MAGNETIC SHIELDING OF LEReC COOLING SECTION*

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Abstract

The transverse angle of the electron beam trajectory in the low energy RHIC Electron Cooling (LEReC) accelerator cooling section (CS) must be much smaller than 100 urad. This requirement sets 2.3 mG limit on the ambient transverse magnetic field. The maximum ambient field in the RHIC tunnel along the cooling section was measured to be 0.52 G. In this paper we discuss the design of the proposed LEReC CS magnetic shielding, which is capable of providing required attenuation.

REQUIREMENTS TO LEReC CS SHIELDING

The LEReC accelerator [1, 2] consists of 400 keV photo-gun followed by the SRF Booster accelerating beam to 1.6-2.4 MeV, the transport beamline, the merger that brings the beam to the two cooling sections (in the Yellow and in the Blue RHIC rings), the two 20 m long CSs separated by the 180° bending magnet and the extraction to the beam dump. The LEReC also includes two dedicated diagnostic beamlines: the DC gun test line and the RF diagnostic beamline.

The LEReC layout is schematically shown in Fig. 1.

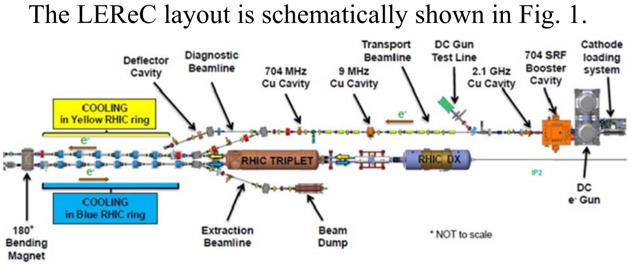

Figure1: LEReC layout.

Each CS includes 6 solenoids separated by drifts. There is a bellow, a beam position monitor (BPM) and a flange located downstream of each solenoid.

The transverse angle of the electron beam trajectory in the LEReC CS must be much smaller than θ_{max} =100 urad. Since the smallest e-beam energy is going to be 1.6 MeV ($B\rho = 68.3$ G·m), the ambient transverse magnetic field must be suppressed to:

$$B_{\perp} \ll \frac{B\rho\theta_{max}}{L} = 2.3 \text{ mG} \qquad (1)$$

where L=3 m is the solenoid-to-solenoid distance in the cooling section.

The maximum ambient field in the RHIC tunnel along the cooling section was measured to be 0.52 G [3]. Assuming that 1 mG residual transverse field is low enough we find the required attenuation factor S to be 520.

From Fermilab Electron Cooler experience [4], due to mechanical joints of the shields, actual attenuation of magnetic shielding can be almost two times smaller than the designed one. Therefore, we suggest adding a safety factor of two to our model making design S=1040.

COMPARING ANALYTIC FORMULAS TO 3D SIMULATIONS

The systematic studies of shielding of the magnetic fields with cylindrical shells of high permeability material [5] were summarized in the form of simple analytic formulas [6, 7].

The attenuation factor of the long cylinder with diameter D, thickness d and magnetic permeability μ is:

$$S = 1 + \mu\frac{d}{D} \qquad (2)$$

For two cylindrical layers with diameters D_1 and D_2 and with respective attenuations S_1 and S_2:

$$S = S_1 S_2 \left(1 - \left(\frac{D_1}{D_2}\right)^2\right) + S_1 + S_2 + 1 \qquad (3)$$

The general formula for N layers is:

$$S = 1 + \sum_{n=1}^{N} S_n + S_N \prod_{n=1}^{N-1} S_n \left[1 - \left(\frac{D_n}{D_{n+1}}\right)^2\right] \qquad (4)$$

Applying (2)-(4) to 4 different shielding setups and comparing obtained attenuations with results of 3D simulations we see that the formulas agree with simulations with ~ 10% precision (results of the comparison are given in Table 1). Therefore, we will use these formulas for initial optimization of the design parameters for LEReC CS shielding.

Table 1: Comparison of S found from analytic formulas (row 6) and S found from 3D simulations (row 7). The second and the third columns correspond to Opera [8] simulations of two possible LEReC setups. The fourth and the fifth columns correspond to the test and the final Fermilab setups [9].

	LEReC1	LEReC2	Fermi1	Fermi2
μ	15000	11000	15000	11000
N layers	2	2	3	3
$D_{1,2,3}$, mm	300, 400	300, 400	219, 233.4, 267.2	219, 241.2, 266.6
d, mm	1	1	1	1
$S_{formula}$	950	537	7538	3356
$S_{simulation}$	877	485	7400	3000

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PHYSICAL DESIGN OF LEReC CS SHIELDING

According to (2) it is beneficial to make the diameter of the first layer as small as possible. The diameter of the vacuum chamber is 5”. Therefore, the radius of the first shielding layer will be 5” as well. There are bellows and flanges of 7” OD at 17.5” downstream from the face of each solenoid and BPM buttons located about 9.5” downstream of the face of each solenoid sticking out even more. Thus, the first layer of shielding can start only at 17.5” downstream of the solenoid face. It can go uninterrupted right to the entrance of the next solenoid.

