Cold head maintenance with minimal service interruption

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Abstract. Turn-key superconducting magnet systems are increasingly conduction-cooled by cryogenerators. Gifford-McMahon systems are reliable and cost effective, but require annual maintenance. A usual method of servicing is replacing the cold head of the cryocooler. It requires a complicated design with a vacuum chamber separate from the main vacuum of the cryostat, as well as detachable thermal contacts, which add to the thermal resistance of the cooling heat path and reduce the reliability of the system. We present a rapid warm-up scheme to bring the cold head body, which remains rigidly affixed to the cold mass, to room temperature, while the cold mass remains at cryogenic temperature. Electric heaters thermally attached to the cold head stations are used to warm them up, which permits conventional cold head maintenance with no danger of contaminating the inside of the cold head body. This scheme increases the efficiency of the cooling system, facilitates annual maintenance of the cold head and returning the magnet to operation in a short time.

1. Introduction
Ion Beam Applications (IBA) recently developed and built the first generation of a compact superconducting synchrocyclotron, S2C2, [1, 2] for their proton therapy treatment system ProteusOne®. S2C2 is conduction cooled by four Gifford-McMahon cryogenerators, which require annual maintenance. The commercial nature of this application requires high availability, with minimal down time for servicing the cryocoolers. Historically, in some applications this was achieved [3, 4, 5] by placing the cryocooler into a separate vacuum partitioned from the main vacuum of the magnet by a thin vacuum chamber. This requires additional space, which is difficult to allocate in a compact S2C2 magnet. For a simple cryostat with single vacuum chamber, like in S2C2, several servicing options can be considered. The first option could be warming the cold mass from 4 K to around 100 K as rapidly as possible, fitting airtight glove boxes on the flanges supporting cryogenerator heads on the cyclotron, purging these cold heads with helium (or another appropriate gas), disassembling the inside of the cold heads in the glove boxes to exchange the parts worn out with new parts, cleaning the inside walls of the cylinder, installing a new motor/displacer, and then, after appropriate flushing, restarting the cold heads and cooling the cold mass from above 100 K to 4 K to restore operational conditions. This option requires sufficient space for the glove box, complex procedures, restricted use of organic solvents for cleaning, and high risk of contamination.
An alternative approach significantly simplifying the servicing procedure was proposed. This method uses intense local heating of the 1st and 2nd stages of a cryocooler by electric heaters installed on specially designed parts thermally connected to the respective stations of the cryocoolers. This permits maintaining the cylinder of the serviced cryocooler at about room temperature, while the cold mass stays at an average temperature well below 100 K.

Patent search revealed that practically the same approach was patented [6] by Leybold in 1991. We do not have any information if Leybold ever used this method. The main principles of the method proposed by MIT are similar to those described in the patent. There is however, a significant difference. The patent proposed installing the electrical heaters on the cylindrical surfaces of the cryocooler, indicated in Fig. 1 (reproduced from the patent) by numbers 51 and 52. This, quite natural idea, was examined and rejected. The reason is that first, the surface available for installing the heaters on the cryocooler cylinder is insufficient and second, this arrangement results in a significant temperature gradient along the heated surface of the cryocooler cylinder and may lead to its damage. Figure 2 shows that for a typical heat flux applied to the 2nd stage of the cryocooler cylinder the temperature of its hot end is 408 K while the cold end is at 300 K.

The design of the arrangement for heating the 2nd stage of the cryocooler of the S2C2 magnet was optimized using numerical finite element (FE) modeling and subsequently tested using two test stands. Results of the analyses and of subsequent tests are described below.

2. Numerical analyses

The key issue for this type of cryocooler service is to properly define dimensions of the cold finger connecting the 2nd stage of the cryocooler to the cold mass and the method for heating the 2nd stage of the cryocooler. The goal is to design the finger so that it would minimize heat leak from the heaters into the cold mass in the “heating” mode, at the same time providing sufficiently small temperature drop between the 2nd stage of the cryocooler and the cold mass during cooldown from room temperature and magnet energization, and maintaining the cold mass at 4 K during routine operation of the magnet.

