The Proposed 2 MeV Electron Cooler for COSY

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The Proposed 2 MeV Electron Cooler for COSY

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Abstract. The design, construction and installation of a 2 MeV electron cooling system for COSY is proposed to further boost the luminosity even with strong heating effects of high-density internal targets. In addition the design of the 2 MeV electron cooler for COSY is intended to test some new features of the high energy electron cooler for HESR at GSI. The design of the 2 MeV electron cooler will be accomplished in cooperation with the Budker Institute of Nuclear Physics in Novosibirsk, Russia. Starting with the boundary conditions of the existing electron cooler at COSY the requirements and a first general scheme of the 2 MeV electron cooler are described.

Keywords: Electron Cooling.
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INTRODUCTION

The COSY synchrotron accelerator and storage ring provides unpolarized and polarized proton or deuteron beams for internal or external hadron physics experiments in the momentum range from 300 MeV/c to 3.7 GeV/c [1]. Electron cooling is applied at low energies, at present mainly at injection energy, to prepare low-emittance beams to be used after acceleration and extraction for internal and external experiments. Stochastic cooling, covering the momentum range from 1.5 GeV/c up to the maximum momentum, is used to compensate energy loss and emittance growth at internal experiments.

Requests for future COSY experiments as WASA – a detection system from CELSIUS accelerator of The Svedberg Laboratory (TSL) at Uppsala with a pellet target [2] - are higher luminosities (> 10^{32} cm^{-2} s^{-1}).
There are two possible ways i) increasing the band width of the stochastic cooling system and/or ii) electron cooling up to maximum momentum. For operations with thick internal targets, fast (magnetized) electron cooling is the only technically feasible solution.

For electron cooling up to maximum momentum of COSY an electron cooler up to 2 MeV electron energy has to be developed together with the Budker Institute in Novosibirsk [3,4].

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EXISTING ELECTRON COOLER

The design of the existing COSY electron cooler represents the state-of-the-art in the eighties [5], see Table 1. The capability to produce a 3 A, 100 keV electron beam was demonstrated during various tests of the electron cooler. At present, only 25 keV beam energy is necessary for the proton injection energy of 45 MeV. Electron beam currents in the range from 50 to 440 mA were used for cooling tests. Higher electron currents are not useful because the advantage of shorter cooling times is foiled by drastically increasing proton beam losses. Currents of 170 to 250 mA have turned out to be appropriate for the physics experiments. The typical cooling time of about 10 s can be tolerated in view of the duty cycle.

TABLE 1. Relevant Electron Cooler and COSY Ring Parameters

COSY Electron Cooler	**Design Parameters**	**Used up to now**	
Mechanical Length (Drift Solenoid)	2.00		m
Effective Cooling Length	≈ 1.5		m
Beam Tube Diameter throughout the Cooler	0.15		m
Potential Tube Diameter in Toroids	0.065		m
Electron Beam Diameter	0.0254		m
Electron Beam Radius in Toroids	0.60		m
Magnetic Field Range	80 ... 165	80	mT
Maximum Electron Energy	100	24.5	keV
Gun Perveance	0.84		µP
Design Electron Beam Current at 100 keV	4		A
Design Electron Beam Current at 25 keV	1.8	0.05 ... 0.5	A
Collector Loss Factor	$\leq 5 \times 10^{-4}$	$1 \ldots 4 \times 10^{-4}$	
Vacuum Pressure in the Cooling Region	$5 \ldots 10 \times 10^{-9}$	5×10^{-9}	hP
COSY Ring			
Particles	Protons and Deuterons (unpolarized and polarized)		
Type of Injection	H^-, D^- Stripping Injection, 20 ...25 µg/cm^2 Carbon Foil		
Injection Energy	45 MeV for Protons, 76 MeV for Deuterons		
Shape of the Ring	Racetrack Type, Two Straight Sections and Two Arcs		
Nominal Circumference	183.473 m		
Dimensions of the Beam Tube	Round in Straight Sections, d = 0.15 m; Rectangular in Arcs, 0.15 m Horizontal (x), 0.06 m Vertical (y)		
Working Point Range	Variable Between 3.55 and 3.7 in Both Planes		
Optical Functions at the Electron Cooler	$\beta_x = 8$ m, $\beta_y = 16$ m, $D = -6$ m		

PROPOSED 2 MEV ELECTRON COOLER

Basic Parameters and Requirements

The basic parameters and requirements are listed in Table 2. The most important restrictions are given by the available space at the COSY ring itself. The height is limited by the building up to 7 m, the length of the cooler in beam direction by the existing electron cooler and the ring itself to 3 m. The acceleration of polarized beams at COSY must to be taken into account. Space for compensating magnets must be foreseen to achieve conservation of polarisation.