We choose our shields to be 1 mm thick. Such shields will keep their form through reannealing process required to improve the permeability of the material after mechanical work on the shields is finished. From Fermilab experience [4, 9, 10] we expect to get μ=11000 for the reannealed mu-metal.

Optimization of the radius of the second shielding layer is demonstrated in Fig. 2.

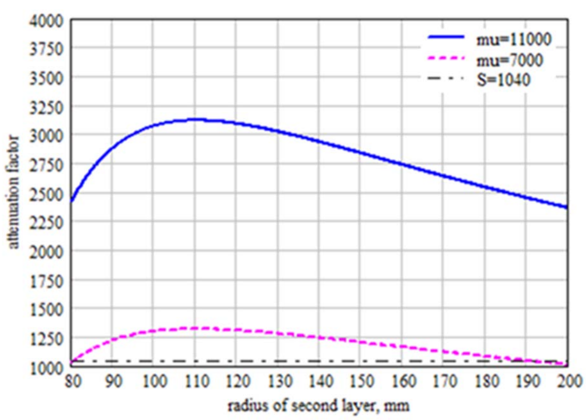

Figure 2: Attenuation is optimized for second layer radius of 110 mm. Solid blue line shows S for nominal μ=11000. Dashed magenta line shows μ=7000 case.

The second layer of shielding would maximize attenuation for R_2=110 mm, yet for the reasons of design convenience we choose R_2=150 mm. Such radius of the second layer of shielding still gives theoretical attenuation factor of 2800, which is much better than our requirements. As a matter of fact, for chosen shielding, as Fig. 1 shows, one can get adequate attenuation even if μ degrades to 7000. The 15 cm radius shield can start at just 1” away from the face of the solenoid.

The first 445 mm of each solenoid-to-solenoid 3 m drift will be covered by a single 15 cm radius layer of shielding. Thus, according to (2) the attenuation in this region will be about 38. As it will be shown in the next section such design of the CS shielding is still acceptable when one considers compensation of acquired transverse angles with correctors (located in each solenoid).

The discussed design is schematically shown in Fig. 3.

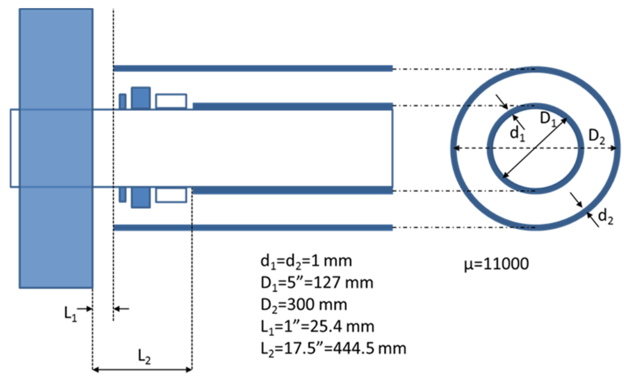

Figure 3: Schematics of the proposed magnetic shielding of LEReC CS.

ELECTRON BEAM TRAJECTORY IN CS

We performed Opera 3D simulations for the shielding setup assuming the external transverse field to be 0.52 G homogeneously distributed and pointing in horizontal direction.

To account for the required safety factor of 2 we assume that the real remnant field in the cooling section can be twice as high as the field found in simulation as Fig. 4 demonstrates.

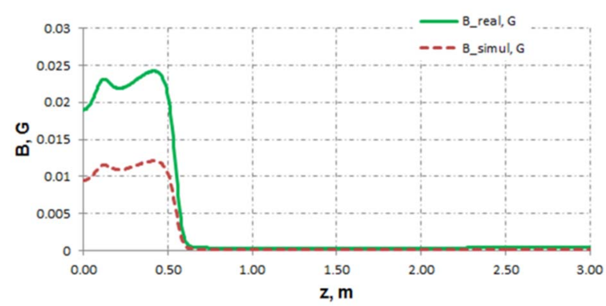

Figure 4: Simulated (brown dash line) and “realistic” (solid green line), i.e. multiplied by 2, residual magnetic field in the cooling section.

Finally, we simulate the trajectory of the 1.6 MeV (kinetic energy) beam traveling for 3 m in the transverse field shown in Fig. 4. As one can see (Fig. 5), the e-beam trajectory angle in such field satisfies LEReC requirements everywhere but in the first 20 cm from the solenoid center (which is OK, since this distance is lost for cooling anyway due to the presence of strong solenoidal field).

In our beam trajectory simulations we compensate the beam deflection through the drift by applying 0.17 mrad kick in transverse corrector located inside the solenoid. We also assume a simple procedure for tuning beam trajectory – we use CS trajectory corrector in every solenoid to zero beam displacement in the next respective BPM.

The nominal strength of CS transverse correctors, which are designed to compensate possible misalignments of solenoids, is 10 G·cm while its measured strength is 8.5 G·cm for 0.8 A current. Thus, for nominal settings such corrector can produce at least 1.25 mrad kick, which is 7 times higher than the kick required for compensating the effect of residual transverse field.

