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TD-08-017
05/14/2008

Heater analysis in LARP Technological Quadrupole Models

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Introduction

Technological Quadrupole (TQ) models are being built and tested within the LARP collaboration. These magnets have nearly identical coils installed in two different mechanical structures based on the collar and skin (TQC models), and bladder and shell (TQS models). All 2nd generation TQ models made of high-J_c RRP conductor, including TQC02a, TQC02e, TQS02a and TQS02b exhibited no quench current improvement at 1.9 K vs. 4.5 K temperature, abnormal ramp-rate dependence at low ramp-rates, and, sometimes, erratic quench current behavior at 1.9 K that may be related to magnetic instabilities triggered by the flux jumps in superconductor.

In order to verify this hypothesis, we propose to use quench heaters installed on the coil outer surface. That technique was successfully applied in Fermilab's LM-02 magnet made of RRP conductor, where warming the outer layer up by DC current in the strip heater allowed to overcome the magnetic instabilities and increase the magnet quench current by ~25%.

Thermal Model

The insulation scheme of TQ magnets consists of multiple layers of ceramic, glass and Kapton tapes. Due to the fine variations of the insulation types and thicknesses between different TQ magnets, the analysis was performed for the insulation scheme of TQC02a magnet that is to be reassembled and retested. In addition to the 5-mil ceramic sleeve comprising the cable insulation, that magnet had:

- 5-mil glass sheet at the inner coil surface of TQC02;
- 5-mil Kapton trace with embedded 1-mil heaters around the coil;
- 5-mil glass sheet around the trace, impregnated with the coil;
- 2x5-mil Kapton sheets around impregnated coils
- 5-mil glass sleeve around the wedges;
- 5-mil of glass between the poles and the pole turns;
- 24 mils of Kapton between the coils in the midplane.

The finite-element thermal model, shown in Fig. 1, was created and solved by Comsol Multiphysics. The boundary conditions included fixed T_0 = 1.9 K temperature at the inner and outer coil surfaces that are in contact with superfluid helium and thermal insulation in the pole plane that is equivalent of powering both octant heaters of one coil at the same time. The coil structure extended sufficiently below the midplane to capture the heat flux crossing the midplane. The thermal properties of epoxy-impregnated ceramic and glass insulation were assumed the same as across the fibers of G-10 material. The material thermal conductivities were parameterized after [1] in the relevant temperature range.

