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SUPERCONDUCTING COILS FOR THE BENDING MAGNETS OF DUAL APERTURE STORAGE RING

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The design of superconducting coils for the bending magnets of dual aperture storage ring is described. These coils could be used for lowering the wall plug power consumption, but required additional 700*W* of refrigerating power.

1. Introduction

The dipole magnet design for dual bore machine is represented in [1]. The power consumption for this three meter long magnet supposed to be around 7 *kW* for 65*mm* vertical gap. Further lowering of the power consumption could be done if the coil cross section is enlarged. In this case, however, the dimensions and the weight of the magnet increased very rapidly.
Here the superconducting coils for this magnet are considered. The coils with cryostat occupy the *same cross section* as the room temperature coils of basic model, opening the possibility to exchange the coils *in future*, *keeping the same iron yoke*.
Motivation for the design represented here, is in the feasibility to improve the power balance for the general wall plug power consumption. The electrical equivalent for 1*W* of heat leak at Helium temperature could be estimated roughly as 0.5-0.6 *kW* of electricity from the wall plug, including mostly refrigerating possibilities of a cooling system. So, to be comparable with room temperature magnet, dissipated 7 *kW* of electrical power, the heat leakage referred to liquid helium must be lower, that 15 *W* for two coils. This limit looks as easy satisfied.
From the other hand one needs an additional expense connected with fabrication of the superconducting coils, so the comparison must include this item. Also, high absolute refrigerating power requires additional investment into a cryogenic system. For example, a power dissipation of 5*W* per magnet requires total 5×140=700*W* of total refrigerating capabilities (and investments).
We represent here these materials for the reference and for the guarantee, that from the *technical* point of view, this design has a sense.

2. Superconducting coils for the basic model.

The magnet with superconducting coils is represented in Fig. 1. The magnetic inductance lines are represented in Fig. 2. In Fig. 3 the magnetic field distribution is represented as a function of the transverse displacement.
The winding of the coil made of NbTi wire of muliturn racetrack type, Fig. 1. Single layer winding of 40 turns placed between profiled copper holder, which has a narrow slot for a wire, positions 30, 31 in Fig. 1. Wire has 54 filaments of NbTi and has a diameter of 0.43 *mm* with insulation, caring 150 *A* each. The holder placed in stainless steel envelope, caring a liquid Helium. The cryostat contains also an intermediate screen, cooled by liquid Nitrogen, position 32. System of spherical holders 33 gives the necessary mechanical stability for all system.