TABLE 2. 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
Cooling Length	3 m
Toroid Radius	1.5 m
Variable magnetic field (cooling section solenoid)	0.5 ... 2 kG
Vacuum at Cooler	10^{-8} ... 10^{-9} mbar
Available Overall Length	7 m
Maximum Height	7 m
COSY beam Axis above Ground	1.8 m

Cooling of 2 GeV Proton Beam at COSY

Calculations are performed with the trubs.exe code [3], in which the cooling force is approximated by the well known Parkhomchuk formula [6]. The effect of intra beam scattering is included by the simple model of relaxation distribution velocity. The increase of the angle spread due to scattering of an internal target is also taken into account. The simulation was made with following parameters: cooler length 3 m, beta function in the cooling section 13 m, electron beam radius 0.5 cm, electron beam current 2 A, magnetic field 2 kG, initial normalized emittance 10^{-6} m rad, 2 GeV proton beam energy and number of protons $2 \cdot 10^{10}$ (5 mA).

As it is seen in Fig. 1, the ion beam emittance is effectively decreased during 10 s. The reached equilibrium emittance is a result of balance between intra-beam scattering and electron cooling.

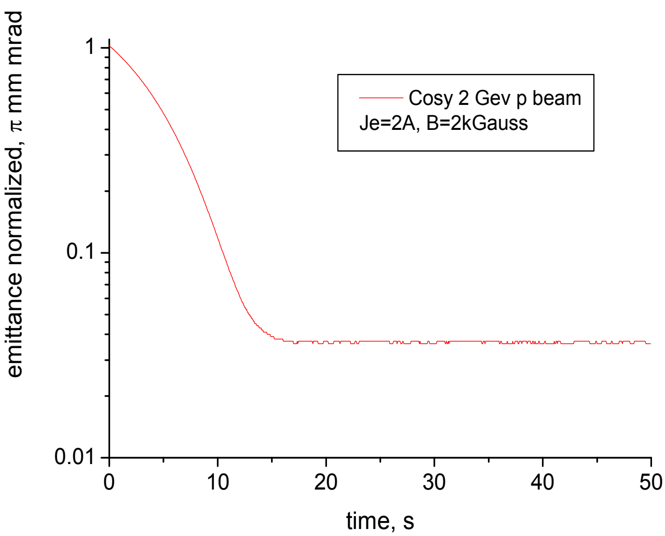

FIGURE 1. Normalized beam emittance versus time at electron cooling of 2 GeV proton beam (without target, parameters see text).

The presence of a target introduces multiple scattering which will be suppressed by the cooling and single scattering at large angles. The single scattering on the aperture limit leads to losses of proton current and can be described as life time of the proton beam. Figure 2 shows the proton beam current versus time with and without target.

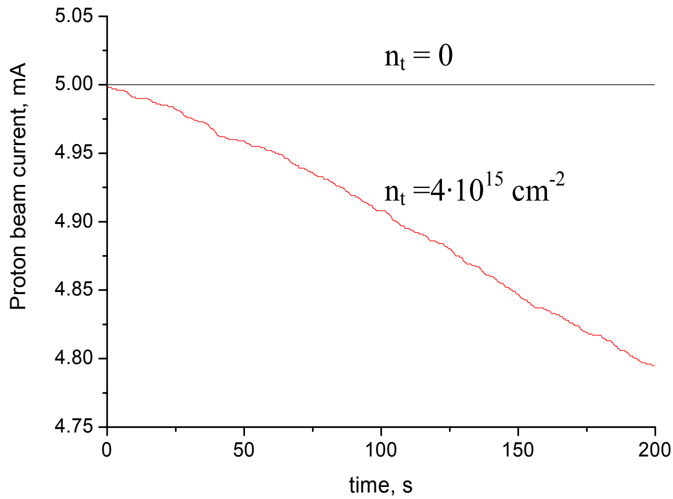

FIGURE 2. Proton beam current versus time with and without target (n_t – target density, parameters see text).

Without target we do not observe any losses of proton beam but with target the life time of the proton beam inside an aperture at the cooling section of 1 cm is about 5000 s. The single scattering at angles larger than the equilibrium but less than the aperture limit leads to formation of beam tails in the distribution.