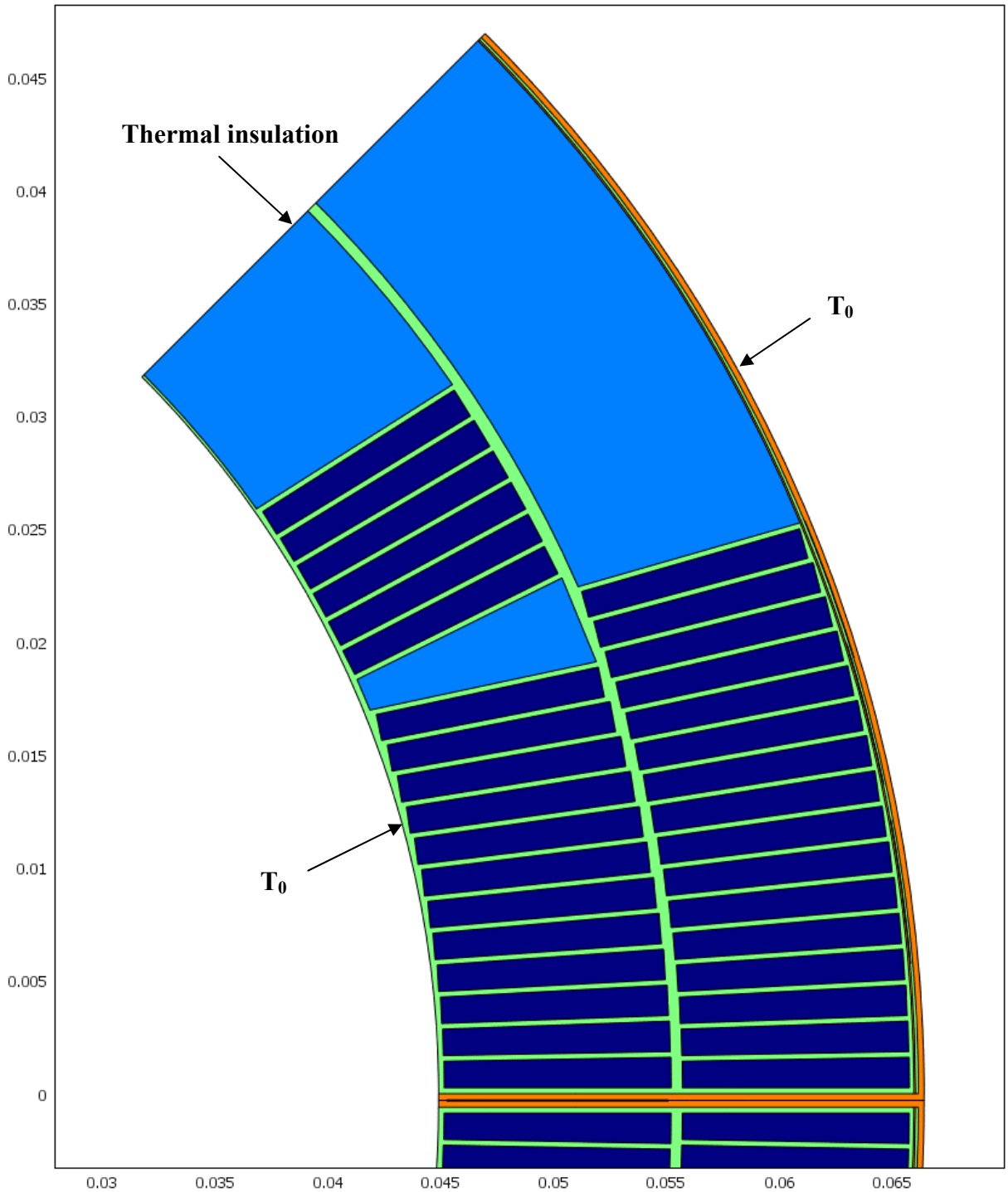

Figure 1. TQC thermal model.

Thermal analysis

The thermal analysis was performed at different heater powers. Fig. 2 shows the temperature distribution in the coil at the heater power of 12 W/m. Under the heater power, we here and after refer to the total power dissipation per coil octant from both strips of the heater. The maximum and minimum temperatures in the outer and inner layer (OL, IL) conductors are shown in Fig. 3 along with the heater temperature.

