Electron Cooler Solenoid for RHIC

Draft R&D Plan, Change Summary

January 5, 2001: First draft

February 14, 2001:

(a) Revised and a more detailed break up of costs are given in Sec. 7. Some items are still not included in the costs. These items are also identified.

(b) Based on discussions held on January 31, 2001, a paragraph on end field shaping requirements is added at the end of Sec. 2.

(c) A paragraph on the requirement of full length dipole coils is added in Sec. 3.1 (based on January 31, 2001 meeting).

(d) A sentence is added at the end of Sec. 3.3 to indicate that the iron yoke size shown is only tentative, and is not yet optimized.

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Draft R&D Plan, February 14, 2001

1. Introduction:

The electron cooler proposed for RHIC [1] requires a solenoidal field of approximately 1 T over a length of ~30 m. The field lines are required to be parallel to the ion beam trajectory, with a transverse field component of less than one part in 10^5. This report presents a conceptual plan for building such a solenoid and developing the necessary diagnostic tools for characterizing the field quality.

2. A conceptual design:

Fig. 1 shows a schematic cross section of the proposed solenoid. The solenoid coil has an inner diameter of 100 mm and is wound with a multistrand superconducting cable, such as the 36 strand SSC outer dipole cable. The cable is a flat one, with no keystone, and is assumed to have a thickness of 1.5 mm including insulation. The solenoid coil consists of two layers of windings, placed on a rigid support tube. An overall current density of ~265 A/mm^2 is needed to produce 1 T solenoidal field, corresponding to approximately 5000 A in the cable. The peak field in the coil is also ~1 T and 5000 A operation at this field uses only a very small fraction of the superconductor capacity. The stored energy is approximately 3.25 kJ/m. Assuming a 5000 A operation, the inductance is therefore only

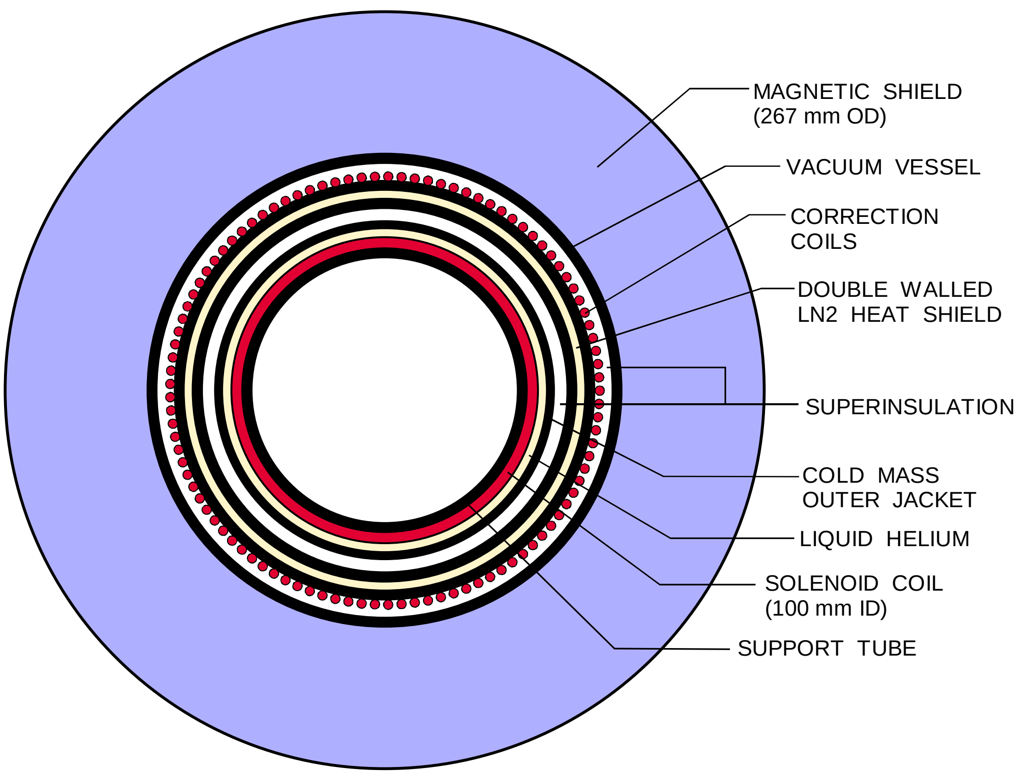

Fig.1 A conceptual design, showing cross section of a solenoid for RHIC electron cooler.

