HIGH ENERGY ELECTRON COOLING

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Abstract

The electron cooler of a 2 MeV for COSY storage ring FZJ is assembled in BINP [1]. This paper describes the first experimental results from the electron cooler with electron beam and high voltage. The cooling section is designed on the classic scheme of low energy coolers like cooler CSRm, CSRe, LEIR that was produced in BINP before. The electron beam is transported inside the longitudinal magnetic field along whole trajectory from an electron gun to a collector. This optic scheme is stimulated by the wide range of the working energies 0.025÷2 MeV. The electrostatic accelerator consists of 33 individual unify section. Each section contains two HV power supply (plus/minus 30 kV) and power supply of the magnetic coils. The electrical power to each section is provided by the cascade transformer. The cascade transformer is the set of the transformers connected in series with isolating winding.

SETUP DESCRIPTION

The schematic design of the setup is shown in Fig.1. The electron beam is accelerated by an electrostatic generator that consists of 33 individual sections connected in series. Each section has two high-voltage power supplies with maximum voltage 30 kV and current 1 mA. The electron beam is generated in electron gun immersed into the longitudinal magnetic field. After that the electron beam is accelerated, moves in the transport line to the cooling section where it will interact with protons of COSY storage ring. After interaction the electron beam returns to electrostatic generator where it is decelerated and absorbed in the collector.

The optics of 2 MeV cooler for COSY is designed close to the classical low-energy coolers. The motion of the electron beam is magnetized (or close to magnetized conditions) along whole trajectory from a gun to a collector. This decision is stimulated by requirement to operate in the wide energy range from 25 keV to 2 MeV. So, the longitudinal field is higher then transverse component of the magnetic fields. The bend magnets and linear magnets of the cooler are separated by a section with large coils for the location of the BPMs, pumps and a comfort of the setup assembling. The length of the linear magnets is defined by the necessity to locate the electrostatic generator outside the shield area of the storage ring.

The vacuum chamber is pumped down by ion and titanium sublimation pumps. The typical diameter of the vacuum chamber is 100 mm and the aperture in the transport channel and cooling section is close to this value. The diameter of the accelerating tube is 60 mm.

MAGNETIC SYSTEM

The magnetic field in the accelerating tube is taken 500 G and this value is related to the maximum power that can be transfer to a high voltage potential with help of the cascade transformer. The value in the transport channel is located in the range 0.5 kG – 1 kG. The energy 2 MeV is high enough in order to don't have the complete adiabatic motion of the electrons because the magnetic field of the bend elements is chosen to provide the length of bend equal to integer number of Larmour lengths. In such case the kick on entry to bend is compensated by kick on leaving and the excitation of the transverse motion of the electron is small. So, it is convenient to change the longitudinal magnetic field according to the electron momentum. At attainment of the maximum magnetic field the transition to another integer number is implemented.

The magnetic field in the cooling section is taken 2 kG in order to have the maximum Larmour oscillation (~ 10) of the electron during its interaction with ion in order to have the magnetized Coulomb collisions even the highest electron energy 2 MeV.

The transition from accelerating tubes to transport channel is made with 7 coils powered by independent power supplies [2]. The transition from the transport channel to the cooling section is made with 5 coils with small regulation of the longitudinal current with regulated electrical shunt. In this region the magnetic field is strong and the electron motion is close to adiabatic so the matching can be realized by the proper location of these coils in order to minimize the amplitude of the transverse motion.

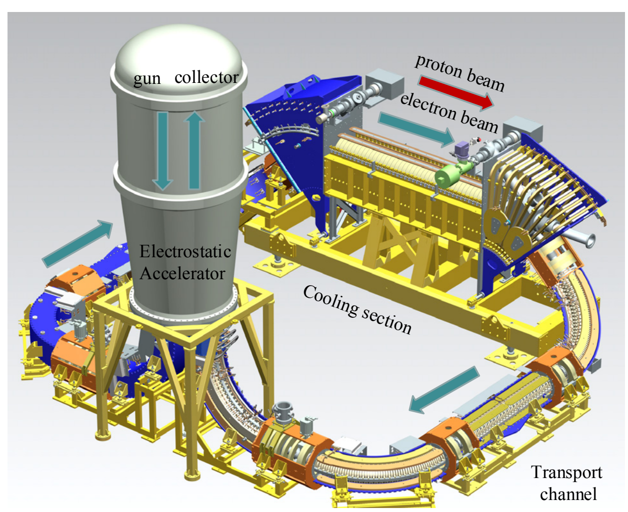

Figure 1: 3D design of 2 MeV COSY cooler.

