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Abstract. The subject of the report is the problem of the technical feasibility of fast electron cooling in the energy range between 0.8 and 14.5 GeV. It is very useful for one of the major objectives of the GSI and COSY future plans. For the realization of the cooler device BINP team proposes the design that is like the conventional and elaborated for the low energy cooling (up to 300 keV). The main features of this design are the accelerating tube immersed in the magnetic field along the whole length and the strong magnetic field in the cooling section. The physics of electron cooling is based on the idea of the fast magnetized cooling. The cooling force at strong magnet field was measured at many experiments and can be surely estimated. The magnetized cooling rate enables to obtain the required beam parameters, eliminate the beam heating due to intrabeam scattering, fluctuations of ionization energy losses and multiple scattering in the internal target

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DIFFERENT SOLUTION FOR ELECTRON COOLER DESIGN

The technical realization of the medium energy electron cooling can be done with different variants. The first method is an electrostatic machine. This method is conventional and elaborated for the low energy cooling (up to 300 keV) [1-2]. The research program of 4.3 MeV electron cooling device is carried out at FNAL/USA [3-4]. Electrostatic machine has the advantage of small spread of the electron beam energy and it provides the continuous electron beam without any time structure that is a good for the cooling of the coasting antiproton beam. Moreover it enables to vary the electron energy in wide range that is necessary for HESR research program.

The second method is an RF linear accelerator. A problem in using of the RF accelerator for the electron cooling device is the requirement to maintain extremely low values of the spreads of longitudinal and transverse momentum ($\Delta p_{||}/p_{||}$ and $\Delta p_{\perp}/p_{\perp} \approx 10^{-4} - 10^{-5}$) at the maximum length of the electron bunch. At the electron energy about 8 MeV the energy spread is few units of 10^{-4} may be attainable. A further improvement of the stability of the electron beam parameters by regular methods like thermostabilisation of the cavities, using feed backs and etc seems problematic. So, the special efforts need for the cooling of antiproton beam to the extremely low value of the longitudinal momentum spread. Another serious problem is the variation of the

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cooling energy in the wide range. It is probably impossible to do it in the whole energy range from 0.44 to 7.9 MeV because of the large variation of the electron flight – time through an RF resonator. The more realistic variant is to restrict oneself by the more narrow energy range 5–8 MeV. Thus, RF linac is not reasonable choice for this project, but it is most likely next milestone in the manufacture of electron coolers. The electron beam energy about 8–10 MeV required for this project seems to be close to the maximum attainable value for electrostatic type of accelerator. The project of the high relativistic electron cooler (electron energy 55 MeV) is designed at BNL/USA [5].

To avoid the problems of the traditional electron cooling system the cooler based on the "modified betatron" scheme was proposed in [6-7]. The electron beam circulates in longitudinal (quasitoroidal) magnetic field. The long-term stability of the beam is provided with additional spiral coils. The magnetic field of such device is similar to the "stellarator" one. The acceleration of the electron beam is produced by using induction (betatron) acceleration. This type of the acceleration is very cheap, enables to obtain coasting (continuous) electron beam and does not induce coupling between the longitudinal position of an electron and its energy in contrast to RF linac system. During few msec it is possible to accelerate the electron from 20 kV to 10 MeV at inductor 1x1 m and the magnetic field 20 kG. But the longitudinal magnet field cannot be changed during of few msec. Thus, it leads to crossing many linear resonances during acceleration process. The possibility to pass theirs without large loss of electron beam should be studied. It is one of the research problems of Meshkov's team at Dubna [8]. For low heating rate at time of acceleration the magnet system should have the smooth changing magnet field along the electron orbit. The low momentum of electron beam (at 1836 times les antiprotons) results to extremely high sensitivity of a costing electron beam to development of coherent instabilities.

The certain thermal capacity of the electron single ring restricted the rate of electron beam refresh. The new cold electron beam should replace the old heated electron beam in the betatron frequently enough for the effective cooling process. For parameters of the Fermilab Recycler ring the repetition rate of the electron injection is about 2 kHz [8].

PHYSICS OF ELECTRON COOLING FOR HESR AND COSY

The process in the target is the source of the energy spread and loss of the antiprotons. The typical method of this effect suppression is use of magnetized cooling [9]. This mechanism was detail investigated in [10-12].