Heating mode was simulated using TEMPO, a thermal package of the VF Opera program. The model of the cold mass is shown in Fig. 3.a. The cryocooler was not part of the model. It is shown to indicate the location of the heated finger in the model. Details of the model at the location of the cryocooler are depicted in Fig. 4. The copper end piece of the second stage (labeled as Cryocooler
Cylinder) represents the second stage of the cryocooler. Heating power was applied to the outer cylindrical surface of the Clamp. The clamp is installed after bolting the flange of the second stage of the cryocooler to the finger; to facilitate this installation the clamp is cut in two parts.

Servicing the cryocooler can be performed when the temperature of the cryocooler cylinder at the second stage is close to 300 K. The heating scenario was defined iteratively to permit cold head servicing with a minimum heating energy deposition. The following sequence was used:

- A total power of 960 W is applied to the cold head clamp during the first 20 minutes of heating. Dividing this power by the heated area yields a heat flux of 5.10 W/cm².
- From this time point (t > 20 min) until the end of the scenario the power is constant 800 W, which corresponds to a heat flux of 4.25 W/cm².

Figure 2 depicts the temperature of the 2nd stage of the cryocooler and the average temperature of the cold mass as a function of the heating time.

With this scenario the integrated heating power deposited into the cold mass is 4.6 MJ per cryocooler. This amounts to 18.4 MJ for all 4 cryocoolers of the magnet. Additional analyses showed that the expected time to service all four cryocoolers with subsequent recooling the cold mass to 4 K is of the order of one day.

Figures 6.a and 6.b depict temperature distributions in parts of the cold mass at the end of the 90-minutes long heating cycle. The largest temperature gradients occur along the length of the cold finger (Figure 6.b) and near the cold finger connection to the aluminum bobbin that supports and aligns the
superconducting coil pair (Figure 6.a). The maximum temperature in the simulation, $T_{\text{max}}=340$ K, appears at the end of the heated clamp (see Fig. 6.b). The temperature distribution across the 2nd stage copper piece varies between 288 K at the inner surface and 300 K outside. This non-uniformity shall be taken into account during installation of the temperature sensors controlling the power of the heaters. The hot spot that occurs near the heated finger is vivid in the aluminum bobbin (Fig. 6.a).

![Figure 6.a. Aluminum Bobbin Temperature (K) at t=1.5 hr](image)

![Figure 6.b. 2nd Stage and Finger Assembly Temperature (K) at t=1.5 hr](image)

Figure 6.a. Aluminum Bobbin Temperature (K) at t=1.5 hr

Figure 6.b. 2nd Stage and Finger Assembly Temperature (K) at t=1.5 hr

Figure 7 shows temperature distributions along the axis of the heated finger at different time points of the heating scenario. The horizontal axis, $Y$, is the radial coordinate starting inside the coil and ending at the cryocooler end of the finger. The ground insulation is in a 3.5 mm thick interval, $R_{\text{in}}=0.6840$ m $< Y < R_{\text{out}}=0.6875$ m, between the bobbin and the coil winding. At all time points (except for $t=0$) of the heating mode there is a temperature drop between $T_{\text{in}}$ at $R_{\text{in}}$ and $T_{\text{out}}$ at $R_{\text{out}}$. These temperatures as a function of time are shown in Fig. 8. Here $dT=T_{\text{out}}-T_{\text{in}}$ is the temperature drop across the ground insulation along the axis of the heated finger.

![Figure 7. Temperature along the Axis of the Heated Finger](image)

![Figure 8. Temperature at the OD and ID of the Ground Insulation and Temperature Drop vs. Time](image)

Figure 7. Temperature along the Axis of the Heated Finger

Figure 8. Temperature at the OD and ID of the Ground Insulation and Temperature Drop vs. Time

This drastic temperature drop due to a thin layer of relatively low thermal conductivity ground insulation contained between the aluminum bobbin and the coil is the cause of a specific stress distribution in this area. The main concern is that it can cause delamination between the coils’ ground insulation and the bobbin, which can change the heat path in the cooling mode.

