STATUS OF DESIGN WORK TOWARDS AN ELECTRON COOLER FOR HESR*

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Abstract

The HESR-ring of the future FAIR-facility at GSI will include both electron cooling and stochastic cooling in order to achieve the demanding beam parameters required by the PANDA experiment. The high-energy electron cooler will cool antiprotons in the energy range 0.8 GeV to 8 GeV. The design is based on an electrostatic accelerator and shall not exclude a further upgrade to the full energy of HESR, 14.1 GeV. The beam is transported in a longitudinal magnetic field of 0.2 T and the requirement on the straightness of the magnetic field is as demanding as 10^{-5} radians rms at the interaction section. Furthermore, care must be taken in order to achieve an electron beam with sufficiently small coherent cyclotron motion and envelope scalloping. This puts demanding requirements on the electron beam diagnostics as well as the magnetic field measuring equipment. Prototype tests of certain components for these tasks are being performed. The paper will discuss these tests and recent development in the design including the high-voltage tank, electron gun and collector, magnet system, electron beam diagnostics and the magnetic field measurement system.

INTRODUCTION

The High Energy Storage Ring (HESR) is a part of the future FAIR facility [1] and will be dedicated to Strong interaction studies with antiprotons in the momentum range of 1.5 to 15 GeV/c. In order to meet the demanding requirements of the experiments both stochastic cooling [2] and electron cooling will be employed. Electron cooling is needed, in particular, to reach the low momentum spread requirements for the high-resolution mode of PANDA.

The design work of HESR is carried out in a consortium formed between FZ Jülich, GSI and Uppsala University. Earlier studies of the electron cooling system for HESR were carried out by the Budker Institute of Nuclear Physics (BINP) and GSI [3].

The design of the high-energy electron cooler is based on an electrostatic accelerator and will be used to cool antiprotons in the energy range 0.8 GeV to 8 GeV. However, the design should not exclude a future upgrade to the full energy of HESR, 14.1 GeV. This was one reason to base the design on a Pelletron which is modular and is possible to extend in energy. [4]. A similar electron cooling system is in operation at Fermilab [5].

The PANDA experiment will use an internal target, most probably a hydrogen pellet target. The cooler will have to compensate for the effects of this target on the antiproton beam. For this to take place efficiently, magnetised cooling is required. The details of the interaction between the target effects and electron cooling in HESR are further discussed in Ref. [6]

Technical Challenges

One challenge for the electron cooler design is beam alignment between electrons and anti-protons. The deviation of the electron beam relative to the anti- proton beam should be smaller than 10^{-5} radians rms to fulfil the beam quality and lifetime demands of the anti-protons. This requires very accurate procedures for beam diagnostics and alignment along the 24-meter interaction section.

Another difficult requirement on the solenoid is that the magnetic field must be continuous enough, that the straightness of the magnetic field, measured within 5 mm distance from the nominal path of the electron beam must be within 10^{-5} radians rms.

The field must also be continuous enough or shaped so than an electron beam with diameter 10 mm and energy anywhere in the range from 0.45 to 8 MeV must not be “heated” by any variation of the magnetic field. The dipole and envelope oscillations created by the total effect of all such transitions in the system should be smaller than a corresponding Larmor radius of 0.1 mm.

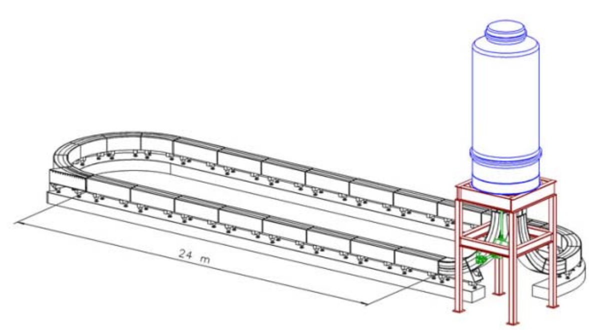

Figure 1: Layout of the HESR electron cooler showing the Pelletron tank and the beam line system of solenoid magnets. The length of the interaction section is 24 m.