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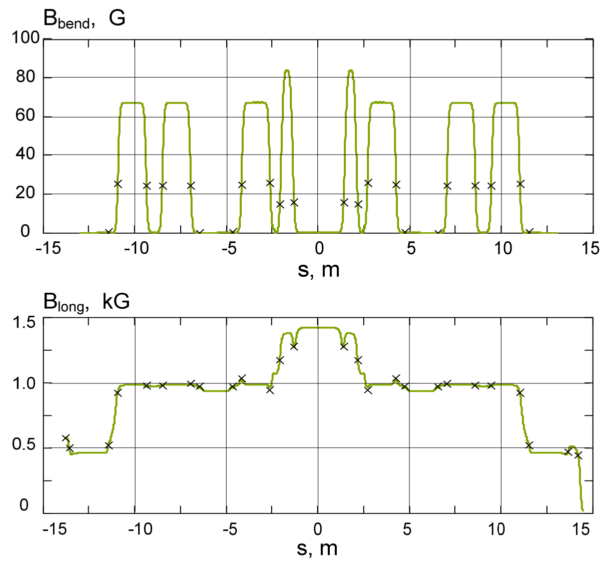

Figure 2: Bend and longitudinal components of the magnetic field along the electron beam orbit from the gun to the collector.

Magnetic field measurement along the electron beam orbit from the gun to the collector was performed by a set of calibrated Hall probes, which were located on a carriage. The probes can't pass through whole trajectory of the electron beam. So, a few magnetic elements were assembled together and the probes measured the selected part of the trajectory. The longitudinal, normal and binormal magnetic field components were measured. Each component was measured at four different points that gives information about dipole and gradients components of the magnetic field. Figure 2 shows the longitudinal and bend component of the magnet fields along the electron beam orbit.

ELECTROSTATIC GENERATOR

The accelerating column consists of 33 identical high voltage sections [3]. The column with high voltage terminal is placed in special tank which was filled with SF6 under pressure up to 5 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. Total power consumption of one section is about 300 W. The coils and the electronic components are cooled with transformer oil. The sections were tested by the spark with voltage up to 1.5 MV without damage. The connection of the control program with each section was done with wireless ZigBee protocol. Because of the mesh topology this communication network shows the good stability at the operation inside the high-voltage tank at the presence of corona and spark discharges.

Figure 3 shows the dynamics of the high-voltage generator at the typical recuperation breakdown. In time of the breakdown the leakage current achieves the maximum value 1 mA and the voltage of the electrostatic generator drop down to zero level. This behaviour is useful because it helps to avoid the mechanical damage of the vacuum chamber induced by the electron beam heating. After detection of the maximum leakage current the control program closes the electron gun and the high-voltage is restored without problem.

CASCADE TRANSFORMER

The key problem of the accelerating/decelerating column is transfer energy to 33 sections, gun and collectors are located at high voltage potential. The base idea of the power supply is based on idea of a high frequency cascaded resonant transformer. The system consists of 33 transformers with cascaded connection. The electrical energy is transmitted from section to section from the ground to high-voltage terminal. Along this way the energy is consumed by the regular high-voltage section. The main problem of such decision is leakage inductance of the transformers. They are connected in series and the voltage from power supply is divided between inductance leakage and a useful load. In order to solve this problem the special compensative capacitance is used. The impedance of leakage inductance is decreased significantly on the resonance frequency. The leakage inductance of one section is 41 μH, the compensative capacitance is 0.94 μF, the effective resistance of the power loss is 0.12 Ohm per section.

