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, an option of using conductively cooled superconducting focusing lenses was evaluated. Superconducting magnet was installed inside existing test cryostat, which was modified by adding current feed-throughs and two conductively cooled current leads. Each lead was equipped with heat sinks at the temperatures of liquid nitrogen and liquid helium. The magnet was mounted inside the cryostat on an individual heat sink plate, and thermometers were installed on the leads, heat sinks, and on the magnet. In this report we provide some details of the test setup and analyse results of the temperature measurements.

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 part of the linac. Required short focusing period in this section is often in contradiction with the size of superconducting accelerating cavities, which becomes even more pronounced when the need for a very low fringe magnetic field is taken into account [1]. On the other hand, quality of the beam is also defined by the 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 compromise achievable precision and reproducibility of lens positioning. Employing conduction cooling can help resolving both mentioned problems by saving some longitudinal space due to the absence of a LHe vessel and improving chances for accurate and reproducible lens positioning by eliminating temperature-dependant forces acting on the magnetic system through the piping associated with the vessel.

Conductive 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 the feasibility of this approach in application to 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 [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 [5] has demonstrated that the current corresponding to the start of the run-off condition is above 80 A; moreover, the leads could carry current above 100 A for several hours before the maximum temperature measured on the leads reaches ~350 K.

The magnet was designed as a solenoid-type coil encapsulated in aluminium (Al) compression ring. It was equipped with heaters attached to the inner layer of the winding and thermometers embedded in the inner and the outer layer of the winding, and installed on a heat sink plate using two Al clamps. Sketch in Fig. 1 shows some details of the magnet design.

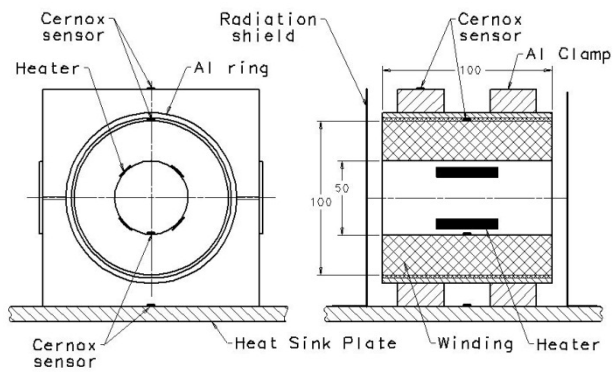

Figure 1: Test magnet and embedded instrumentation.

It is important to say that the design quench current of the test magnet was below 100 A at 4.5 K, so the performance of the current leads allowed us to bring the magnet to the quench point.

The magnet was wrapped in multi-layer insulation and equipped with radiation shields to protect it from environmental heat flux. To check on the heat flow patterns and in attempts to identify hidden heat sources in the system, spatial orientation of both the clamps and the radiation shields were changed during the study. 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 that had 9954 turns [6]. Performance of this strand was compared with what was specified by the company by direct measurements and then parameterized using the approach described in [7]. Knowing winding parameters of the coil and performance of the strand makes it possible calculation of the quench current of the system at any temperature. On the other hand, the heaters installed in the coil (shown in Fig. 1) provide a means for

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changing the temperature of the winding; the temperature can be readily evaluated if the quench current is known.

To bring the temperature of a conductively-cooled magnet below the superconductivity threshold one needs also to limit heat flux coming through current leads.

Heat Flux Management

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

a) Heat exchanger was installed on each of the current leads and thermally connected to the pipe that supplied liquid Nitrogen to the 80 K thermal shield of the cryomodule [4]. This measure has allowed intercepting most of the thermal flux coming from the room temperature part of the leads. Details of the design and performance of this heat exchanges are 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. Turbulizators installed inside each pipe made them efficient heat sinks. As a result, the temperature of the superconducting leads was close to the temperature of LHe in the piping (~4.5 K).

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

Fig. 2 shows sub-assembly of the test coil installed on the heat sink plate and the LHe heat exchanger, made of two pieces of electrically insulated copper piping, installed on G-10 plate. Copper current leads and superconducting leads of the test coil are soldered to the pipes. Flexible hoses attached to the piping deliver the flow of LHe.

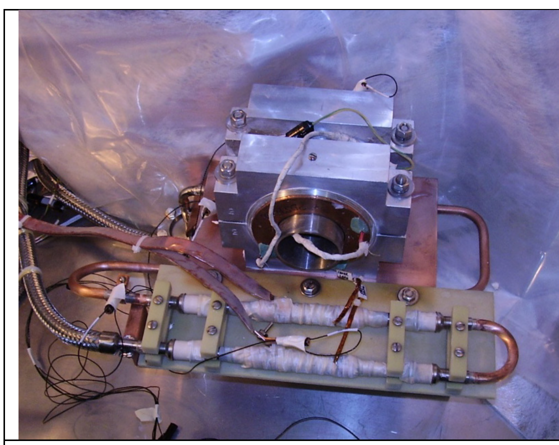

Figure 2: Test coil and LHe heat sink

TEMPERATURE MEASUREMENTS

Cernox™ cryogenic sensors were used where the expected temperature was below ~20 K. Type “E” thermocouples were used to measure higher temperature. Performance of the current leads and the heat exchangers was consistent with the results of numerical modelling: with the expected 1.1 W of heat flow towards the LHe heat sink 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.