MAGNET SYSTEM

The Layout of the HESR Electron Cooler is shown in Fig. 1. The electrons are produced by the gun in the high voltage tank and circulate the beam transport system before being captured by the collector. The beam transport system is 94 meter in total and has been divided into several sections listed in Table 1.

Table 1: Overview of the different sections in the magnetic field system.

Section	field strenght [T]	length [m]	angle [degree]	number of pancakes
Acceleation column	0.07	4		15
Transition	0.07- 0.2	3		22
Entrance bend	0.2	6	90	48
Interaction straight	0.2	24		184
Exit bend	0.2	13	180	96
Return straight	0.2	25		192
Horizontal return bend	0.2	6	90	48
Vertical return bend	0.2	6	90	48
Transition	0.2 - 0.07	3		22
Deceleration column	0.07	4		15
Total		**94**	**450**	**690**

The Solenoid Field

The magnetic field strength outside of the high voltage tank is 0.2 T and has been chosen according to the following criteria:

- The electron beam size at interaction straight should be of the same size as the antiproton beam which is of the size 5×5 mm (including 50% of particles). This puts an upper limit of the solenoid field to 0.2 T because in the acceleration column, there is an aperture limit of one inch. With 0.2 T and some safety margins this corresponds to an electron beam diameter of 10 mm at the interaction section.
- A strong solenoid field enhances the cooling force. To get fully magnetised electrons in HESR, more than 0.2 T is required. Recent force calculations show however that magnetised cooling appears at lower field strength.
- One technical challenge associated with electron beam transport is generation of Larmor oscillations, especially at high energy and low solenoid field. Therefore, all the bending should take place at highest possible field strength.

The field transition between 0.07 T and 0.2 T takes place semi-adiabatically over two meter long sections which reside half inside and half outside of the high voltage tank. The excess magnetic flux is returned without need of long return bridges.

On high voltage there are limitations in both generating and cooling away of power in the tank column. The solenoid field in the acceleration and deceleration columns is therefore limited to 0.07 T.

The over all bending radius is chosen to be 4 meters to reduce generation of Larmor oscillations. This choice also allows for electrostatic centrifugal drift compensation in the case the collector efficiency will be lower than expected. Secondary electrons can then travel back and forth between the gun and collector until its energy is restored to the average electron energy.

Modules

The electron beam transport system outside of the high voltage tank is divided into a number of manageable modules, see Fig. 2. These modules are about three meters at the straight sections and two meters in the arcs, corresponding to a bending angle of 30 degrees. The modules consist of short pancake solenoids mounted in a rigid iron stand. The pancake solenoids can be adjusted individually to a high precision [7].

The modules are designed to be mechanically rigid so that floor instabilities or other mechanical shifts should not deform the modules. Corrector windings of the same length as the modules will be used to correct the direction of the magnetic field.

During build-up or after repair the modules will be brought into the beam-line fully equipped with the solenoids pre-aligned to give the required field straightness. Thereafter the modules will be aligned mechanically relative to each other and to the HESR ring.

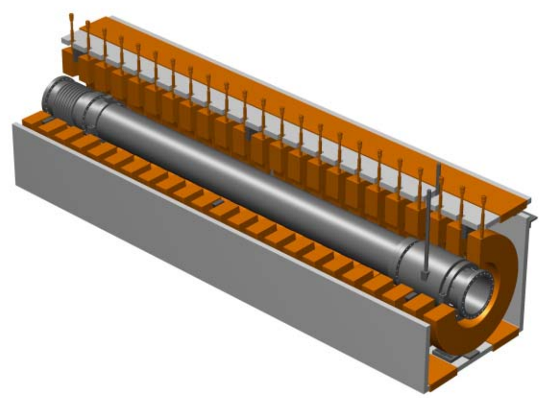

Figure 2: Each straight module on the interaction straight includes: 23 pancake solenoids, four corrector windings, a vacuum chamber with diagnostic unit and bellows.