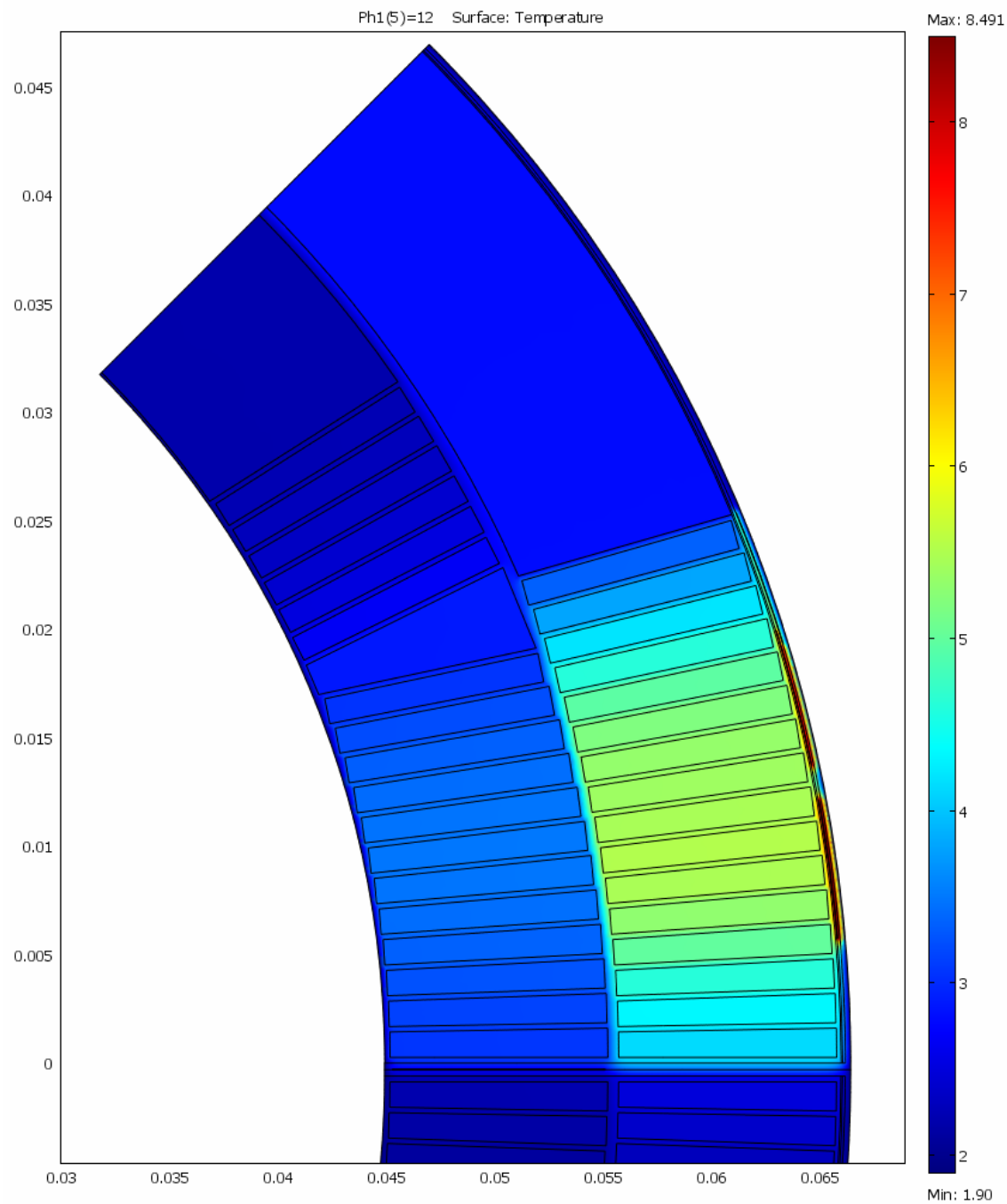

Figure 2. Coil temperature distribution at the heater power of 12 W/m.

There is rather large temperature variation between the conductors of the same layer and between the layers. However, it turns out that the minimum temperature of the OL conductors is close to the maximum temperature of the IL that creates thermal separation of the two layers. As a starting point, we propose to use the heater power of 25 W/m that results in the OL staying above 4.5 K and the inner layer below 4.5 K. Thus, if the magnetic instabilities in the OL were the performance-limiting factor at the bath temperature of 1.9 K, one would see the quench current improvement with respect to the 4.5 K test after switching the heater on due to the lower temperature in the IL and suppression of the instabilities in the OL. Afterwards, the heater power may need to be finely tuned to find the balance between the IL temperature and the level of instabilities in the OL that yields the maximum quench current.

