FEASIBILITY OF USING CONDUCTIVELY COOLED MAGNETS IN CRYOMODULES OF SUPERCONDUCTING LINACS

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Abstract

As part of a search for optimal ways to configure cryomodules of the low-beta section of a high-current, high-power superconducting linac, the option of using conductively cooled superconducting focusing lenses was evaluated by testing specially designed superconducting magnet inside existing Spoke Cavity Test cryostat (STC). The cryostat was modified by adding current feed-throughs and a pair of conductively cooled current leads. Each lead was thermally anchored inside STC to 80 K liquid nitrogen and 4.5 K liquid helium circuits by two heat intercepts. The magnet was mounted on individual heat sink plate, and temperature sensors were installed on the leads, on the heat sink plate, and on the magnet. In this report, details of the test setup and analysis of the temperature measurements are presented.

MOTIVATION

The rate of the beam loss in high-power proton (or ion) superconducting RF linacs strongly depends on quality of the beam transport in the low-beta sections of the linacs. The requirement of having short focusing period in these sections is often in contradiction with the available longitudinal real estate because of significant footprint of superconducting accelerating cavities and the need for beam line instrumentation. The problem becomes even more pronounced when the requirement of a very low fringe magnetic field is taken into account [1].

On the other hand, quality of the beam is also defined by precision of alignment of magnetic focusing elements in the beam line. When superconducting solenoid-based focusing lenses are employed, the presence of pressure vessels, needed to contain liquid Helium (LHe), and corresponding piping greatly compromises achievable precision and reproducibility of lens positioning. Employing conduction cooling can help resolving both mentioned problems by saving some longitudinal space and improving chances for accurate and reproducible positioning of the lenses by eliminating temperature-dependant forces applied to the magnets through the piping attached to the vessels.

Conduction cooling of superconducting magnets is routinely and successfully employed for small scale magnets (e.g. see [2],); attempts are being made also for using this approach in large scale magnetic systems [3].

The main goal of this study was to check on applicability of this approach to the design of densely packed cryomodules of high-power linacs.

All tests associated with this study and corresponding measurements were made using a test cryostat developed at FNAL for testing superconducting accelerating cavities of HINS linac [4]. The cryostat was modified by adding conductively cooled current leads and equipped with heat sinks both at the LHe and liquid Nitrogen (LN) temperature levels [5]. A specially designed solenoid-type test magnet was used for this study.

TEST SETUP

The test of the leads, designed to carry 50 A current, has demonstrated that the current corresponding to the start of the run-off condition is above 80 A [5]; moreover, the leads could carry current above 100 A for several hours before the maximum temperature measured on the leads exceeds 300 K. The design quench current of the test magnet was well below 100 A at 4.5 K, so the performance of the current leads made it possible bringing the magnet to the quench point.

The magnet was designed as a solenoid-type coil encapsulated in aluminium (Al) compression ring. Four temperature sensors were installed on and in the close vicinity of the test coil: one was embedded into the inner layer of the winding, the second one was in the outer layer, the third one was attached to the top of the Al clamp, and the last sensor was on the heat sink plate below the magnet. Four film heaters were glued into the inner layer of the coil winding, as shown in Fig. 1.

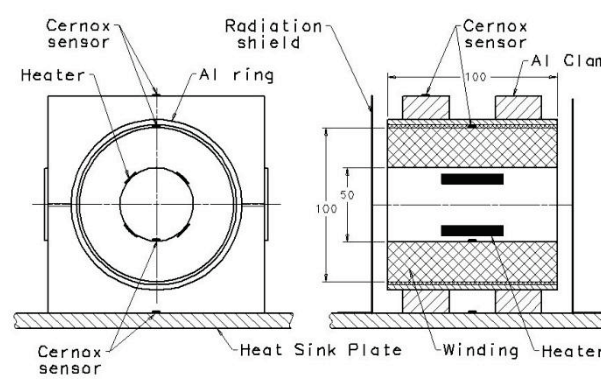

Figure 1: Test magnet and embedded instrumentation.

Round, 0.5 mm, 54-filament, 1.35:1 copper to non-copper ratio NbTi strand made by Oxford Instruments Inc. was used to wind the magnet [6]. Performance of the strand was measured at FNAL and parameterized using the approach described in [7]. The parameterization made possible calculation of the quench current of the system at any temperature based on the known strand performance and winding parameters of the coil. On the other hand, the heaters installed in the coil (shown in Fig. 1) provided a mean for changing the temperature of the winding; this

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temperature could be readily evaluated once the quench current was measured.