Pancake Solenoids

The design parameters of the pancake solenoids are summarized in Table 2 and have been chosen to meet the following requirements:

- Generate a homogenous field. The magnetic field along the interaction straight must be continuous enough, that the straightness of the magnetic field, measured within 5 mm distance from the nominal path of the electron beam must be within 10^{-5} rad. rms. This is to ensure that accurate field measurements can be carried out.
- Make room for diagnostics and bakeout equipment.
- Allow assembly, especially to fasten 24 bolts on the Conflat flanges between adjacent modules.
- Minimize cost (copper and power consumption)

Table 2: Parameters for pancake solenoids

Pancake Solenoid Parameters		
Inner radius	R	170 mm
Period	L	130 mm
Wire dimension	δ	13 mm
Width	D	80 mm
Height	H	145 mm
Number of turns	N	63
Conductor		
Copper cross section	A_{CU}	116 mm^2
Cooling water hole	D	∅ 6 mm
Length	λ	96.5 m
Weight	M	100 Kg
Power consumption		
Current	J	328 A
Power consumption	P	1.8 kW
Voltage	U	5.5 V

ELECTRON COOLING OPTIMIZATION

Straightness of the Longitudinal Magnetic Field

The straightness of the longitudinal magnetic field at the interaction straight section is an important parameter in order to reach the necessary cooling force. As already mentioned the straightness has to be adjusted to 10^{-5} rad. rms. It should be possible to verify the magnetic field straightness without opening the vacuum system.

A prototype straightness measurement system, which is UHV-compatible, has been designed and manufactured. The system is based on a compass needle sensor and consists of a carriage with wheels that can be moved along the interaction straight under vacuum. The vacuum tube at the interaction section is made of aluminium and has integrated rails which the wheels rest on. The sensor should be kept in a position closer than 5 mm from the symmetry axis.

Similar devices have been used for verification of the straightness of the magnetic field lines in much shorter electron cooling systems. [8] Also, previous devices have not been designed to be ultra-high vacuum compatible.

The magnetic field sensor has been designed and manufactured by BINP [9, 10]. The design goal is to measure the field direction with a resolution of 2×10^{-6}. The sensor mounted in its dedicated holder is shown in Fig. 3. The entire magnetic field measurement system is presently being tested at TSL.

Figure 3: Carriage used for magnetic field measurements (left). Compass based sensor mounted in dedicated holder mechanism (right).

Alignment Between Electrons and Antiprotons

The antiproton beam needs to be made parallel or accurately tilted with respect to the direction of the straight magnetic field within 2×10^{-6} radians (50 µm over 24 m).

To minimise deviations of the electrons relative to the antiprotons, beam-based alignment will be applied. The offset of the electron beam relative to the antiproton beam will be measured and corrected for using the corrector windings. This requires pick-up electrodes in each module with a resolution of 10 µm.

Suppression of Dipole Oscillations

Coherent dipole oscillation will be kept to a minimum by applying beam matching of high accuracy. The corrector windings in arcs will be used to generate the bending field. The angles of the pancake solenoids are adjusted so that the solenoid field matches a reference path determined by the bending field. Simulations using TOSCA have been carried out showing that the matching can be made so that beam dipole oscillations are reduced to the required Larmor radius of 0.1 mm. Electron beam diagnostics (see next Section) and correction systems will be used to detect and quench remaining oscillations.

Suppression of Beam Envelope Oscillations

The solenoid of merging modules is made out of ordinary and racetrack shaped pancakes. To make the solenoid field uniform along the electron reference path extra current will be added to the ordinary power supply.

Electron beam diagnostics (see next Section) and correction systems will be used to detect and quench remaining oscillations.

ELECTRON BEAM DIAGNOSTICS

First of all, it will be necessary to commission the electron beam diagnostics to establish a recirculating electron beam. A pulsed electron beam is used to start with, and it will be necessary to measure its position along the beam transport system. Once recirculation is established, it will be necessary to measure the alignment of the electron beam to the antiproton beam most accurately in order to achieve the required alignment angle of 10^{-5} rad. rms. An even more challenging task will be to measure the envelope oscillation of the electron beam. The following list of different types of electron beam diagnostics elements is anticipated:

- Integrated beam position monitor and scraper unit. 9 units.
- Beam position monitors. 6 units.
- Beam loss monitors. 18 units.
- Beam profile monitors: OTR (Optical Transition Radiation) devices. 3 units.