The maximum temperature drop occurs at the end of the boosted heating at $t=20$ min. We can expect that at this time point the associated thermal stresses in the ground insulation will reach the maximum over the whole scenario. Figure 9 shows azimuthal distributions of temperatures $T_{\text{in}}$ and $T_{\text{out}}$, around a circle at the elevation of the centreline of the cryocooler, at the $t=20$ min. time point.
Radial stresses were modelled using the STRESS Module of VF Opera and their distribution on a cylindrical surface at the midplane of the ground insulation at the OD of the closest to the heated finger, upper, coil are shown in Fig. 10.

A maximum tensile radial stress of 30 MPa is observed directly under the cold finger hot spot. This stress is an order of magnitude smaller than the tensile strength of G10 in the normal direction. (Mechanical strength of G10 provided by different sources varies over a wide range. MatWeb [7] specifies the Tensile Strength at Break of G-10 Fiberglass Epoxy Laminate Sheet in the “crosswise” direction as 262 MPa.) Calculated azimuthal and shear stresses (not shown here) are below 66 MPa and 13 MPa respectively. These are also safely low, which implies that there is no danger of delamination leading to the degradation of the insulation as a result of this temperature distribution.

On the other hand, the same 30 MPa of normal stress at the interface between the insulation and the aluminum bobbin may or may not lead to debonding. In fact, MatWeb defines the Adhesive Bond Strength of epoxy in the range between 2 MPa and 65 MPa. Let us conservatively assume that there will be debonding at this location. First of all, since there will be no delamination it will have no consequences for the electrical integrity of the insulation. Second, debonding at the OD of the insulation at the base of the cold finger will degrade the heat path from the heaters to the cold mass in the heating mode. This will reduce the amount of heating power required to warm up the cryocooler and consequently will reduce the overall heating energy deposited into the cold mass. During regular cooldown and normal operation the aluminum bobbin will always be colder than the coil and there will always be compression between them (due to differential thermal contraction mismatch) providing an excellent thermal path for cooling the cold mass.

Based on the results of the FE modeling the parameters of the optimized cold finger and the warming scenario were defined. We conclude that the heating mode bears no danger to the structural integrity and functionality of the cyclotron magnet and will permit the whole cycle of servicing all four cryocoolers with subsequent re-cooling the cold mass to 4 K in less than one day.

3. Test in a bucket cryostat
The intent of the first experiment was to test the suitability of a 125-W Kapton heater with dimensions, 7.9x432 mm, certified for operation at 120 V and a power density of 3.66 W/cm² for use on the 2nd stage cold head clamp.

Three turns of this heater were wrapped on the OD of a copper cup bolted to an aluminum rod that was partially submerged in a bucket dewar containing LN₂. This setup is illustrated in Fig. 11. The 280 mm length and 795 mm² cross section of the 2024-T6 Al rod between the LN₂ level and the cup were optimized to achieve a temperature distribution reaching 300 K at the location of the copper cup at less than maximum heater power. A Styrofoam float installed at the base of the Al rod provided the
constant position of the cup with respect to the LN2 level. All metal parts of the setup above the LN2 level were insulated by Styrofoam.

Temperature sensors, T_1-T_5 and T_CLTS, were installed as shown in Fig. 11. Several different heating scenarios were used. The temperature versus heating time readings shown in Fig. 12 correspond to the fastest heating test. They indicate that the goal of reaching 300 K was successfully accomplished at a maximum heater power of 160 W. The required heating power was 28% higher than the heater’s nominal power rating because of unmodeled convective cooling by the boil-off gas.

The experiment successfully demonstrated the viability of the proposed method of servicing S2C2 cryocoolers and the validity of the analytical and numerical methods used both for designing and post-processing the results of the test.