To cool down conductively-cooled magnet below the superconductivity threshold, one needs to make sure that the heat influx is sufficiently small.

Heat Flux Management

Copper current leads provide the main route for the heat to get into the cryostat. To prevent this heat from reaching the magnet, the next measures were undertaken:

a) Heat intercept was installed on each of the current leads and thermally anchored to the pipe that supplied LN to the 80 K thermal shield of the test cryostat [4]. This way most of the thermal flux entering inside the cryostat was filtered out before reaching the magnet. Design and performance of this heat intercept were described in [5].

b) Each copper current lead was connected to corresponding superconducting lead of the test magnet through intermediate electrically insulated copper pipe with forced flow of LHe; to increase the efficiency of the heat transfer, specially designed inserts were used. As a result, the temperature of the superconducting leads was close to that of LHe in the pipes (~4.5 K).

c) The test magnet was installed on the copper heat sink plate cooled by LHe flowing through copper piping brazed to the plate.

d) The magnet was thermally insulated by MLI and equipped with intercepting shields. To check on the heat flow patterns and in order to identify hidden heat sources in the system, spatial orientation of the clamps and the radiation shields were changed during the study.

Fig. 2 shows sub-assembly of the test coil with the heat sink plate and the LHe heat intercept. Copper current leads and superconducting leads of the test coil were soldered to the heat intercept pipes. Flexible hoses attached to the piping delivered the flow of LHe.

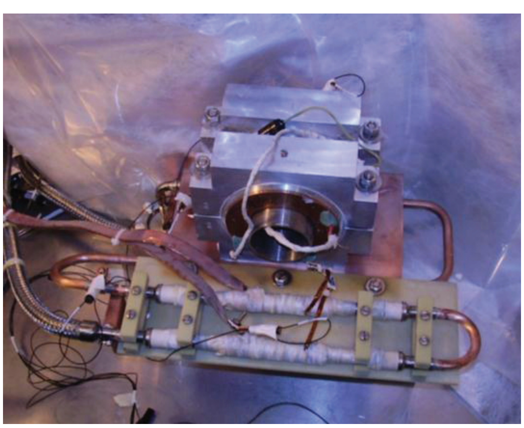

Figure 2: Test coil and LHe heat sink.

TEMPERATURE MEASUREMENTS

Cernox™ cryogenic temperature sensors were installed on the magnet, on the piping, and on the leads at places with the expected temperature below 20 K. To measure higher temperature on the leads, type "E" thermocouples were used. Performance of the current leads and the heat intercepts was consistent with the results of numerical modelling in [5]: with the expected 1.1 W of heat flow towards the LHe heat intercept at 70 A, the measured value was ~1.2 W. The temperature of the heat sink plate remained ~4.6 K at any current below 100 A.

During testing, at several settings of the heating power, the current in the coil was elevated until quench and the temperature of the coil was evaluated based on the known performance of the strand and the magnet. On the other hand, the temperature registered by the thermometers installed around the coil was constantly recorded. Fig. 3 compares the measured quench current with what would be expected based on the readings of the temperature sensor in the inner layer of the coil.

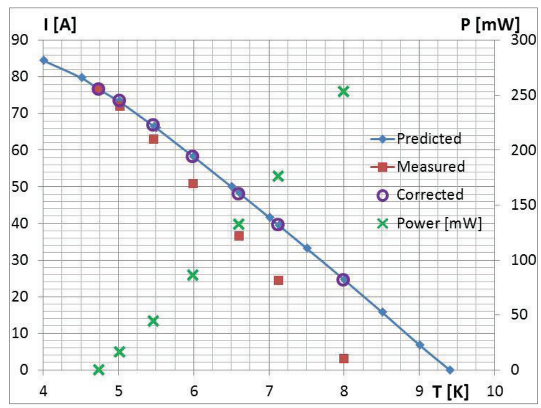

Figure 3: Expected, measured, and corrected quench performance of the test magnet.

Red squares in the figure reflect the correspondence between the measured quench current and the readings of the sensors in the inner layer. Blue line shows the expected quench current at different temperatures. Green crosses refer to the total power of the heaters (the scale on the right) corresponding to the measured temperature. The reason of the discrepancy between the expected and the measured quench current can be understood if to realize that the heater and the thermometer are spatially separated in the inner layer; the presence of a heat flux within the winding must be assumed. As this flux changes linearly with the heating power, the difference in the temperatures at quench location and at the spot where the temperature was measured can be taken into account. Violet circles in Fig. 3 present quench current data corrected for this temperature difference. Correspondence between the corrected and predicted quench performances indicates that the accuracy of the measurements is adequate. Hence further analysis of the thermal environment can be made by comparing the readings of all sensors.