Integrated Pick-up and Scraper

In the interaction straight section of the electron cooler there will be 9 pairs of beam position monitors, horizontal and vertical. Due to space limitations, the position monitors have to be integrated with scrapers. A prototype of such a device has been designed and manufactured and will be tested at TSL, see Fig. 4. This unit has been named SPUC, Scraper and Pick-Up Combined.

The position monitor consists of 4 electrodes that together form a cylinder. The radius of the electrode cylinder is 100 mm. The radius of the cylinder behind the electrodes in the position monitors is 125 mm. This cylinder is kept at ground potential. The length of the monitor is 200 mm. The radius of the vacuum chamber at the position monitor is 134 mm. The radius elsewhere of the vacuum chamber is 100 mm.

Between the electrodes there are four plates, which are at ground potential. Two of these plates are used as scrapers, the two plates positioned to the right and to the left of the vacuum chamber centre. These two plates are possible to fold in towards the centre of the vacuum chamber. At the end of each of these plates there is an orifice with a diameter of 10 mm. The electron beam will pass through this orifice.

When the scraper plates are folded in to the beam centre the unit acts as a scraper, and when the scraper plates are in their parking position, the unit acts as a position monitor. The scraper will mainly be used to measure the envelope oscillation of the beam.

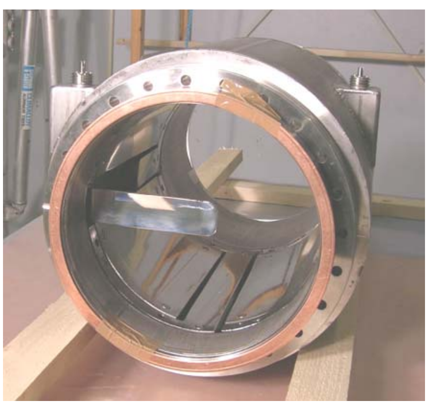

Figure 4: SPUC prototype. (Before the orifice is drilled in the scraper.)

GUN AND COLLECTOR

Electron Gun

The electron gun has a similar design as the one at the Fermilab cooler [11]. The main difference is that the cathode diameter is increased from 7.6 mm to 10 mm and that the magnetic field at the cathode is increased from 0.02 T to 0.2 T.

The parameters of the electron gun are

Anode voltage	26	kV
Beam current (max)	1	A
Cathode diameter	10	mm
Cathode field	0.2	T

The gun has a negatively biased control electrode which can be used for production of a pulsed beam and for fast closing of the gun. Simulation of the electron optics in the gun has been carried out using the UltraSAM [12] code.

Electron Collector

The design of the collector is also based on the Fermilab collector [11, 13] and assumes that the collector size is large enough and the collector perveance is low enough to suppress the secondary electrons by applying a transverse magnetic field to the collector cavity. The transverse component of the magnetic field in the cavity is created by permanent magnets and two iron plates outside the chamber. An electrode near the collector entrance, the collector control electrode, can be used for fine tuning of the primary beam envelope. Its operational potential is close to the one of the collector.

The collector cavity consists of a stainless steel bottle, inside of which a cylinder of OFHC copper is brazed. The copper cylinder has water channels for cooling. The power deposited by the beam is 5 kW (at a beam current of 1 A and a collector voltage of 5 kV) and the beam spot diameter is about 60 mm.

Simulations of electron optics in the collector have been carried out using the UltraSAM [12] code (2D with space charge) and with Mag3D and TOSCA (3D without space charge).

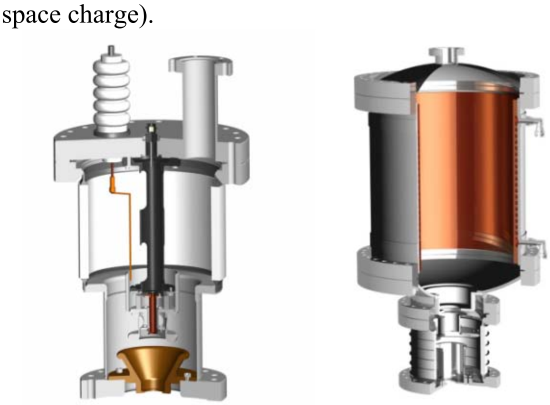

Figure 5: CAD drawings of electron gun (left) and collector (right). The components generating the magnetic field are not shown.