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 attached to the base plate below the magnet.

Four film heaters were embedded into the inner layer of the coil winding, as shown in Fig. 1.

At several settings of the heating power, the readings of the temperature sensors in the coil were compared with the coil temperature evaluation based on the quench current measurements. Fig. 3 compares the measured quench current with what would be expected based on the readings of the sensor in the inner layer.

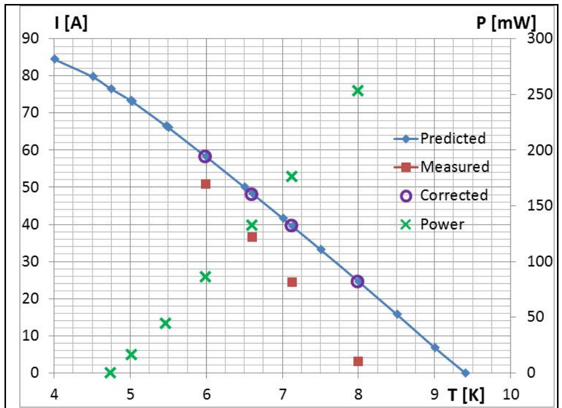

Figure 3: Expected, measured, and corrected quench performance of the test magnet

The blue line in the figure shows expected quench current in the coil at different temperatures. The crosses refer to the total power of the heaters (the scale on the right) needed to raise the temperature measured by the sensor in the inner layer. The red squares reflect the correspondence between the measured quench current and the readings of this sensor. The reason for the discrepancy between the expected and the measured quench current can be understood if to realizing that the heater and the thermometer are spatially separated in the inner layer and by assuming the presence of heat flux within the winding. Circles in Fig. 3 present quench current data corrected for corresponding temperature difference in the coil. Good correspondence between the measured and predicted quench performances indicates that the accuracy of the temperature measurements is adequate. This permits further analysis of the thermal environment by comparing the readings of all temperature sensors.

HEAT FLUX ANALYSIS

Temperature field in the test magnet was shown to depend on the position of the clamps (vertical vs horizontal orientation) and of the radiation shield (attached to the sink plate or to the clamps). The lowest flux to the magnet was registered when the gaps between the halves of the clamps were oriented vertically and the radiation shields were attached to the heat sink plate, which seems quite natural. Graphs in Fig. 4 show the temperatures measured by the thermometers installed on the magnet at different settings of the heater; dashed curves linearize the data.

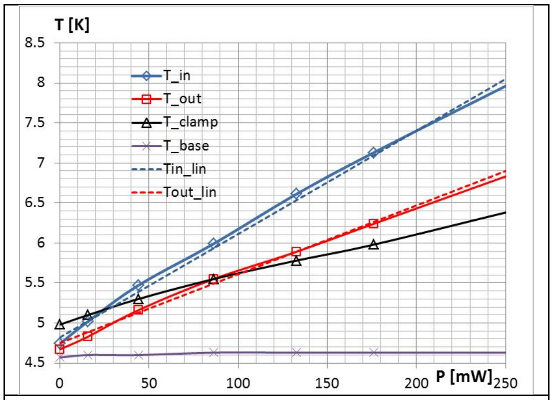

Figure 4: Temperatures in the test magnet at different settings of the heater.

With the heater off, 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 into the system. 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 a possible source. The amount of the flux can be evaluated by using the relation

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

In this expression, 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 $\partial P/\partial T$, where P refers to the heating power. Liner character of the curves in Fig. 4 points towards the existence of an environmental heat flux. For example, the readings of the sensor at the top of the clamp can be explained if the environmental heat flux $P_{flux} \approx 70\ mW$.

The temperatures in the inner and the outer layer can be expressed as functions of the heater power:

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

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

With no heat flux in the coil, one expects $T_{in} = T_{out}$. To explain the measured difference, one needs to assume the presence of an additional heat flux between the inner and the outer layer: $P_{flux} = 16.3\ mW$. Without this flux, and without use of the heaters, the expected temperature of the test coil is 4.61 K; this value 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. Nevertheless, although obtained data seem quite reliable, no clear understanding was obtained at this point on what is the source of the heat flux with two suspects being 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 could be obtained. On the other hand, radiation shields shown in Fig. 1 and installed to intercept direct migration of relatively warm gas towards the surface of the coil definitely resulted in significantly lower environmental heat flux.

Inadequate amount (or poor usage) of MLI material used around the test coil to shield it from the ~90 K nitrogen shield radiation 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 at FNAL by using a conductively cooled test coil in a cryostat equipped with conductively-cooled current leads. Temperature measurements revealed the presence of an environmental heat influx to the test coil; the source of the flux has not been positively identified in this series of tests.

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