertical field action on protons by the toroids. For better compensation of transverse components of magnetic field generated by current leads, two types of coils with opposite direction of winding are used. Magnetic field measurement along the electron beam orbit from gun to collector was performed by a set of calibrated Hall probes, which were located on a carriage. Representative parts of the magnetic system were selected for measurements. The carriage passed step by step through selected part on rails. Longitudinal, normal and binormal magnetic field components were measured. Each component is measured at four different points that gives information about dipole and gradients of these field components???.

Discontinuities of field arise at joints of different parts of magnetic system (solenoid – toroid, bend – solenoid etc). Profiles of curvature of longitudinal field $B_{long}(s)$ of bends and toroids and profiles of their bending fields $B_{bend}(s)$ do not coincide and centrifugal drift counteracts only on average. From here resonant dependence arises between electron energy and values of magnetic fields for passing of electron through magnetic system without heating. Fig.8 shows longitudinal and bend component of magnetic fields along the beam orbit for 1.5MeV electrons. Joints are marked by ×.

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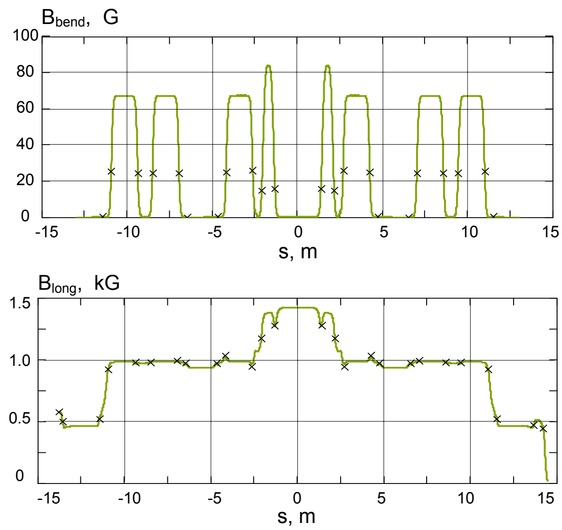

Figure 8: Bending and longitudinal components of magnetic field on path from cathode to collector

Beam orbit optimizations for different electron energies were made by computations of corresponding values B_{long} and B_{bend}.

Dynamics of Electron Motion in the Magnet System

High energy electrons can reach high amplitudes of oscillations while moving along magnetic field with small variations. This can occur at edges of solenoids with different diameter of coils. The criterion of low energy is small length of spiral in comparison with length of perturbation (lb) in magnetic field B according to equation $\bar{\lambda} = \dfrac{mc^2\beta\gamma}{qB} << lb$. Fig. 9 shows that high energy electron (1MeV) is excited to high amplitude oscillation.

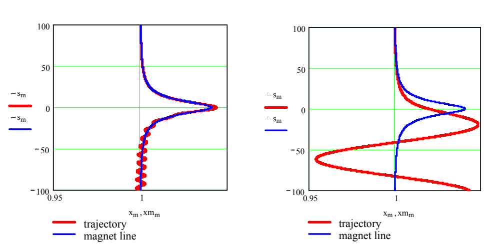

Figure 9: Passing of 10% variation of magnetic field by 0.2 MeV and 1MeV electron.

To obtain low amplitude of this oscillation in the cooling section a short dipole magnet is used to compensate the rest amplitude. Figure 10 shows the rotation amplitude in the cooling section for different amplitudes of vertical and horizontal dipole kick.

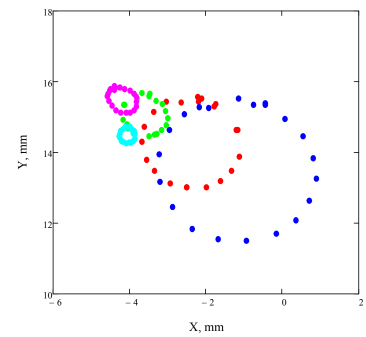

Figure 10: Larmor rotation of electron beam for different horizontal and vertical kick generated by the short dipole corrector. Energy of electron is 1MeV.

We see that radius of Larmor circle changes from 2 mm to 0.1 mm.

ELECTRON BEAM EXPERIMENTS

First experiments with electron beam were started November 23, 2011. A 30 keV electron beam was transferred along the magnet system and captured in the collector.