HIGH-VOLTAGE SOLENOID

The high-voltage solenoids are used to create a longitudinal magnetic field in the accelerating tubes of the Pelletron. The solenoids are mounted on the separation boxes in the high voltage column. The separation boxes with attached solenoids are cooled by convective heat transfer to the surrounding SF6 gas.

The coil consists of 690 turns of enamelled copper wire with a cross section of 3 x 7 mm. The coil consists of two concentric windings separated by an aluminium ring. The coil is surrounded by an aluminium cover. The distance between the solenoids in the accelerating column is 0.305 m centre to centre. A current of 25 A generates the desired average field of 0.07 T in the accelerating column.

A prototype solenoid has been designed and manufactured. To test the principle of cooling it has been mounted on an aluminium box with geometry similar to a real separation box. The cross section is shown in Fig. 6.

Test Set-up and Measurements

The solenoid was mounted on a test "separation box". The surface flatness of the separation box was < 0.1 mm. The separation box was cooled by a tangential fan blowing air (16° C, 20 liters/s) between the two aluminium plates. The distrubution of temperatures at steady-state (24 h) applying 25 A are shown in Fig. 6.

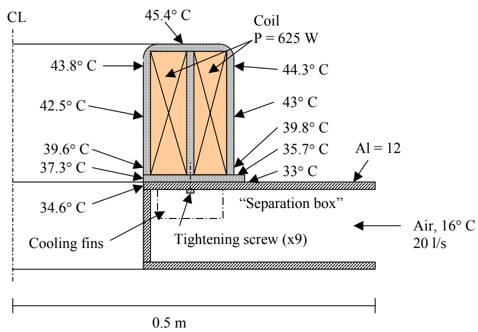

Figure 6: Cross section of the solenoid mounted on the test separation box and the measured steady-state temperatures (after 24 hours) on the surface.

The average coil temperature rise was calculated from the resistance variation assuming that the temperature coefficient of copper $\alpha = 0.00393$, see Fig. 7.

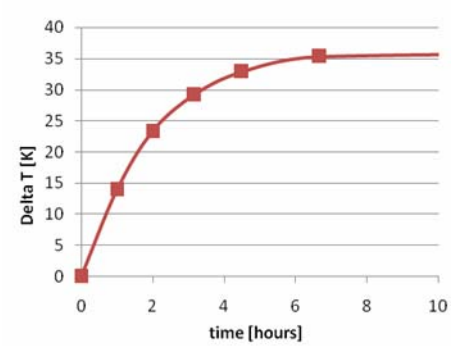

Figure 7: Average coil temperature rise with current 25 A (P=625 W after 8 hours).

Simulations

Simulation of heat transfer in the solenoid has been done with COMSOL Multiphysics, see Fig. 8. Uncertain parameters in the simulations are heat transfer coefficients between solenoid and separation box and between the conductors in the coil. Comparisons between measurements and simulations will be used to determine the heat transfer coefficients.

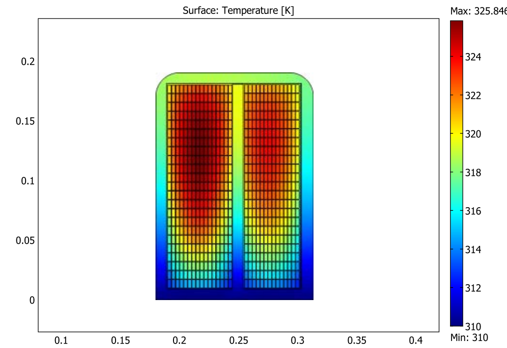

Figure 8: Simulation of temperature distribution in a cross-section of the coil. The temperature of the bottom surface is fixed at 310 K (=37° C). The other surfaces are isolated.

Conclusions

The maximum temperature inside the coil must be kept below 70° C to avoid epoxi softening.

The tests show that this can be achieved by:

- Cooling the SF6 gas to 20 ° C.
- Forced circulation of SF6 inside separation box.
- Good thermal contact between solenoid and separation box.

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