HEAT FLUX ANALYSIS

Temperature field in the test magnet changed depending on the position of the clamps (vertical vs horizontal orientation) and of the radiation shields (attached to the sink plate or to the top of the clamps). The lowest heat flux reaching the magnet was registered when the gaps between the halves of the clamps, oriented horizontally in Fig. 1 and Fig. 2, were re-oriented vertically and the radiation shields were attached to the heat sink plate. Graphs in Fig. 4 show the temperatures in the magnet measured by the thermometers at different heater settings and corresponding linear fits (dashed curves).

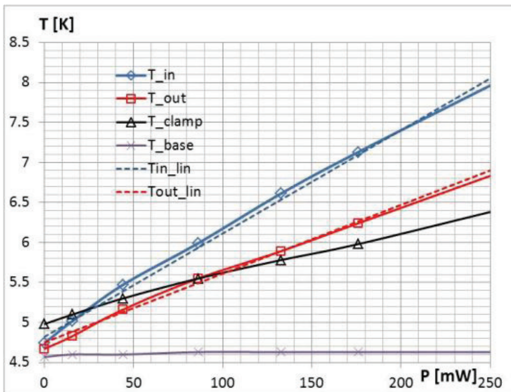

Figure 4: Temperatures in the test magnet at different settings of the heater.

With the heaters off (P = 0), the temperature of the coil is higher than that of the base plate by ~0.2 K; the temperature on the top of the clamp is ~0.4 K higher. The difference in the temperatures can be explained only by the presence of a heat flux. This heat cannot come through the leads as the temperature on the heat sink plate is lower than that of the coil; only radiation flux and poor vacuum can be counted as possible sources. The amount of this flux can be evaluated by using the relation

$$P_{flux} = \frac{\partial P}{\partial T} \times (T - T_{base}) - P_{heater},$$

where the temperature T is taken at the location of a particular sensor, and appropriate curve from Fig. 4 must be taken to find the derivative ∂P/∂T. Relative position of the graphs in Fig. 4 points towards the existence of a heat flux additional to what was provided by the heaters. For example, the readings of the sensor at the top of the clamp can be well explained by assuming the presence of additional (environmental) flux of ~70 *mW*.

In similar way, the curves describing the temperatures in the inner and the outer layer can be interpreted. Let's employ linearization and solve the resulting system of equations for power and temperature.

$$T_{in}\,[K] = 4.82 + 0.0129 \cdot P_{heater}\,[mW],$$
$$T_{out}\,[K] = 4.75 + 0.0086 \cdot P_{heater}\,[mW].$$

With no heat flux in the coil, one expects $T_{in} = T_{out}$. To explain the measured difference between these temperatures, one needs to assume the presence of an additional heat flux between the inner and the outer layer: P_{flux} = 16.3 *mW*. Taking into account this flux, the expected temperature of the coil with zero heating power can be found: T_0 = 4.61 *K*; this is close to the measured temperature of the base plate as one can see in Fig. 4.

DISCUSSION

The maximum measured temperature in the test coil was below 5 K; this demonstrates the feasibility of using pure conductive cooling for magnetic focusing elements installed inside cryomodules. The data related to the temperature in the system seems quite accurate; nevertheless no clear understanding was obtained at this point on what is the source of the heat flux in the coil. Two possible suspects are poor vacuum in the cryostat and insufficient thermal insulation of the test coil.

Unfortunately, no reliable data on the vacuum condition in the test cryostat was available at the time of the testing. On the other hand, installation of two radiation shields shown in Fig. 1 with the goal of intercepting direct migration of relatively warm gas towards the surface of the coil resulted in significantly lower heat influx.

Inadequate amount (or poor usage) of MLI material installed around the test coil to shield it from the radiation coming from the 80 K nitrogen shield can definitely be a reason, although attempts to improve this insulation did not produce desired result.

It becomes obvious that one needs to pay significant attention to the quality and proper installation of any shielding when conduction cooling is considered.

CONCLUSION

Feasibility of using conductively-cooled magnets inside cryomodules of linacs has been demonstrated by testing a conductively cooled magnet in a cryostat and using conductively-cooled current leads. Temperature measurements revealed the presence of an environmental heat influx to the test coil; the sources of the flux can be thermal radiation and direct energy transfer by gas.

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