In the case of magnetized cooling the cooling force is enough strong to suppress the antiproton scattering and the average energy loss in the internal target. According the expression for the cooling force supposed in [9]

$$\Delta\vec{p} = \vec{F}\cdot\tau = -\frac{4e^4 n_e \vec{V}\tau}{m_e\left(\sqrt{V^2+V_{eff}^2}\right)^3}\ln\left(1+\frac{\rho_{\max}}{\rho_L+\rho_{\min}}\right) \tag{1}$$

the strong magnetic field in the cooling region is essential on two reasons. The first is reducing the role of the transverse electron velocity $v_{e\perp}$. If the impact parameter of ion

$$\rho_{\max} \approx V \cdot \tau \qquad (2)$$

is larger than the Larmour radius of the electron $\rho_L = m_e c v_{e\perp} / eB$ then the effective electron velocity

$$V_{eff}^2 = V_{\Delta\Theta}^2 + V_{E\times B}^2 + V_{e\parallel}^2 \qquad (3)$$

doesn't contains the term with $v_{e\perp}$. The other terms are the effective velocity induced by the curve of the magnetic field lines $V_{\Delta\Theta}$ and the electron drift velocity in the crossed the space charge fields of the beams and the guiding magnetic field of the cooling device $V_{E\times B}$.

At the small value of the magnetic field and large transverse velocity of the electron can be realized the condition $\rho_L > \rho_{\max}$. In this case the Coulomb logarithm can be written as

$$\ln\left(1 + \rho_{\max} / \rho_L\right) \approx \tau \omega_L V / v_{e\perp} \qquad (4)$$

where τ is flight time ion through the cooling section in the bam reference system and ω_L is the electron Larmour frequency. Thus, the transverse electron velocity becomes the essential factor and the cooling force drops as $F \propto 1/\left(V v_{e\perp}\right)$. This situation was observed in NAP-M experiments [13]. The friction force dropped down only as $F \propto 1/V$ and not as $F \propto 1/V^2$. The measurements made in these experiments showed that the cooling force decreased with increasing the transverse Larmour velocities of the electrons as $F \propto 1/v_{e\perp}$.

Another role of the strong magnetic field is reducing the drift velocity $V_{E\times B}^2$ induced by the space charge. At the electron current

$$J_{opt} = \frac{1}{2\sqrt{2}} \gamma \beta B a_e \sqrt{V_{\Delta\Theta}^2 + V_{e\parallel}^2 + V^2} \qquad (5)$$

the maximum cooling force is achieved. In Figure 1 one can see the cooling rate versus antiproton/proton energy (Eq.1). Two variants are considered. The first variant deals with the injection parameters of the antiproton beam when the emittances and momentum spread are large. The emittance of pbar beam is taken as ε_n=1 mm·mrad (normalized, 1 σ) and the momentum spread is $\sigma_p = 10^{-3}$. The second variant describes situation after some cooling procedure. The pbar parameters are taken as ε_n=0.05 mm·mrad and $\sigma_p = 10^{-4}$. The dash lines are calculated at absence any restriction on the electron current and the magnetic field in the electron gun. The last parameter enables to change the electron beam radius in the cooling section and regulate the electron density in the cooling section. The solid lines are calculated at the following restriction. The minimal and maximal magnetic fields on the cathode are 200 G and 1000 G. The maximum electron beam current is 3 A. The other parameters of the calculation are the cooling length 30 m, the electron temperature on the cathode 0.3

eV, beta function in the cooling section 100 m. The radius of the electron beam is equal to the radius of the ion beam if it allows by the magnetic field on the cathode. In a different case it is nearest maximum or minimum value. The magnetic fields in the cooling section are taken 500 G, 2 kG and 5 kG. The cathode radius is taken 0.33 cm, 0.63 and 1 cm correspondingly.