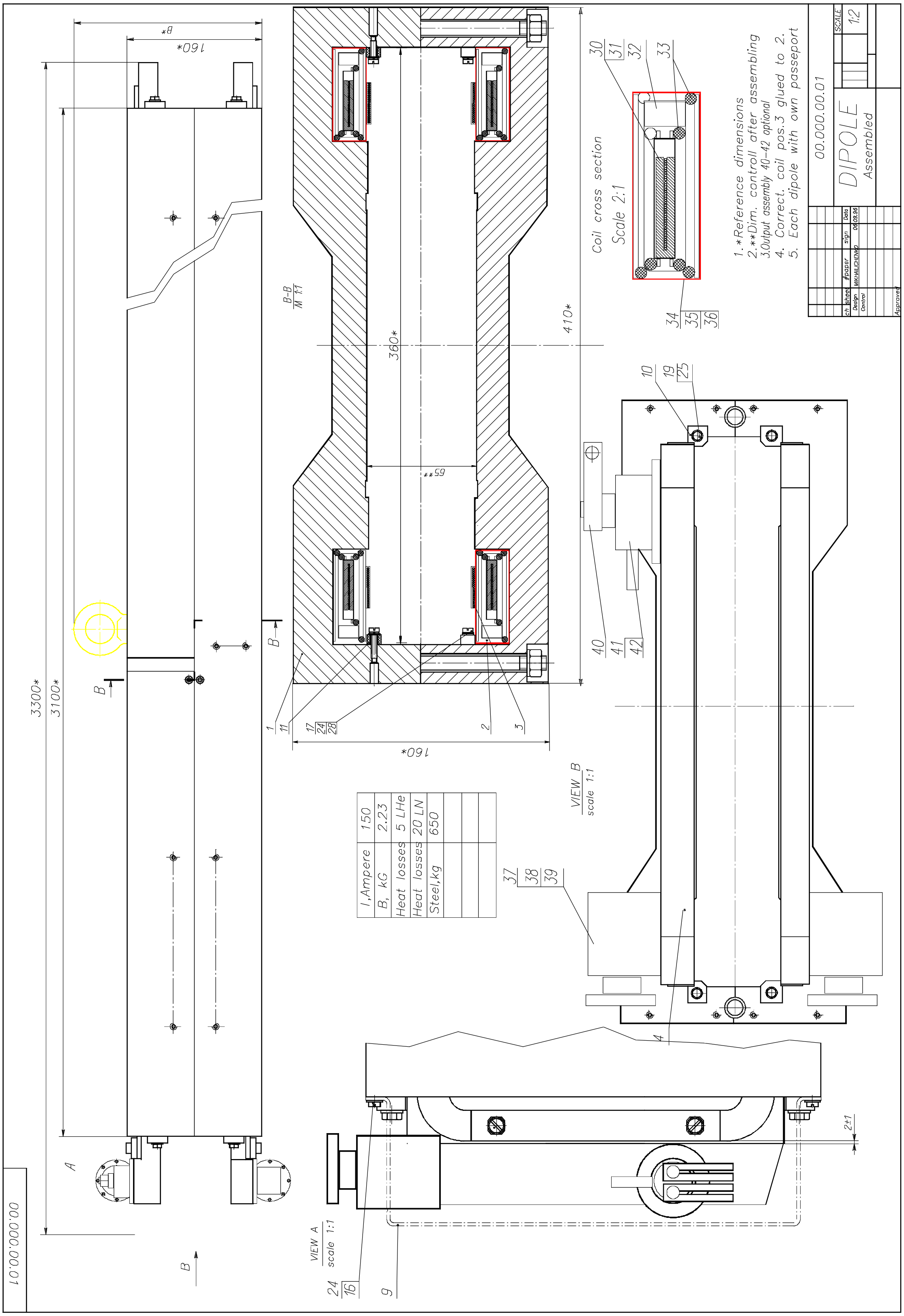

Fig. 1. The basic model yoke with superconducting coils.

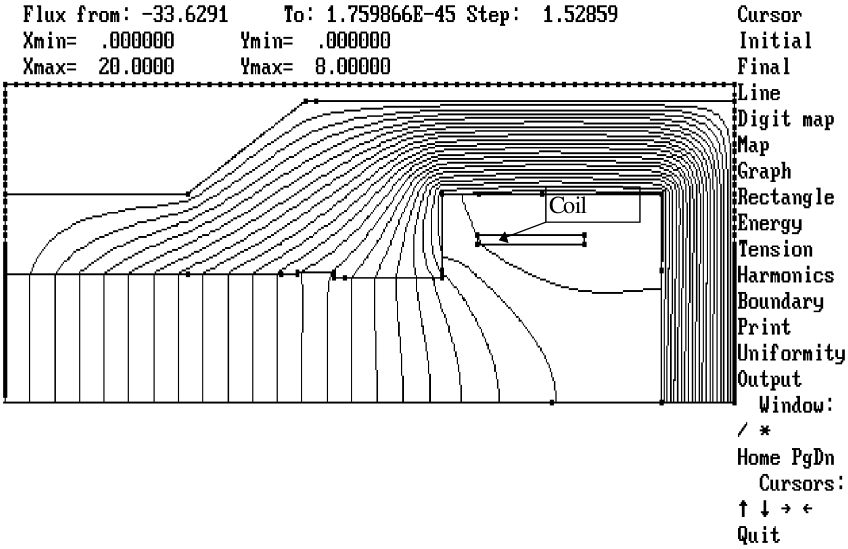

Fig. 2. The magnetic lines. Print out from MERMAID [2]. Shown is ¼ of the magnet.