~260 μH/m. The use of a multistrand cable thus helps to keep the inductance reasonably low for a solenoid which is many meters in length. Other superconductor possibilities, such as a 6-around-1 cable carrying ~1000 A are also worth investigating.

Ideally, one would like to build a single solenoid ~30 m in length in order to achieve maximum electron-cooling efficiency. However, such long lengths present several practical difficulties in production, testing, transportation and installation of the magnets. It is therefore proposed that the solenoid be split into two sections, each approximately 13 m to 14 m in length (depending on the actual space available in the RHIC rings). Fig. 2 shows the radial component of the field near one edge ($z = 0$) of the solenoid. It is seen that the radial component is below 10^{-5} after ~0.9 m into the solenoid at a radius of 1 cm, and after ~1.3 m into the solenoid at a radius of 3 cm. The peak value of radial field is 0.17 T at a radius of 3 cm. A similar profile is expected at the far end of the second solenoid. The radial component of the field in the gap between the two solenoids depends on the gap size.

It is anticipated that the radial field at off-axis points in the gap will be well above the required 10^{-5} level. Some sort of field shaping will be required in the gap regions to compensate for the end field effects, requiring additional short solenoidal coils. The exact details of this shaping are not available at present. Consequently, the costs associated with these compensating coils are not included in the estimates presented later in this report. If the total length is divided into only two or three solenoids, then the compensating coils are expected to add only a small amount to the total cost. However, if the solenoids have to be made much shorter (e.g. ~3 m long), then the cost could increase noticeably.