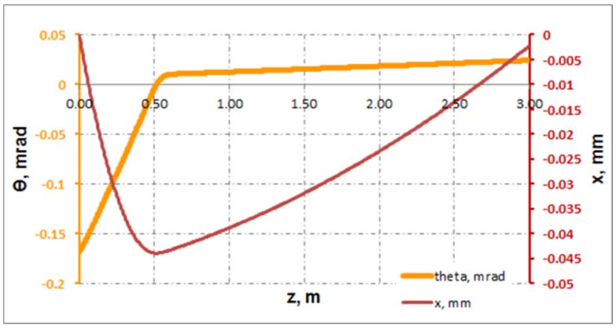

Figure 5: Beam angle (orange) and trajectory (brown) in the "realistic" field shown in Fig. 4.

Finally, it is important to notice that the longitudinal component of the ambient field will not be well shielded by cylindrical shells. Nonetheless, this field is so small (less than 0.35 G) that it has negligible effect on the angle of beam trajectory.

FIRST SHIELDING TESTS

We procured 1 mm thick formed and re-annealed mu-metal shields of 127 mm and 300 mm diameter. Each piece of shield is a half cylinder of 2' length. When two pieces are clamped together they form a cylinder with horizontal junctures shielded by two overlaying halves. Each of the two shielding layers on our test bench is composed of three shielding cylinders placed next to each other. The test bench setup is shown in Fig. 6. The distance between solenoids on the test bench is 2 m. We measure magnetic field with Magnetoresistive Milligauss Meter [11], which has a guaranteed accuracy of 0.5 mG and the precision of 0.01 mG.

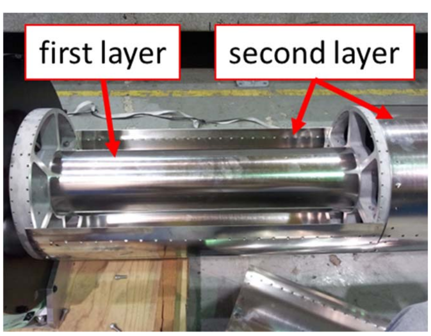

Figure 6: Test bench setup.

We performed the first test bench measurements with the solenoids turned off. The results of the measurements are shown in Fig.7. We are planning to shield the vertical junctures between the cylinders by 3 layers of 0.010" thick mu-metal foil and to repeat the measurements.

To improve the CS shielding we will maximize the length of mu-metal cylinders that will be used in the actual CS, thus, minimizing the number of vertical joints between the cylinders.

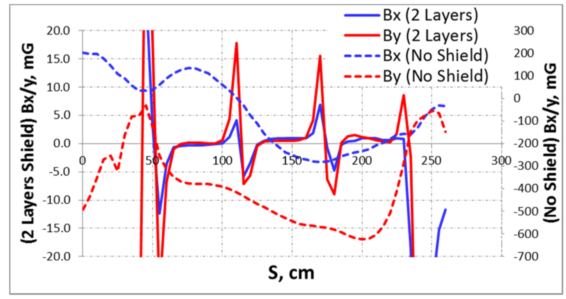

Figure 7: Transverse magnetic field inside the unshielded beam pipe and the pipe shielded by 2 layers of mu-metal (vertical junctures between cylinders are not shielded).

CONCLUSION

We considered design of magnetic shielding of LEReC cooling sections. We are planning to use 2 layers of 1 mm thick cylindrical mu-metal shields with $\mu \geq 11000$. The radius of the first layer sitting on top of the vacuum chamber is 63.5 mm. The second layer radius is 150 mm. Such shielding guarantees adequate transverse angles of the electron beam trajectory in the CS.

REFERENCES

[1] A. Fedotov *et al.*, "Accelerator physics design requirements and challenges of RF based electron cooler LEReC", presented at *NAPAC16*, Chicago, IL, USA, October 2016, WEA4CO05.

[2] T. Miller et al., in *Proc. IBIC2016*, Barcelona, Spain, TUPG35, 2016.

[3] S. Seletskiy *et al.*, C-A/AP/561, BNL-112084-2016-IR, 2016.

[4] A. C. Crawford *et al.*, FERMILAB-TM-2224, 2003.

[5] A. P. Wills, "On the magnetic shielding of tri-lamellar spherical and cylindrical shells," *Phys. Rev.*, vol. 9, 1899.

[6] A. K. Thomas, *IEEE Trans. Electromagn. Compat.* 10, 142, 1968.

[7] A. Mager, IEEE Trans. Magn. MAG-6, 67, 1970.

[8] `http://operafea.com/`

[9] J. Leibfritz *et al.,* FERMILAB-Conf-01/163 E901, 2001.

[10] T. K. Kroc, C. W. Schmidt, A. Shemyakin, FERMILAB-CONF-05/106-AD, 2005.

[11] `http://www.trifield.com/`