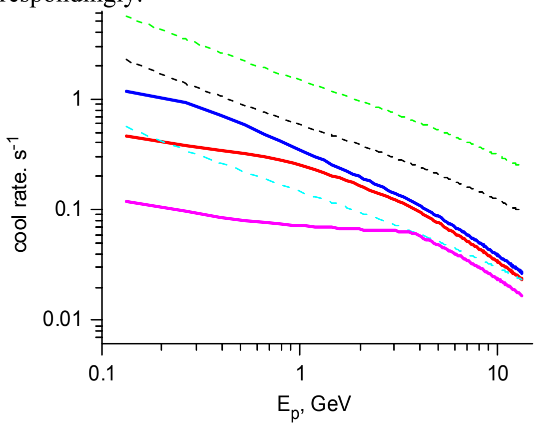

FIGURE 1. Cooling rate versus proton/antiproton energy. The normalized emittance (1 σ, r.m.s) is 1 π·mm·mrad, the momentum spread is 10^{-3}. The dotted lines is highest possible value of the cooling rate without taking technical restriction into consideration. The solid lines are cooling rates calculated with the following technical restrictions. The minimal and maximal magnetic field on the cathode are 200 and 1000 G. The maximum electron current is 3 A. The magnetic filed in the cooling section are 500 G, 2 kG and 5 kG from bottom to top.

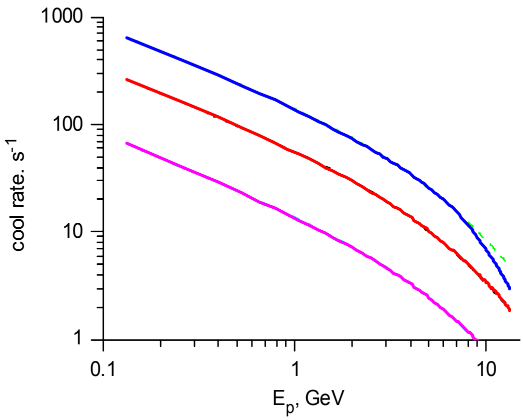

FIGURE 2. Cooling rate versus proton/antiproton energy. The normalized emittance (1 σ, r.m.s) is 0.05 π·mm·mrad, the momentum spread is 10^{-4}. The dotted lines is highest possible value of the cooling rate without taking technical restriction into consideration. The solid lines are cooling rates calculated with the following technical restrictions. The minimal and maximal magnetic field on the cathode are 200 and 1000 G. The maximum electron current is 3 A. The magnetic filed in the cooling section are 500 G, 2 kG and 5 kG from bottom to top.

One can see that the cooling rate isn't sensitive to the magnetic field value at the high pbar energy and injection parameters (Figure 1). At low energy the high value of the magnetic field gives preference for obtaining maximal cooling rate. After the cooling the high magnetic field enables to obtain large cooling rate (Figure 2). The space charge effect isn't viewed essential but the high ratio between the magnetic fields in the electron gun and the cooling section enables to have a very large density of the electron beam in the cooler.

KEY SOLUTIONS.

The technical solution of the BINP team is based on the standard low-energy design for the electron coolers.

The longitudinal magnetic filed in the kilogauss range is used for the transportation of the electron beam. The magnetic filed in the cooling section is strong enough for guarantee magnetizing collision of the ions and electrons. The acceleration tube is also located in the magnetic field with value about 500 G. The equal value of the magnetic field in the cooling and transportation section enables to close the magnetic flux without the large iron circuit (the flux closed in the toroidal device as plasma tokamak).

The cooling solenoid is constructed as the set pancake section assembled in series. The design of solenoid enables to incline and rotate each coil so the quality of the magnetic field can be obtained $\Delta B_{\perp}/B=10^{-5}$ [14].

The bending of the electron beam is realized with help of the electrostatic fields. In this case the dynamic of the primary electrons and secondary electrons reflected from the collector is similar. Such optics of the electron beam is capable to pass the beam both the forward and reverse directions. In this case the electron, which was not absorbed by the collector, has several attempts to get in the collector. There exists a friction force between the bulk electrons and the scattered electrons. Thus, the velocities of the scattered electrons and others are equalized and the scattering electrons are absorbed by the collector. The decrease of the leakage current leads to an improvement of the vacuum condition. These effects were observed in the cooler manufactured for IMP (Lanzhou, China)[15]. The point of full compensation of the centrifugal force by the electrical force is characterized by the minimum of leakage current and good vacuum condition.

DESIGN OF ELECTRON COOLER FOR HESR

A layout of the electron cooling device is shown in Figure 3. The electron beam starts its path in the gun located in the head of the electrostatic column (Fig.3, 2). The cathode of the gun is immersed in the magnetic field. The electron beam is accelerated to energy up 8 MeV. Immediately after the electrostatic accelerator the electron beam transferred from magnetic field 500 G to 5 kG. After that the electron beam is bent in the vertical and horizontal planes and is moved to the cooling section (Fig.3, 4). After the main solenoid the beam is returned (Fig.3, 5) to the electrostatic column. Here it is decelerated and is absorbed in the collector located in the head of the electrostatic column (Fig.3, 2).