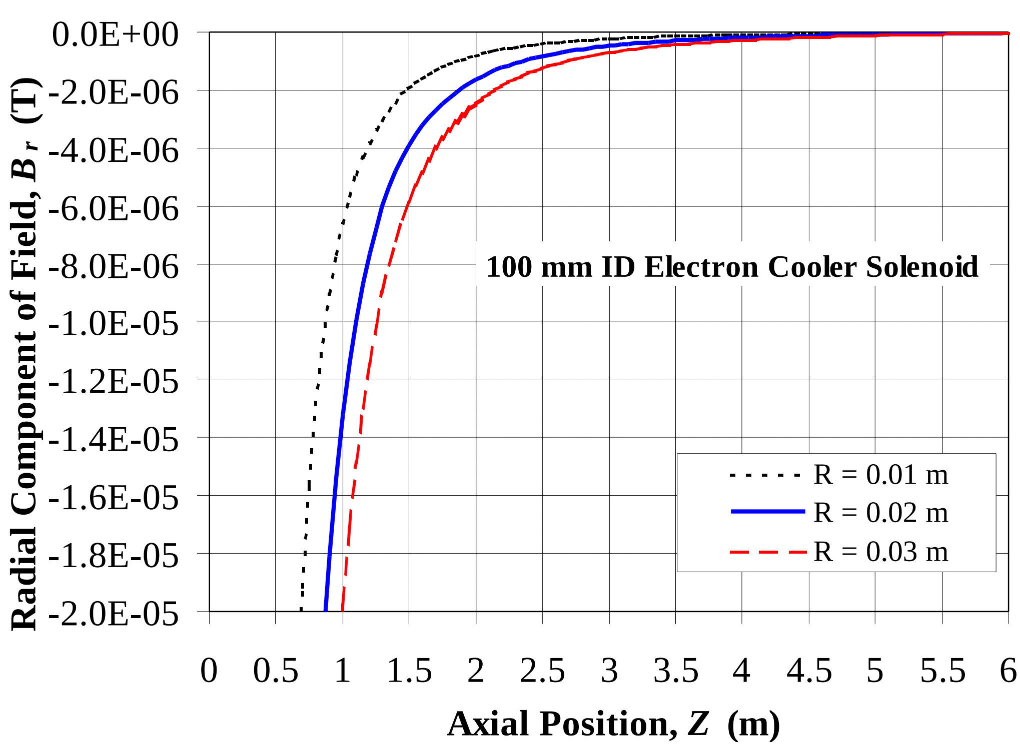

Fig.2 Radial component of the field near one edge of a long solenoid at 1 T.

3. Achieving the desired field quality:

The field quality in an actual solenoid is subject to many types of construction errors, and in general will be considerably inferior to that shown in Fig. 2. The trajectory of the ion beam is a straight line. However, the local axis of the solenoid may deviate from a straight line. A transverse field of 10^{-5} implies a straightness of the solenoid axis within 0.1 mm over a distance of 10 m. This will be difficult to ensure by mechanical means alone. Nevertheless, it is foreseen that some type of mechanical shimming will be carried out to straighten the solenoid axis as much as possible. Details of such a shimming scheme are not worked out yet, and will be part of a R&D plan. The goal of mechanical alignment will be to achieve a transverse component of the field well below one part in 10^{3} measured along a straight line.

3.1 Dipole correction coils:

The remaining correction to achieve a transverse component below 10^{-5} will be done using an array of normal and skew dipole coils, as shown in Fig. 1. These correction coils will each be approximately 100 mm to 150 mm long, in order to correct local curvature of the magnetic axis. Details of these correction coils are not worked out yet. It is planned to provide a correction strength of ~10^{-3} T at a current of ~1 A to 2 A. Both normal and skew dipoles will be provided to correct the curvature along the horizontal and the vertical planes. To avoid persistent current effects, as well as hundreds of leads going to liquid helium temperature, these correction coils will be normal conducting, and placed outside the cold mass. To minimize any heat load to the main solenoid, and the thickness of the wire needed to wind the coils, the correction coils will be cooled to liquid nitrogen temperature by mounting them directly on the outer surface of a double walled liquid nitrogen shield (see Fig. 1). The hundreds of leads must be handled such that the field distortions are minimal. Also, the aspect ratio of these coils will be very close to one, with practically zero straight section. The field quality from such coils must be studied in detail to ensure that no unwanted effects on the beam are generated. The excitation current for each correction coil will be determined based on a measurement of the magnetic axis along the length of the solenoid, as well as the measured transfer function profiles of each correction element. The software required for this, as well as power supplies and other related hardware will be developed as part of the R&D plan.

In addition to the short dipole coils for local correction, it is foreseen that full length normal and skew dipole coils will be needed to provide the ability to tilt the overall magnetic axis by up to 1 mrad. This is to accommodate changes in the ion orbit from run to run. These coils will be similar in construction to the correction coils mentioned above, except that these will span the entire length of the solenoid.

3.2 Solenoidal correction coils:

The field quality in the solenoids may suffer from another type of construction error. If the parallelism of field direction is required over a cylindrical volume of finite radius (rather than just on the axis), then it is essential that the field strength be very uniform along the length of the solenoid. In practice, small radius variations along the length and other winding non-uniformities may produce enough gradients to produce large radial fields at off-axis points (~10^{-3} T at radius ~ 1 cm). It is not clear at present what the required good field zone is. If transverse fields less than 10^{-5} T are needed over radial distances of the order of 1 cm or more, then an additional layer of solenoidal correction coils may be needed. This layer is not shown in Fig. 1, as it has not been determined whether these are really needed. Also, such a layer is not included in the cost estimates presented in Sec.7.