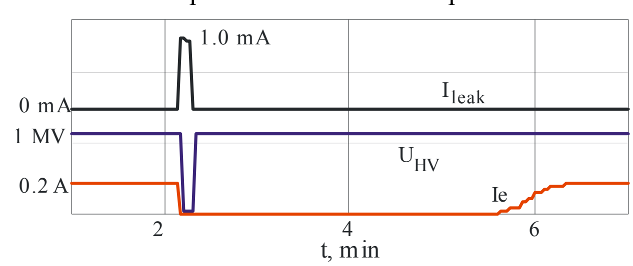

Figure 3: Collector current, voltage of the electrostatic generator and leakage current in time of the recuperation breakdown.

A problem was discovered for such type transformer. The problem induced by use of the simple type rectifier as power supply of the electron collector. The non-resistive and non-linear load leads to large dropping down of the voltage on the top of the cascade transformer because the cascade transformer has a good transfer coefficient for the fixed frequency only. Using the capacitance as load of the cascade transformer solves this problem but it increases the reactive current. In principle the power supply of the collector with impedance correction may be appropriate decision. The experiments with the operation of the cascade transformer loaded by a resistor result to the coefficient of voltage transfer 0.9 at 25 kWt power loading.

Figure 4a shows distribution of the auxiliary power supplies along accelerated column. At no-load operation the maximum auxiliary voltage is 200 V. Switching on the coil current in the high-voltage sections (7.0 kWt) reduces auxiliary voltage to 150 V. Adding the collector loading (0.5 A current, 4 kV voltage) changes the

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auxiliary voltage to 125 V (see Fig. 4b). The range of variation of the auxiliary voltage is 125-200 V that is sufficient for the possibility of the modern electronics modules.

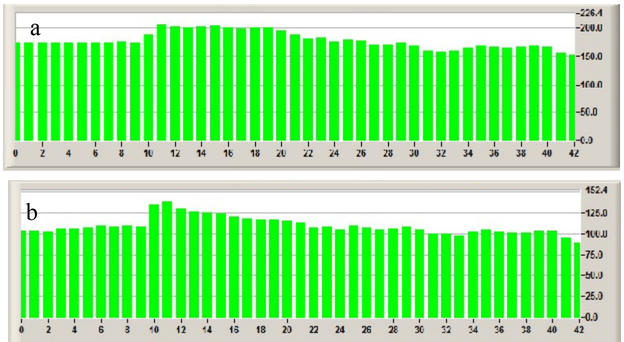

Figure 4: Distribution of auxiliary voltage along the accelerating column. The sections 10-42 correspond to column; the sections 0-9 are high-voltage terminal. The variant (a) is no-load operation of the cascade transformer, the variant (b) is operation at the nominal current in high-voltage sections (2.5 A) and the electron current 0.5 A in the collector.

DIAGNOSTICS

The beam line is equipped with several types of the beam diagnostics. The electron beam trajectory is measured by 12 BPMs. The sinusoidal modulation with amplitude 10 V at frequency 3 MHz is applied to the control electrodes of the electron gun and the AC component of the electron current is added to its DC value. Two BPMs located in the cooling section can work with proton component also. They will be used for alignment of the electron and ion beams.

The effective cooling and beam passing demands to minimize the electron angles and envelope oscillation of the beam. For this purpose the special electron gun with 4-sectors control electrode was designed and manufactured. The design of the gun is shown in Fig. 5. The modulation signal may be supplied to each sector of the control electrode. So, the position of one quadrant sector of the electron beam can be measured by BPM system. Comparing the positions of each sectors from BPM to BPM or the sector positions in the single BPM between the different values of the corrector coils it is possible to analyze the optics of the electron beam in the transport channel.

The control of the beam shape can be done independently by a set of the Faraday cups located in line05-4 (see Fig.8). The electron beam is shifted by the correctors on the diagnostics device. In order to minimize the load of the electrostatic generator the electron beam was modulated in the pulse mode (5 µs pulse at 20 Hz repetition rate). So, the electrostatic generator is able to work in nominal regime because the average DC current to the ground is small enough.