The bending of the electron beam is realized with the electrostatic field for creating a centrifugal force. In this case there is no drift of the electron across the driving magnetic field. The value of the electrical field is 21 kV/cm at the electron energy 8 MeV and the bending radius 400 cm.

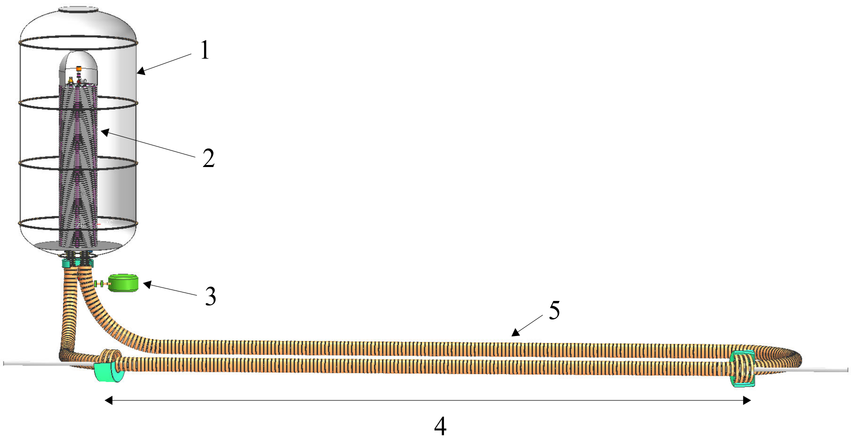

FIGURE 3. Layout of the high voltage cooler for HESR .1 – high voltage tank; 2 – electrostatic column; 3 – cyclotron for charging of the head of electrostatic column; 4 – coolling section; 5 – reversal track.

The main cooling solenoid will have length 30 m and maximum magnetic field up to 5 kG. This solenoid may be constructed as the set pancake section assembled in series. The diameter of one pancake solenoid is 80 cm. The step of the regular structure is 20 cm. The flexjoint should enable the incline 0.6° in the longitudinal direction for the field correction in the cooling section. The total length of the coil with isolation and their construction should enable the incline 3° in the arc section of the cooler.

The obtaining of the parallelism of the magnetic field 10^{-5} is realized by tuning of each pan-cake solenoid. This method was used in the cooler for the IMP. The non-parallelity of the magnetic field lines 8×10^{-6} at a length of 300 cm was obtained. This tuning is hard to be done "on-the- fly" because for fast and operative regulation of the magnetic filed the set of the dipole correction coil is planned. The correction coil may be low-power as the main tuning will be done with the pan-cake coils.

The important part of this project should be a system, which automatically measures and corrects the straightness of magnetic field. It should operate inside the vacuum chamber at ultra-high vacuum condition. For this purpose the laser beam will be sent through a vacuum window and system of mirrors at the center of vacuum chamber. The magnetic compass with movable mirror reflects the laser beam. The deflection of the laser beam is used as the signal for the correction magnetic lines. This system was used at BINP at the single pass measuring of the magnetized cooling force and the accuracy was achieved near 10^{-5}. These experiments made on this system show that for keep the magnet line straightness on level 10^{-5} rad we need to did correction each week.

The electrostatic column contains of three optic channels. Two optic channels are used for the beam acceleration and deceleration on its way from the electron gun to the collector. Third optic channel is used for the charging of the head of electrostatic column by the H^- beam. At the same time it used for the transport test H^- beam generated in the head of electrostatic column. The voltage of the head is measured with the energy of the H^- beam.

There are some possible methods for the charging of the head of electrostatic column.

The most popular high voltage generator system for a voltage over 5 MV are either a mechanical charging device like PELETRON or Van De Graff. In this system a small pellet charged at a ground potential to a voltage near of 50 kV mechanically moved to a high voltage terminal. The charging current of this system is near 100 mkA. For reaching a current near 1 mA used a many chain systems should be used. The ion accelerators with such type of a high voltage system work stably for many days without problems. But the system of moving pellet is very complicate mechanical system in any case.