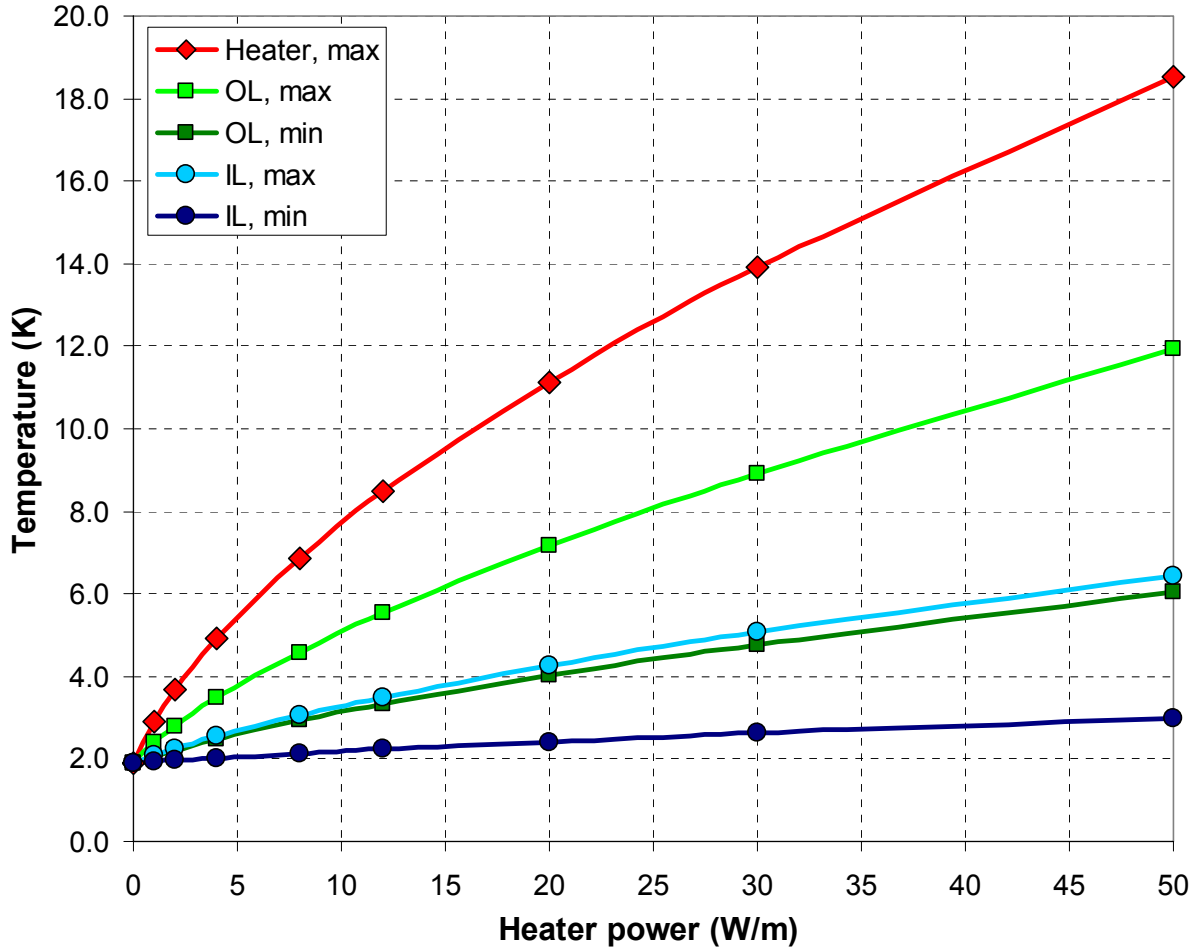

Figure 3. Coil temperatures as functions of the heater power.

Effect of copper cladding

The coils 17 and 19 did not limit the TQC02a quench performance and are to be reassembled with two MJR coils from TQC01 magnet and retested. Both of these coils have 1-mil stainless-steel strip heaters with copper cladding. Because of that, the heater power is delivered in discontinuous manner along the coil. In order to check the effect of cladding on the temperature distribution, a simplified 2D model was built.

The model represents the coil section by a plane formed by the magnet longitudinal axis and the midplane axis, tilted around the magnet center by ~8 degrees towards the pole, such that it cuts through the middle of the lower heater strip. The coil dimensions, properties, and boundary conditions were identical to the previously described model. In the coil straight section, the heater had copper-clad regions of ~112 mm separated by the non-clad regions of ~58 mm. The model included one heater pitch, from the middle of the non-clad region to the middle of the next copper-clad region. Two cases were simulated. In the first one, the power was applied to the whole heater strip (non-clad case); in the second one, all heater power was applied to the non-clad region (copper-clad case). The power averaged along the strip pitch was the same in both cases. The temperature distributions are shown in Fig. 4-5 for both cases. One can see that while the heater temperature is higher in the copper-clad case, the longitudinal variations of the conductor temperatures are small and the average temperatures are equal to those in the non-clad case. So, for our purposes, the effect of copper cladding can be neglected.