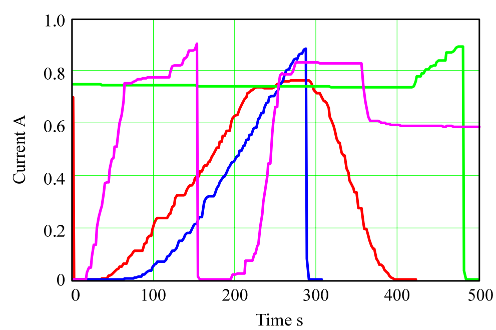

Figure 11: Experiment with 30 keV electron beam.

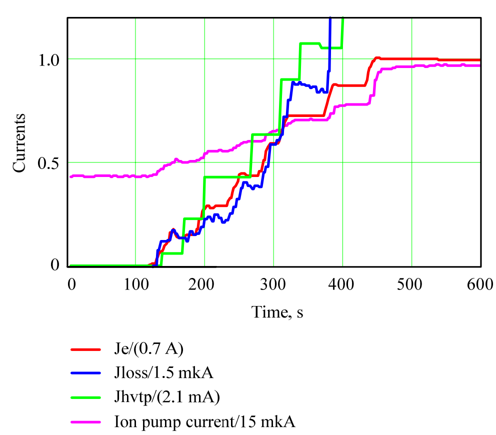

Figure 12: Measuring efficiency of collector capture at 30 keV.

The collector efficiency was about J_{hvtp}/J_e= 3.0E-3 and Wien filter suppressed reflection current to J_{loss}/J_e=2E-6 as shown in fig12. The main source of losses are the

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secondary ions generated by ionisation of residual gas. An increase of electron current causes a rise of residual gas pressure. For this condition exists a maximal steady current.

$$J_{loss} = (\alpha + a * p) * J_e$$

$$p = p_0 + b * J_{loss}$$

Where a describes losses generated by ionization of residual gas and b describes the increase of residual gas pressure due to bombardment the vacuum chamber by lost particles. At a*b*Je>1 stable recuperation is not possible. Extended conditioning of vacuum surfaces with electron beam helps increasing electron current. This behaviour is explained by lower desorption efficiency (coefficient b).

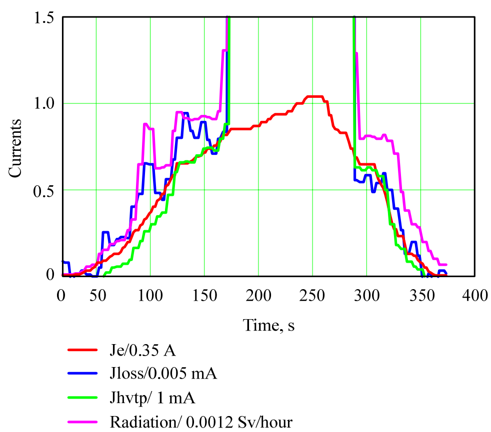

Figure 13: Experiment with 1000 keV electrons.

The experiments at high energy (fig.13) show very similar behaviour. At current values close to maximum, losses were a few times higher.

Table 2: Parameters measured during beam experiments

Energy keV	Current A	Losses mA	Rad Sv/hour
30	0.9	0.0015	0
150	0.6	0.0075	0
1000	0.5	0.002	0.001
1250	0.35	0.004	0.002
1500	0.2	0.01	0.01

The main limitation was lack of time for cooler conditioning in radiation regime. The hall where the cooler was commissioned was also used by many other teams. While personel were working in the experimental hall the cooler could not operate at high voltage.

CONCLUSION

Successful commissioning of the electron cooler demonstrated that scientific and engineering solutions were well chosen for the task. Some parameters were limited by using temporary equipment that did not fully fulfil the requirements. For example, for the high voltage tank an old vessel from industrial accelerator was used. The final vessel with smoother inner surface had to be manufactured in Germany due to limitation imposed by the pressure vessel code. Older ion pumps were used. Those will be replaced by the modern ones in Jülich. At time of commissioning it was found that level of pollution of cooler with small pieces of wire was too high causing a few short-circuits. However using cascade transformer along acceleration column showed high efficiency and opened the path for the next magnetized cooler operating at higher energy.

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