The efficiency of the cooling process strongly depends on a quality of the longitudinal magnetic field in the cooling solenoid section. The ripple of the force line of the magnetic field doesn't exceed angular dispersion of the ion beam. In order to control the quality of the magnetic field the special magnetic probe was designed, manufactured and located inside vacuum chamber. The basic idea of the probe is similar to devices used BINP and FermiLab [4] for the same purpose. The compass-based probe is located inside the vacuum chamber. The light beam generated by a laser falls to the mirror attached to the compass. The light beam is reflected and goes to a 4-segmented photodiode. Using a pair of differential signals from photodiode segments, the electronic feedback system generates currents in horizontal and vertical compensative correctors. The value of these currents corresponds to the transverse magnetic fields in the cooling section. Fig. 6 shows the design of the device. The main feature of the given probe is capability for the operation in the vacuum. Therefore the gimbal suspension was used instead of an organic polymers thread. This engineering solution decreased the accuracy of the probe but improved the mechanical strength of the device. The permanent magnets were replaced by the needles from a soft magnetic material. The measurable field is strong enough so there is no problem with sensitivity. But the probe should stand the baking at 200 ºC without loss of characteristics and soft magnetic material is suitable for this purpose. For mechanical stability of the mirror surface it was done from polish molybdenum without any additional reflected layer.

Figure 7 shows the transverse magnetic field in the cooling solenoid initially and after coils adjustment. The r.m.s. ripple of the magnetic force line was decreased from $6\cdot10^{-4}$ to $2\cdot10^{-5}$.

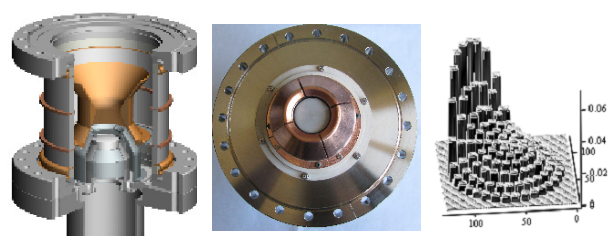

Figure 5: Design of the electron gun and 4-sectors control electrode. The right picture shows the distribution of the electron current when the control voltage is applied to the single sector.

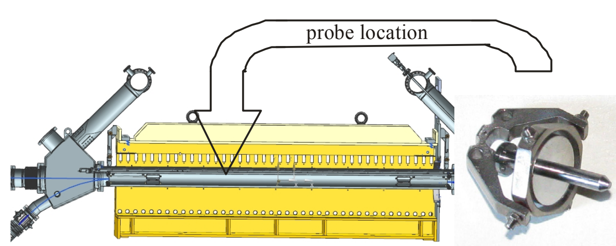

Figure 6: Schematic design of the magnetic probe in vacuum.

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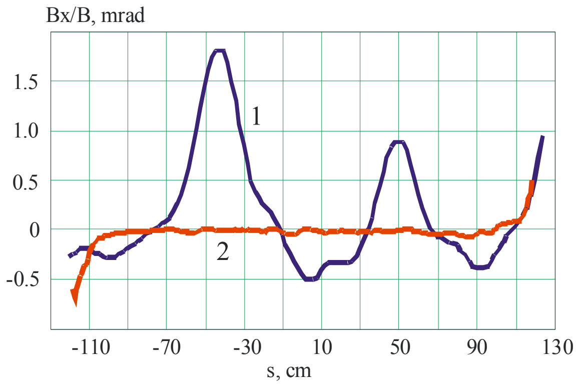

Figure 7: Horizontal magnetic field in the cooling solenoid initially (curve 1) and after few iteration of coil adjustment (curve 2).

ELECTRON BEAM PROPERTY

The adjustment of the trajectory of the electron beam was done with corrector sets (see Fig. 8) that may be divided on four groups. The first group controls the centre of the electron beam (bends and line17 elements). The second group controls the passing beam with large gradient of the longitudinal magnetic field (match and torbnd elements). The third controls fast Larmour oscillation of the electron beam (line10 elements). This corrector has minimal longitudinal size and located in the nearest place to the vacuum chamber in order to have minimal longitudinal length of the magnetic field. The forth set is located in the cooling section and controls the convergence of ion and electron beams (cool element).