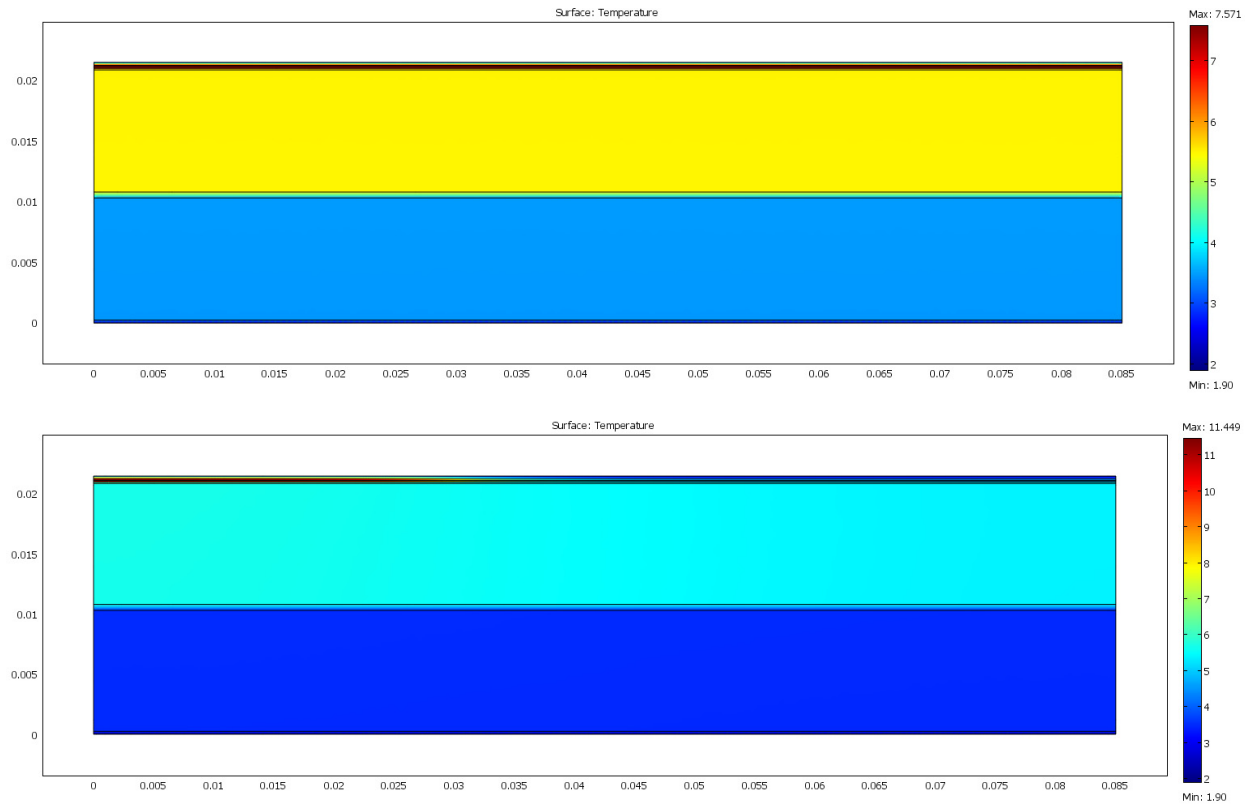

Figure 4. Temperature distribution in the coil longitudinal cross-section without the copper cladding on the heater (top) and with the copper cladding (bottom).