3.3 Shielding against stray fields:

A transverse field of one part in 10^{-5} at 1 T corresponds to only 0.1 G. Clearly, one must guard against all stray fields in order to achieve the desired field quality. An iron "yoke" is used to provide the shielding, as shown in Fig. 1. Since the yoke is not really needed to enhance the field, it can be at room temperature, located outside the vacuum vessel. The outer diameter of the iron shield is expected to be the same size as the yoke for the RHIC arc dipoles (10.5 inches). No optimization has been done yet to determine the minimum amount of iron required.

4. Quench Protection

The solenoids in this proposal will require no special quench protection with the proposed use of SSC outer dipole cable, an operating current of 5000 A, and an approximate total inductance of less than 8 mH. The only quench protection required will be the shutting off of the power supply when a quench is detected. It is planned that one solenoid will be powered by a single power supply. The RHIC arc dipole magnets which are self protecting under all operating currents have an inductance which is four times that of this 30 m solenoid.

5. Measurement of field quality:

The Magnet Division has no facilities currently available to measure field quality in solenoids. For achieving a field quality at 10^{-5} level, the measurements are an integral part of the production and correction cycle. Axis mapping techniques based on Hall probes as well as a small magnetic needle mounted on a mirror [2] have been used at other laboratories. Both of these techniques will need to be developed at BNL as part of the R&D program. This includes design and fabrication of the mirror mount, the associated optics and electronics, and related data acquisition and analysis software. It may also be necessary to adapt the measurement system such that the measurements can be made in-situ after the magnets are installed in the ring, since the alignment of the magnets can change during transportation and installation.

The requirements of measuring the parallelism or the straightness of the field in these solenoids to a level of 0.01 mm in a 1 m length is very challenging. To date, in the optical/field measurements that were done on RHIC triplet magnets, the field centers were measured to about 0.10 mm over 3 m length. This was done in a controlled room temperature environment. It is even more difficult to perform these measurements when the magnet is operating at its normal cryogenic temperature.

Two methods of measurement will be explored in this R&D program. The first method would be to develop a probe that would use an array of Hall sensors or a combination of Hall and NMR sensors to locally measure the field around the probe. This probe would then have adjustments that can position it inside the magnet to an optical reference line. This reference line would maintain the probe's position in both X and Y planes better then

0.010 mm over the length of the solenoid. A computer-controlled optical system and vision capture system would determine the position of the probe and make adjustments to it to get the required straightness. The second method could use a magnetic "needle" mounted on a probe using a precision gymbal system and a very precise mirror attached to the needle. The "needle" will then track the field of the solenoid and move the mirror. An external laser would be reflected off the mirror to a vision capture system that would be able to determine the movement of the "needle". This probe will most likely have the same type of adjustments the first method had. It is to be determined whether an optical system is used to align the probe along the length of the solenoid or some laser system similar to the one used to measure the movement of the "needle". Both methods would require the same basic vision capture system and the same method of probe adjustments. The differences being the method of field measurements and how to determine if the probe is in the correct position. Both systems would require special provisions to enable accurate measurements to be made when the solenoid is operating cold. The thermal gradients that are produced when using a standard warm bore tube will have to be overcome by both systems.

6. Prototype:

In view of considerable amount of development needed to build the solenoids at BNL, it is proposed to build a 3 m long prototype to demonstrate proof-of-principle and validate the test equipment and procedures. Since measurements of field quality are of utmost importance in this project, all the necessary diagnostic techniques will have to be developed at the prototype phase itself. It is expected that building and testing a prototype will require a period of approximately two years.

7. Cost estimates:

Some preliminary cost estimates are presented in this section for the prototype R&D plan, as well as for the production of required full length magnets. Not all costs are included at this stage, as noted under each of the headings below. Also, the figures presented include overheads, but no contingency.