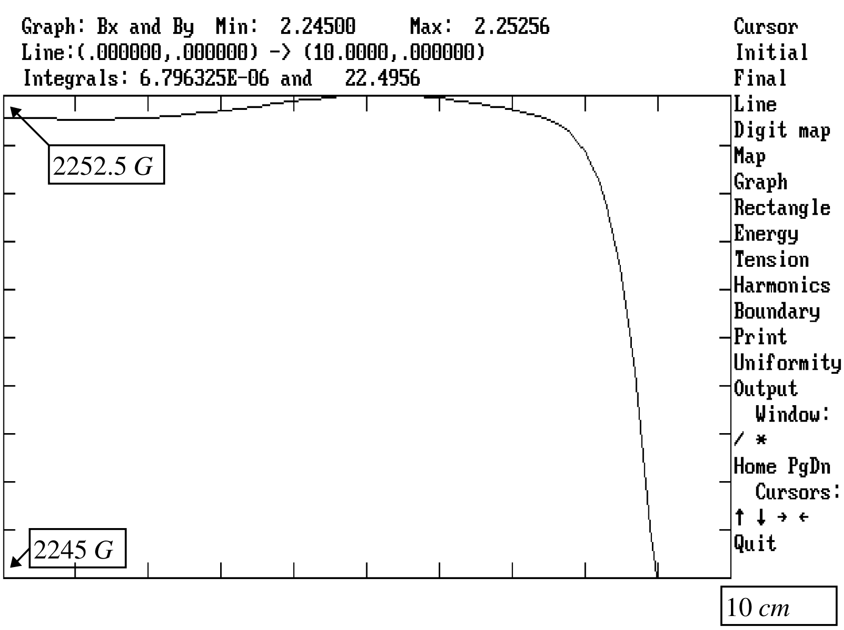

Fig. 3. An example of the field behavior across the gap of the magnet. Zero transverse coordinate corresponds to the magnet center. One division on vertical scale corresponds to $3.3 \cdot 10^{-4}$ of relative variations. So, the good region is about ± 8 *cm*. The relative field variations here are within $\pm 1.6 \cdot 10^{-4}$.

Utilization of a high temperature superconductor for a coil winding is not economically proved at present times, due to the high cost of materials. If the cost of high temperature superconductor will drop in a future, all necessary *simplifications* of the cryostat will be easily done. These simplifications, after all, will be minor, however.
Indeed, the current inputs (positions 40-42 in Fig. 1) made of BSCCO or YBCO ($YBa_2Cu_3O_x$). These inputs have reasonable balance of the cost and heat losses with a simplicity of utilization. As the coils connected in series, these inputs placed only at the end of each stream.
Magnetic field strength in the coil region is about 1.7 *kG* at the end of the coil, (left side in the Fig. 2), 0.7*kG* in the middle, 0.55*kG* at 75% distance from this end and 0.9*kG* at the right end. So this field is much below the critical field for this wire. The forces acting on each linear (in longitudinal direction) centimeter of the coil are $F_x \cong 0.26$ *kg/cm*, $F_y \cong 0.39$ *kg/cm*.
Jumpers 37-39 on Fig. 1 used for transporting the liquid Helium, Nitrogen and current from one coil to another.

3. Heat leakage

Heat leakage consists of losses by thermal conductivity of the supports, radiation, convection and associated with the current inputs.