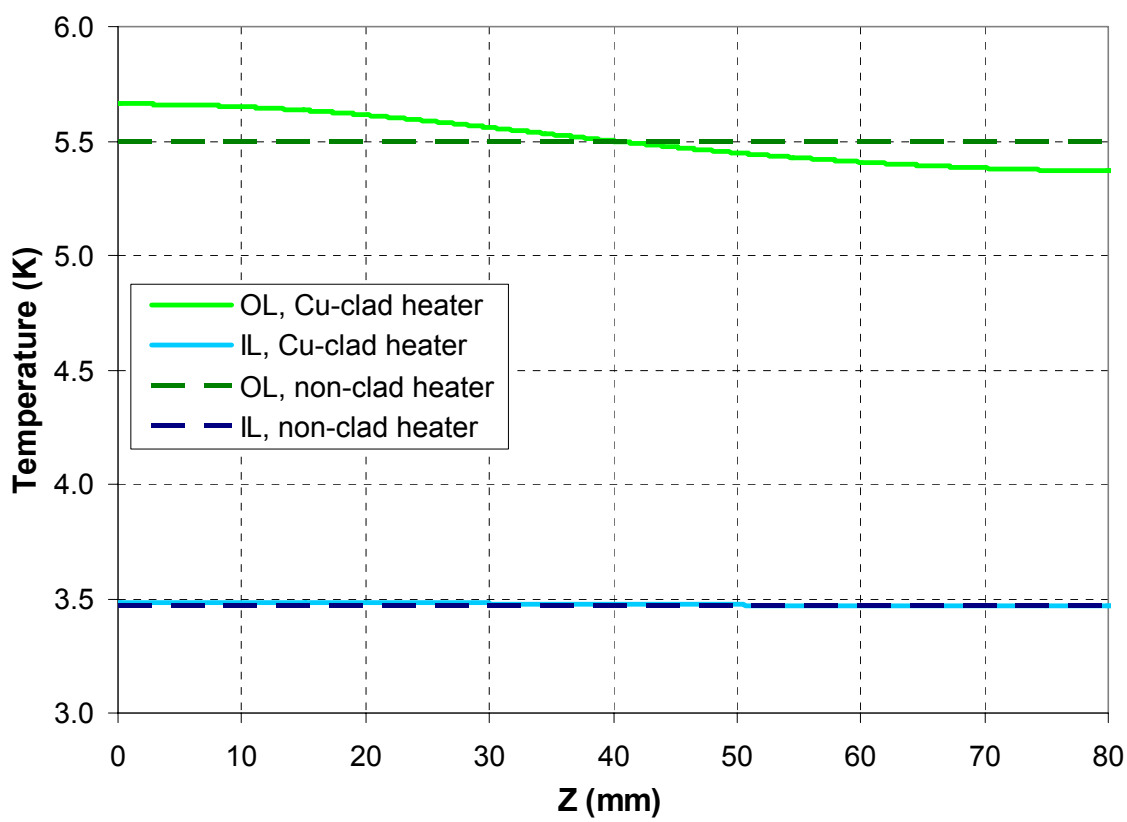

Figure 5. Temperatures in the OL and IL conductors as functions of the longitudinal coordinate.

Current and cryogenic requirements

The heaters of TQC02a coils 17 and 19 were interconnected in two circuits, each consisting of one octant heater of coil 17 and one octant heater of coil 19. The resistances of the heater circuits measured at the liquid helium temperature were 5.14 Ω and 5.17 Ω. It translates to the average resistance of one octant heater of 2.58 Ω. The total loop length consisting of two heater strips is ~1.8 m. Now it is possible to express the coil temperatures and heater power in terms of current in the octant heater, as shown in Fig. 6-7. The initial objective on the heater power of 25 W/m corresponds to the heater current of 3 A. The total power dissipation in this case is 46 W per coil (both octants) or 92 W for both coils 17 and 19 made of RRP conductor. During the LM02 test, the total heater power dissipation was in excess of 100 W without an adverse effect on VMTF cryogenics [2]. However, in case of TQ magnet assembled of all RRP coils that need to be simultaneously warmed up, the total power dissipation may exceed the cryogenic capacity, in which case the heater current has to be reduced.

It was mentioned earlier that the thermal analysis was performed in assumption of a constant 1.9 K temperature at the IL and OL coil surfaces. This condition is satisfied for the heat flux below the critical value of λ-transition that depends on the cooling channel dimensions and pressure. Figure 8 presents the normal heat flux at the IL and OL coil surfaces that are in contact with liquid helium for the heater power of 25 W/m. The maximum surface heat flux in that case is 300 W/m^2. The serrated heat flux structure at the IL represents the individual coil turns.