The experimental analysis of the influence of magnetic elements on the electron trajectory was done by diagnostics tools. The typical scheme of experiments consists of the excitation of motion by a magnetic element, the phase incursion of the Larmour rotation changing magnetic field in the cooling section (cool, see Fig.8) and the registration of the beam position by BPM. Fig.9. shows moving of the centre orbit at the different value of the dipole corrector.

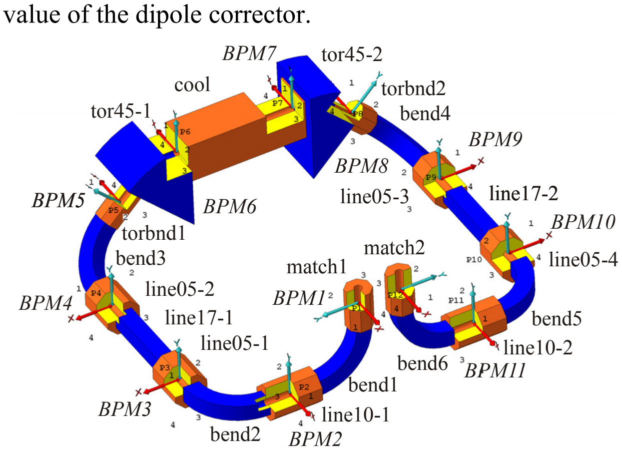

Figure 8: Location of the BPM (marked by arrows) and magnetic elements of COSY cooler.

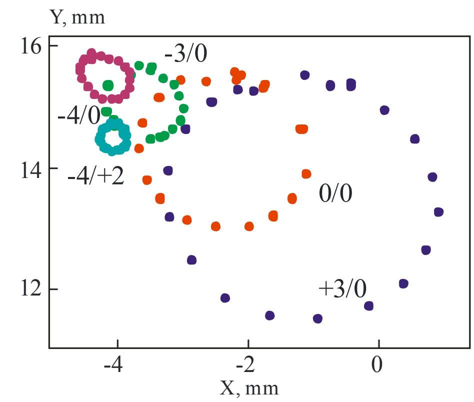

Figure 9: Larmour oscillation of the electron beam at the currents in the dipole correctors (line10-1). The numbers near curves are currents in the horizontal and vertical correctors. The electron energy is 1 MeV. The electron angle without correction is 40 mrad. The magnetic field in BPM region is 950 G.

Figure 10 demonstrates the possibility of the diagnostics tools for the diagnostics of the envelopes galloping modes. The coils of the dipole corrector were connected as quadruple magnet. The effect of such corrector is a distortion of the beam shape. The distortion oscillates along cooler with Larmour length. The galloping induced by match corrector coils is measured also but the pictures aren't visual. At the small amplitude of the galloping modes the Fourier transform enables to detect the amplitudes about 0.05 mm or less even at the total electron current 0.5 mA.

Figure 11 shows the necessity matching the longitudinal magnetic field to the electron momentum in order to the action of the edge field on the input and output of bend magnet compensates each other. The difference of the longitudinal magnetic field from optimum value 570 G on 20 G leads to excitation of Larmour oscillation with amplitude about 2 mm.

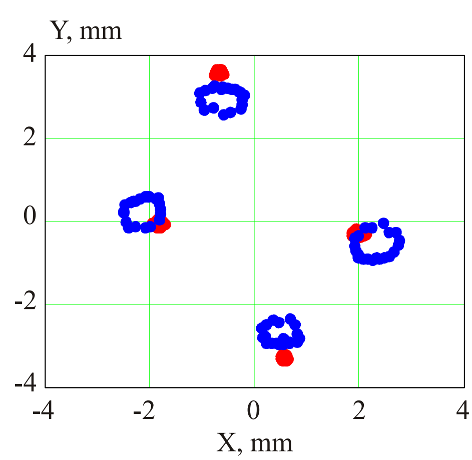

Figure 10: Envelope dynamics of the electron beam after quadruple kicks from the corrector located in line10. The electron energy is 150 kV.