For the electrostatic cooler we propose to use a small cyclotron at an energy 10 MeV H^- ions as a charging system. The commercially available cyclotrons with similar parameters are widely used for isotope production. The ion beam charging eliminates the mechanical vibration of electrostatic columns and gives the high charging current for more stable operation of a cooler at present of some sort sparking effects in the high voltage system.

Table 1. Parameters list of the HESR cooler.

Length of cooler section, m	30 m
Magnetic field in the cooler section, G	5 kG
Magnetic field in the transport section, G	5 kG
Magnetic field in the acceleration section, G	0.5 kG
Electron current, A_y	1 A
Electron energy	8 MeV
Radius of the electron beam	0.3-0.5 cm
Divergence of the magnetic force line	10^{-5}

DESIGN OF ELECTRON COOLER FOR COSY

Electron design for COSY is similar to the HESR design. It is shown in Figure 4. The electron beam is immersed to the magnetic field from the gun to the collector. The electron beam is accelerated to energy up to 2 MeV. After that the electron beam moves in the matched section for the smooth transition from the magnetic field 500 G to the magnetic field 2000 G. After that it is bent in the toroid and it 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 part. The first one bend magnetized electron beam in vertical plane on 90^0. The second one bends the electron beam on 180^0 in plane that canted on 45^0 from vertical. Such complicated 3-D geometry provides compactness of system.

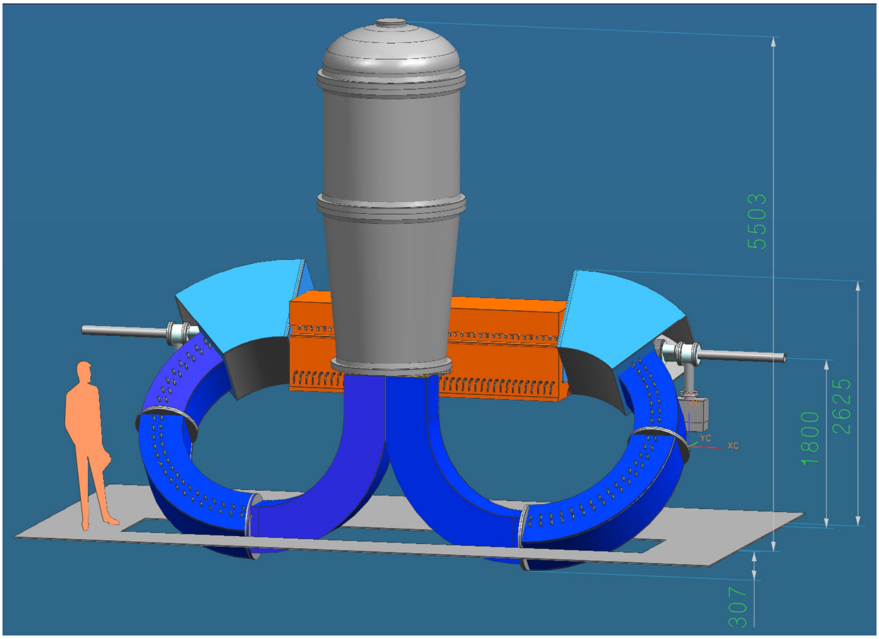

FIGURE 4. Layout of COSY cooler.

The power supply of the acceleration section is planned to be done with gas turbine. The turbine is located in each section and it is provided by SF_6 gas under pressure. The expanding gas rotates the turbine blade and the motor generator shaft. This generator supplies electrical power to the solenoid coil. The flux of gas after turbine is used for cooling coils and keep the temperature inside vessel constant. The preliminary test of such turbine was made in BINP.

The high voltage power supply is located in each section too. Thus there are the set of the high voltage power supplies in series connection. The voltage per section is about ±30 kV. This solution enables easy regulation from the high to low energy. However it is convenient from optic of electron beam point view. It is possible to have the voltage on the limits number section. This may be useful at operation in low energy of the electron beam.

CONCLUSION

The magnetized cooling enables to obtain high cooling rate. The convenient technical decisions for the low energy coolers (up to 300 keV) can be extrapolated to the region of 2 MeV electron cooler (COSY project) or even of 8 MeV (HESR project). The projected based on the quality-checked solutions is reliable with phyics point of view. The technical problem related to this way looks solvable as it is shown in this report.

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