7.1 Prototype design and manufacturing:

	Man Months		$$$			$$$ incl. overhead
A. Labor:	**Design/ Tech.**	**Engg.**	**Design/ Technician**	**Engg.**	**Total**	
1) Prototype Magnet Design & Engineering	24	9	$ 163.2 K	$ 75.6 K	$ 238.8 K	$ 427.4 K
2) Tooling Design & Engineering	24	14	$ 163.2 K	$ 117.6 K	$ 280.8 K	$ 502.5 K
3) Tooling Assembly	8.25	4	$ 53.6 K	$ 33.6 K	$ 87.2 K	$ 156.1 K
4) Magnet Assembly	11	4.5	$ 71.5 K	$ 37.8 K	$ 109.3 K	$ 195.6 K
Total Prototype Design & Manuf. Labor	**67.25**	**31.5**	**$ 451.5 K**	**$ 264.6 K**	**$ 716.1 K**	**$ 1,281.6 K**

B. Materials:		
1. Magnet Materials (Coils, heat shield, yoke, cryostat, supports)	$ 253.0 K	
2. Tooling Materials (Modifications to various machines and MagCool, etc.)	$ 169.0 K	
Total Prototype Manufacturing Materials:	**$ 422.0 K**	**$ 606.7 K**
Total Prototype Design & Manufacturing (Labor and Materials):	**$ 1,138.1 K**	**$ 1,888.3 K**

The above estimates do not include the costs of coils needed for end compensation, full length dipole coils for tilting the magnetic axis and an array of short solenoidal correction coils, if needed.

7.2 R&D related to the measurement system:

	Man Months	$$$	$$$ incl. overheads
1. Physicist	6	$ 52.9 K	$ 94.6 K
2. Software Development	12	$ 66.9 K	$ 119.7 K
3. Electrical Engineering	9	$ 62.8 K	$ 112.4 K
4. Mechanical Engineering	6	$ 39.0 K	$ 69.7 K
5. Technicians	24	$ 111.2 K	$ 199.1 K
Total R & D Labor for Measurement System:	**57**	**$ 332.7 K**	**$ 595.5 K**
Material Costs (probes, sensors, computers, electronics, power supplies, optics, etc.)		**$ 200.0 K**	**$ 287.6 K**
Total R & D Labor and Materials related to the measurement system:		**$ 532.7 K**	**$ 883.0 K**

The above estimates do not include the cost of actually testing the prototype magnet.

7.3 Design and manufacturing of full length solenoids:

A. Design & Manufacturing Labor:	**Man Months**		**$$$**			**$$$ incl. overhead**
	Design/ Tech.	**Engg.**	**Design/ Technician**	**Engg.**	**Total**	
1) Production Magnet Design & Engineering	14	4.5	$ 95.2 K	$ 37.8 K	$ 133.0 K	$ 238.0 K
2) Tooling Design & Engineering	16	7.5	$ 108.8 K	$ 63.0 K	$ 171.8 K	$ 307.5 K
3) Tooling Assembly	6	4	$ 39.0 K	$ 33.6 K	$ 72.6 K	$ 129.9 K
4) Magnet Assembly	93.5	5.25	$ 607.8 K	$ 44.1 K	$ 651.9 K	$ 1,166.6 K
Total Production Design & Manuf. Labor	**129.5**	**21.25**	**$ 850.8 K**	**$ 178.5 K**	**$ 1,029.3 K**	**$ 1,842.0 K**

B. Production Magnets Materials:

1. Magnet Materials (Coils, heat shield, yoke, cryostat, supports)	$ 1,854.0 K	
2. Tooling Materials (Modifications to various machines and MagCool, etc.)	$ 159.0 K	
Total Production Magnets Manufacturing Materials:	**$ 2,013.0 K**	**$ 2,894.2 K**
Total Production Design & Manufacturing (Labor and Materials):	**$ 3,042.3 K**	**$ 4,736.2 K**

In addition to the production costs, there will be additional costs associated with R&D to adapt the measurement system to the full length magnets, as well as the cost of actually testing the magnets.

References:

[1] *Electron Cooling for RHIC*, Report by V. Parkhomchuk and I. BenZvi, September 26, 2000.

[2] See, for example, *Magnetic Field Alignment in the Beam-Beam Compensation Device*, C. Crawford, et al., Proc. of 1999 Particle Accelerator Conference, pp. 3321-3.