3.1 Thermal conductivity

According to Fourier law a heat transfer rate Q can be calculated by

$$Q = -kA\frac{\partial T}{\partial y}, \tag{1}$$

where $\partial T / \partial y$ is a temperature gradient in the direction, normal to the area A, k is the thermal conductivity.
The cold mass of the coil supposed to be supported by the spherical balls. The problem with spherical support is basically a three dimensional one. The accuracy of thermal calculations, however, is not more, than 10%, so some simplifications could be done. Physically it is clear, that the temperature gradient will be concentrated in the contact points. From the mechanical point of view, the strength in these points will yield a deformation, what is defined by the properties of the materials. In reality, the contact occurs over some complex area. We supposed, for simplicity, that deformed sphere is *flat* on the top and has a view, represented in Fig. 4.
Heat transport coefficient is a strong function of temperature. In the region between 4.2^oK to 77.6^oK it drops up to ten times.

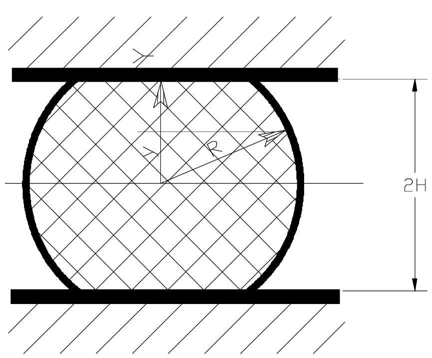

Fig 4. Model of the support.

Integrating equation (1), one can obtain

$$2Q\int_0^H \frac{dy}{A(y)} = \frac{2Q}{\pi}\int_0^H \frac{dy}{R^2-y^2} = \frac{2Q}{\pi}\frac{ArcTanh[H/R]}{R} = \int_{T_{LHe}}^{T_{LN}} k(T)dT \cong -\bar{k}\cdot(T_{LHe}-T_{LN}) = -\bar{k}\cdot\Delta T\ ,$$

where $\bar{k}$ is an averaged heat transport coefficient value.

So
$$Q \cong -\frac{\pi}{2}\frac{\bar{k}\cdot R\cdot\Delta T}{ArcTanh[H/R]}.$$

Function $ArcTanh[H/R] \Rightarrow \infty$, when $H/R \Rightarrow 1$. In this case the heat transport is zero. Physically it is clear: under assumption $H/R=1$, the contact area shrinks to the point what yields an infinite thermal resistance. Supposing that $H/R \cong 0.8$, i.e. that the sphere penetrates to the material on 20%, one can obtain $Q \cong -\frac{\pi\bar{k}\cdot R\cdot\Delta T}{2}$. It is interesting, that the same heat flow will have a cylindrical support having the height, equal to diameter.

So $Q \approx -1/2\cdot\pi\cdot kR\Delta T$ and one can see, that the heat transport is lowering *linearly* with lowering the radius. Substitute here for estimation $R \cong 1mm$, $\bar{k} \cong 0.8$ $W/m/^{o}K$, one can obtain for the heat transport between helium cold surface and nitrogen cooled one, $\Delta T \cong 74^{o}K$, as $Q \approx -1/2\cdot\pi\cdot 0.8\cdot 0.001\cdot 74 \cong 0.1W$. Let us suppose, that the supports are located every meter along the cryostat. So the total number of the balls is 24 (four balls at the place), what yields a heat transport on the level of $5W$ for two coils (upper and lower). Pure epoxy has a k value about ten times lower, than if filled with inorganic filler in percentage 65%, but mechanical properties are not clear. For the ratio H/R=0.95 the heat transport will be about two times lower. So, mechanical properties of the sphere are crucial for this business.

PYREX ball is a good candidate for the support. In any case, the figures are optimistic.

3.2 Radiation

For a heat exchange by the radiation between helium and nitrogen surfaces, one can write

$$Q = -\sigma_{eff}\cdot 5.67\cdot 10^{-8}\cdot S\cdot(T_{LHe}^4 - T_{LN}^4)[W],$$

where $1/\sigma_{eff} \cong 1/\sigma_{He} + 1/\sigma_N - 1$ is the effective gray coefficient[1], what is the sum of reverse gray coefficients of the helium and nitrogen cooled surfaces, S $[m^2]$ is an area involved in radiation exchange. According to Fig. 1, the area $S \cong 2\times 0.1\times 6.6 \cong 1.32$ m^2, where the first factor two associated with two coils, 0.1 is a perimeter of the helium container. For a polished stainless steel, $1/\sigma_{eff} = 1/\sigma_{He} + 1/\sigma_N - 1 \approx 13+13-1 = 25$, so total power flux will be

$$Q = -(1/25)\cdot 5.67\cdot 10^{-8}\cdot 1.32\cdot(4.2^4 - 77.6^4) \cong 0.1[W],$$

what is negligible, if compared with the losses, described in 3.1.