4. Small-scale test demonstration
The key objective of the second experimental setup was to warm both the 1st and 2nd stages of a Leybold Cool-Power 4.2GM cryocooler connected to a 275-kg iron cold mass in a vacuum vessel to above 300 K within 15-20 minutes using Kapton tape and cartridge heaters mounted near the cold head stages, and to maintain those stages near 300 K temperature for duration of ½ to 1 hour. Figure 13 shows the general arrangement of the test setup.

Figure 13. General arrangement of the cold head test arrangement
Figure 14. Cold Mass
Initial cooling of the cold mass was performed by liquid nitrogen flowing in a tracer soldered to the cold mass OD, shown in Fig. 14. A total of nine temperature sensors were used to monitor the temperature distribution at select locations on the test stand. These sensors included a MicroMeasurements cryogenic linear temperature sensor (CLTS-2B) mounted to each cold head stage, a Lakeshore silicon diode temperature sensor (DT-670C) mounted near the top and bottom surface of the radiation shield, another DT-670C silicon diode mounted to the bottom of the cold mass, and four Lakeshore Cernox temperature sensors mounted along the length of the cold finger that connected the 2nd stage of the cold head to the cold mass. The CLTS sensors were used in a feedback control loop to control the heating power applied near each stage of the cold head. The sensor attached to the 1st stage was labeled CLTS-1, while that on the second stage was labeled CLTS-2. The silicon diode mounted to the top surface of the radiation shield was labeled D1, while that mounted to the bottom surface of the radiation shield was labeled D2. The diode sensor labeled D3 was mounted to the bottom surface of the cold mass. Cernox sensor Cx1 was mounted to the 2nd stage of the cold head. Cernox sensors Cx2 and Cx3 respectively, were installed 18 mm from the top and 18 mm from the bottom end of the 19 mm diameter, 154 mm long cold finger, while Cernox Cx4 was embedded roughly 10 mm below the surface of the iron cold mass, near to the base of the cold finger.

Three, low voltage, high current dc power supplies operated in voltage-controlled mode were used to power the 1st and 2nd stage heaters. Data logging was performed using an Automation Direct Productivity 3000 PLC, which also controlled the heating cycle applied during the tests.

Figures 15.a – 15.b and 16.a – 16.b depict the heating power versus time scenarios and temperature sensor readings as a function of time for the 1st and the 2nd stages respectively. Roughly 350 W peak heating power was applied during each of the tests shown. The results were obtained during different heating experiments. Due to an unanticipated increase in the cryostat vacuum during one of the heating tests, the lead wires to the first stage heaters were damaged by an electrical arc occurring at a voltage of roughly 180 V, before the final 2nd stage test sequences were performed. Both stages of the cryocooler successfully reached the desired 300 K temperature within the allotted 15~20 min. time frame. For both stages, the heating power automatically decreased as the measured temperature at the cold head stage approached its targeted 300 K set point. By comparison, the temperature rise observed at the radiation shield (Figure 15.b) and at the cold mass (Figure 16.b) increased much more gradually. That is, the applied heating power went principally towards increasing the temperature of components near to the cold head stages, with only modest conduction to the radiation shield and cold mass.
Numerical FE modeling of heating at both the 1st and 2nd cold head stages was performed prior to the experiments. The results of the experiment agree reasonably well with the analyses, given inherent uncertainties in the pre-test analytical model. The heat capacities of the internal cold head components needed for more precise analysis of the heating scenarios could not be obtained from the cold head manufacturer. The assumed cold head heat capacity values for the analysis, while close to those deduced from post-test data reduction, resulted in under estimation of the heating power required to warm the 1st stage of the cold head to room temperature in 15 minute by roughly 10%, while over estimating the required heating power at the 2nd stage by roughly 12%.

5. Summary
We developed a method of in-situ maintenance of the cryocoolers for the IBA S2C2 cyclotron magnet by local heating of their 1st and the 2nd stages and used the FE modelling and following experiments to confirm the reliability of the numerical optimization and the viability of the proposed engineering solution.

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