Preliminary Cooler Technical Design

The proposed electron cooler consists of a high voltage vessel with electrostatic acceleration and deceleration columns, two bending toroids and cooling drift section. The preliminary scheme of the cooler is shown in Fig. 3 [3]. The basic features of the design are i) the longitudinal magnet field from the electron gun to the collector, in which the electron beam is embedded, ii) the collector and electron gun placed at the common high voltage terminal and iii) the power for magnet field coils at accelerating and decelerating column is generated by turbines operated on SF_6 gas under pressure. The gas flux which drives the turbines is also used for cooling the magnetic coils and for keeping the temperature inside the vessel constant. The cathode of the electron gun is immersed in the magnetic field. The electron beam is accelerated to an energy up to 2 MeV. After that the electron beam is bent in the toroid and is guided to the cooling section. After the main solenoid the beam is returned to the electrostatic column. Here it is decelerated and is absorbed in the collector located in the head of the electrostatic column. Each toroid consists of two parts. The first one bends the magnetized electron beam in the vertical plane on 90^0. The second one bends the electron beam on 180^0 in a plane, which is inclined on 45^0 to the vertical plane. Such a complicated 3-D geometry provides compactness of the system. The dipole kick for protons in the bending toroids near the cooling section will be compensate by dipole magnets which will be installed near the large toroid coils as close as possible. The Electrons receive dipole kicks due to the inhomogeneity of the magnetic field. These kicks must be compensate by electrostatic kickers which will be inserted in front of the cooling section. Electrostatic bending for better recuperation efficiency will be used [7,8].

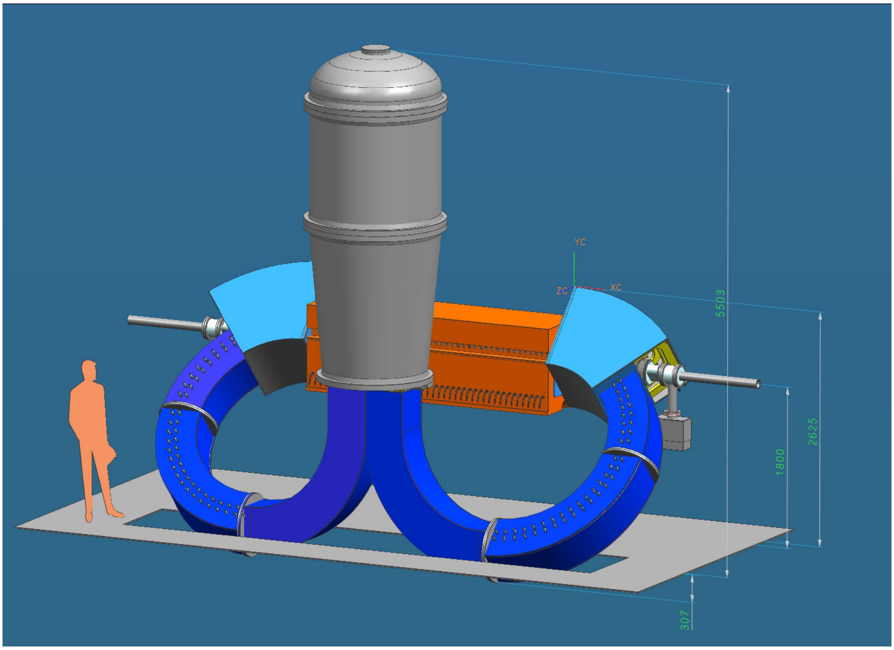

FIGURE 3. Layout of the proposed 2 MeV electron cooler for COSY.

High Voltage System

The high voltage system consists of the vessel, the accelerating and decelerating column, high voltage sections and high voltage head with gun and collector. For the vessel and column the main parameters of the industrial accelerator ELV-8 which works on 2.5 MV are taken [9]. The vessel geometry is identical to the vessel of the ELV-8. The vessel withstands pressures up to 10 bars. The diameter of the high voltage sections amounts to 80 cm. At the ELV-8 accelerator SF_6 gas is used as insulation gas. The ELV-8 has no magnetic coils inside. The electron current is equal to 0.05 A. The beam power is 100 kW. Budker Institute has experience in recuperation of high voltage beams with an energy of 1 MeV and a current of 1A [10].

The high voltage sections (Fig. 4) contains: high voltage power supply, coils for the magnet field along acceleration and deceleration columns, power source and control units for measurement and control of parameters for each section.