3.3 Vacuum

The pressure P in the volume between helium vessel and outer wall will produce a heat exchange on the level

$$Q[Watt] = \kappa\cdot P\cdot\alpha_1\cdot\Delta T\cdot S,$$

[1] We supposed that the areas having helium and nitrogen temperatures are about the same and equal S.

where $\kappa \cong 0.016$ for an air, $\alpha_1 \cong 0.5$ is a coefficient of accommodation, depending on the gas and wall properties, S is the area of the surface, cm^2. Substitute here the numbers, one can obtain that

$$Q[Watt] \cong 8.2 \cdot 10^3 \cdot P[Torr].$$

For heat transport on the level $Q \cong 0.1\ W$, the vacuum must be below $1.2 \cdot 10^{-5}$ *Torr*, what is easily satisfied. After preliminary pumping, the helium and nitrogen containers will pump the gases.

3.4 Heat losses associated with the current inputs

For the current leads made on BSCCO, these losses will be within 0.1*W/pair* for the driving current 150*A* at the average temperature 64^oK and self field. Once again, these leads will be installed at the end of the stream, what might be tens of magnets.

One- two layers of super insulation could be applied here for the heat losses reduction of the nitrogen.

So, the heat losses are expected on the level of 5*W per magnet*[2]. For total amount of 140 magnets this yields a 700 *W* of losses in the coils only. The wall power will be at the level 400-500*kW*, compared with 1*MW* of losses, associated with the coils made on copper conductor.

4. Power supply

Power supply must generate 150 *A*. It must have a protection over the quench. Even the field is far below the critical, this may create a problem, if not managed. The total energy *E*, stored in one magnet is roughly

$$E \cong \frac{\mu_0}{2} B^2 \cdot V \cong \frac{4\pi \cdot 10^{-7}}{2} (2200 \cdot 79)^2 \cdot 3 \cdot 0.065 \cdot 0.25 \cong 925[J],$$

so the protection system must accept this energy. This system looks much easily, however, than the protection systems for the superconducting systems, routinely used around the world.

5. Conclusion

The superconducting coils for the magnets for CESR post III stage could be used for lowering the wall plug roughly from 1*MW* to 500*kW*. The refrigerating system requires some investments, however. It requires additional 700*W* of cooling productivity at helium temperature.

It is important, that the coils made as a separate unit and occupy the *same* space as the warm coils of the basic magnet. The coils described is rather simple, and the cost of these coils is expecting to be comparable with the cost of the coils made on copper conductor.

Further lowering of the heat losses might be done if the number of supporting balls is reduced. PYREX balls might be used to reduce the contact area what might yield further reduction of the heat losses. All this need to be tested experimentally.

Heat losses about 5*W* per magnet make the magnet competitive with one having room temperature coils and dissipating about 3.5 *kW* of power. Referring to the main model [1], that means that the coil cross -section of the basic model must be increased about two times to yield the same heat losses.

So, coming to conclusion, one can see, that the coils with superconducting wires have a good perspective.

6. References

[1] A. Mikhailichenko, D. Rubin, Bending Magnets for Dual Aperture Storage Ring, CBN 97-28, Cornell University, Wilson Laboratory, June 25, 1997.

[2] A.N. Dubrivin, E.A. Simonov, **MERMAID**- **ME**sh-oriented **R**outine for **MA**gnet **I**nteractive **D**esign, Novosibirsk, BINP, 1990.

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[2] For liquid helium.