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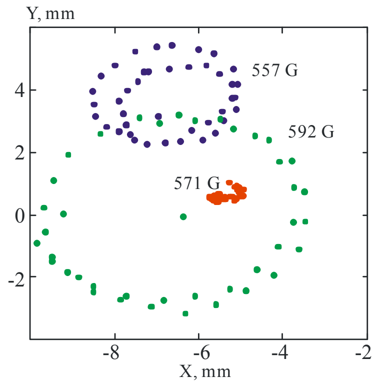

Figure 11: Radii of Larmour rotation at the different value of the longitudinal magnetic field in the bend magnets. The electron energy is 500 keV.

RECUPERATION STABILITY

The electron beam should stay for hours at the nominal energy and currents. Figure 12 shows the example of the long-term test at the electron current 200 mA and energy 1 MeV. Sometimes the recuperation breakdown occurs often and some time rarely. It seems that this behaviour can be improved by a training procedure. The physical nature of breakdowns isn't clear because any precursors weren't observed before breakdown. The spontaneous recuperation breakdowns were observed also at low energy (30 kV for example). Today the main hypothesis concerned with the fast changing of the vacuum condition in the accelerator tubes. It can be induced by some dust particle evaporation or the accumulation of the secondary ions. The ions can be trapped in the potential well formed by the electron beam. After reaching a threshold value the accumulated ions fast escape from the trap region to the vacuum chamber and accelerating tube which has negative potential respect to the ground. The pumping of the secondary ions with special device [5] slightly improves the situation with breakdowns but it doesn't solve this problem completely. Figure 13 shows the vacuum fluctuation that was observed in time of the operation. The typical vacuum value is a few 10^{-8} mbar. The fast peaks in the leakage current to high-voltage terminal are observed also. This current arrives to terminal region but isn't absorbed by the collector.

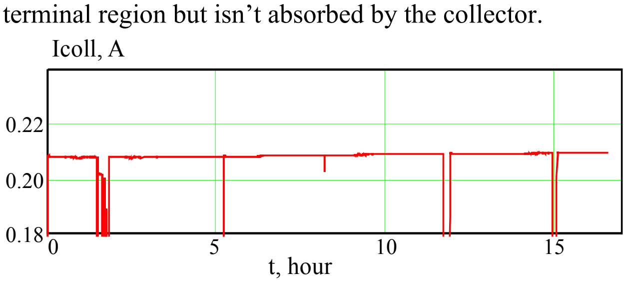

Figure 12: Collector electron current versus time. Fragment of 24 hours of running the electron beam.

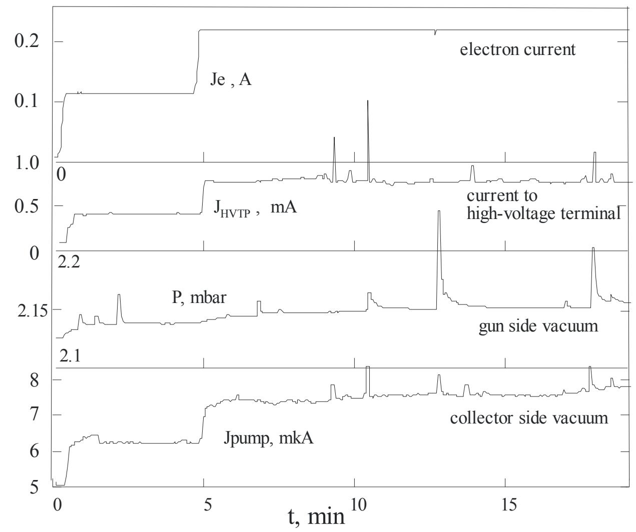

Figure 13: Electron current, leakage current to the high-voltage terminal, vacuum condition in the gun and collector sides versus time. Fragment of training of a new regime.

The important parameter for the stable operation of the high-voltage cooler is low leakage current. At the beam current about 500 mA the relative value of the leakage current was 10^{-6} - 10^{-5} in the different electron energy range.

SUMMARY

1. The key problems of the electron cooler 2 MeV (modular approach of the accelerator column, the cascade transformer, the compass base probe located in the vacuum chamber, the design of the electron gun with 4-sectors control electrode) is experimentally verified during commissioning in Novosibirsk.
2. The strong surprises aren't observed and the cooler are ready to assembly and commissioning in COSY.
3. The strong longitudinal field is useful for the electron beam transportation.

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