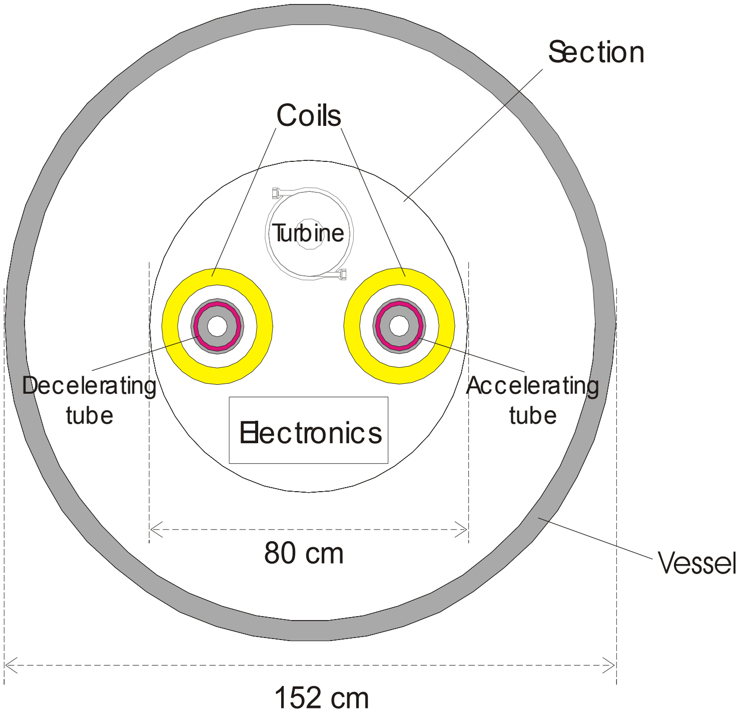

FIGURE 4. High voltage section

The experience from the Budker Institute in the design of high voltage sections with ± 30 kV is used. Each section has two high voltage power units on 30 kV. Using of two power units allow to decrease the voltage for insulation from 60 kV to 30 kV.

Using 60 kV for the sections (±30 kV) means that the whole 2 MV column consists of 34 sections. The electric field between the sections will be 30 kV/cm. The pressured SF_6 gas can be used for protection from sparking. At a pressure of about 10 bars an electric field strength of up to 500 kV/cm can be stable operated [11].

Computer simulation of the electric field distribution at the high voltage column showed that the maximum electric field strength occurs at the edge of the upper section and amounts 132 kV/cm. To suppress sparking a SF_6 gas pressure of about two bars is sufficient in this case [11].

Special measures must be taken to prevent destructions from sparks. Accelerating rings are surrounded by collar rings. The width of the gaps between the collar rings are chosen in a manner that in case of a discharge, it occurs between the collar rings.

Magnetic Field at the Acceleration Tube

The magnetic field at the cathode of the electron gun and at the drift section define the electron beam radius in the cooling section. The electron beam size should be close to the proton beam size for effective cooling. The proton beam size at low energies is larger than at higher energies. For a cathode radius of 1.5 cm in the low energy case the magnetic field in the electron gun should be the same as the magnetic field at the cooling section. But in the high energy case it is difficult to obtain an optimal ratio of magnetic fields. A maximum magnetic field in the cooling section of 2 kG corresponds in the gun region to a magnetic field of 150 G. The minimum necessary magnetic field in the electron gun is limited by the space charge of the electron beam inside the anode region which requires a higher field. With an electron current of 3 A the minimum value of the magnet field is 120 G. But the experiments with electron coolers built by the Budker Institute shows that for magnetic fields a few times higher (about 250-300 G) the normal regime of recuperation of the beam became very sensitive and very often crashed. For safe operation the magnetic field value in the electron gun should be about 1 kG. Along the acceleration tube it is not easy to realize the electric power for the 1 kG magnetic field coils. But in the acceleration tube the electron beam has an energy higher than in the cathode region and therefore a magnetic field of 0.5 kG is sufficient. The diameter of the acceleration tube ceramic rings is about 120 mm and the pancake coils for the magnetic field can be made with inner diameter 240 mm, external diameter 320 and thickness 40 mm. These coils are installed at each HV section along acceleration and deceleration tubes with an gap of 20 mm. The consumption of electric power for one coil at a section with a value of magnetic field of 500 G is equal 130 W (for filling efficiency of copper 0.7, weight of a single coil 6.7 kg). The current density at each coil amounts to 2.1 A/mm^2.

For maximal voltage of 60 kV the high voltage power at each section is about 60 W. For powering of the high voltage sections a mechanical generator with a maximum electric power of 0.5 kW with enough power reserve will be used.

The electron gun and the electron beam collector are placed very close to each other. In the electron gun a magnetic concentrator (magnetic steel) is used to increase the magnetic field by a factor of two from 500 G at the column solenoids to 1000 G at the surface of the cathode. The gun concentrator also improves the field homogeneity at the cathode surface. The collector magnetic shielding is used to decrease the magnetic field to spread the electron beam inside the collector. The fast decreasing magnetic field at the collector entrance produces a magnetic mirror for the soft secondary electrons emitted from the collector due to bombardment from the primary electron beam. The magnetic mirror together with the electrostatic suppression electrode suppress secondary electron emission.

To adjust the electron beam radius in the cooling section the magnetic field at the cathode of the electron gun will be changed with additional coils. Increasing the magnetic field up to 1000 G is possible. Decreasing magnetic field is achieved by reversing the current direction in these coils.

The power consumption of the complete magnetic system including the coils of the high voltage column, toroids and cooling section amounts to 280 kW. The total mass of copper is about 2.7 tons.

Electric Generator at the High Voltage Section

The simplest system of powering the high voltage sections and power supply for the magnetic field is a mechanical electric generator. The most popular system consists of a electric engine on ground potential and an insulation shaft (plastic) which transfers power to an electric generator on high voltage potential. In the present case too many generators (>35) along the acceleration column and to the high voltage terminal would be necessary. The twisting moment of the shaft for the first generator would be 35 times larger than for the last one. Vibrations of the whole system could be an other disadvantage. Therefore turbo engines with integrated electric generators at each section are proposed. A compressor at ground potential will pump SF_6 gas from the vessel, compress it to 4-5 bar and feed it to a thermo exchange chamber and gas filter. After this the pressurized gas is directed with plastic tubes along the high voltage column. At each section the pressurized gas is used to drive a turbo generator for production of the electric power and after this the gas is used for cooling and regulating the temperature constant.

The electron cooling requires very low level of high voltage ripple, less than $\Delta U/U<10^{-5}$ over the whole dynamic voltage range (0.025 – 2 MV). For simplification of the high voltage power supply it is possible to use for low voltage only 1 section. In this case, instead of 60 kV, this section will operate on a voltage of 25 kV.

At each section an optical communication block, few DAC for control of magnetic coil current and high voltage power supply (0-60 kV) and few ADC for measuring parameters of section operation should be installed.

Matching Section

After acceleration in the longitudinal magnetic field of 500 G electrons enter into the toroid with a field of 2000 G. This transition excites transverse motion to a big temperature which is unacceptable for electron cooling. Therefore a special matching section is foreseen to smooth the magnetic field in the transition.

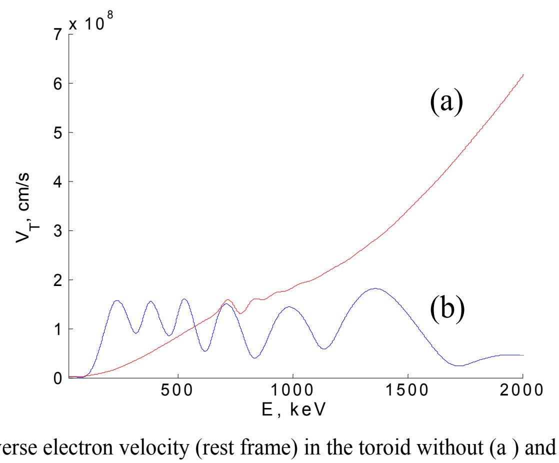

FIGURE 5. Transverse electron velocity (rest frame) in the toroid without (a) and with (b) matching section.

SUMMARY

The development of a 2 MeV electron cooling system for COSY is essential for the future COSY physics program, it delivers higher beam quality and higher luminosity.

The operation of a 2 MeV cooling system at COSY together with a high-density internal target of WASA detector would uniquely allow to optimize the cooling performance for "tail" particles. This involves both the electron cooling system alone and a combination of the electron and stochastic cooling systems. Realization of such a cooling system will be an important step toward creation of a novel experimental technique aiming to reduce significantly parasitic effects related to halo in accelerated beams – a step to "backgroundless" detection systems.

For operations with thick internal targets, fast (also known as *magnetized*) cooling is the only technically feasible solution. Engineering design of a magnetized cooling system would be sufficiently different from the Fermilab 4.3-MV system [12] to warrant a dedicated effort to design a 2-4 kG warm or superconducting solenoid of a high field quality. The 2 MeV COSY electron cooler would be an intermediate energy step to future high-energy magnetized cooler projects like the HESR high energy electron cooler in the FAIR project [13] and would be extremely useful for finding optimal technical solutions and prototyping many elements.

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