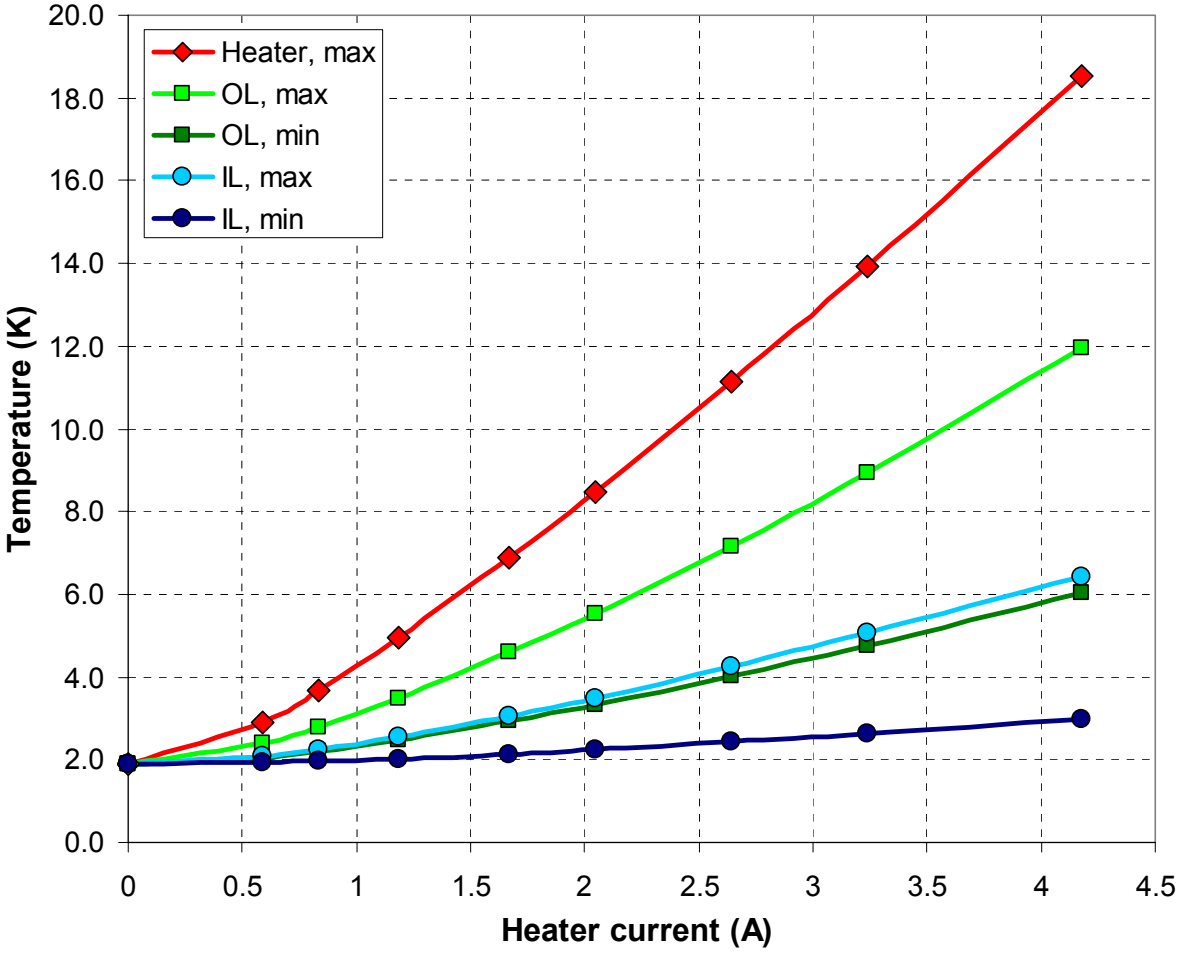

Figure 6. Coil temperatures as functions of the heater current.

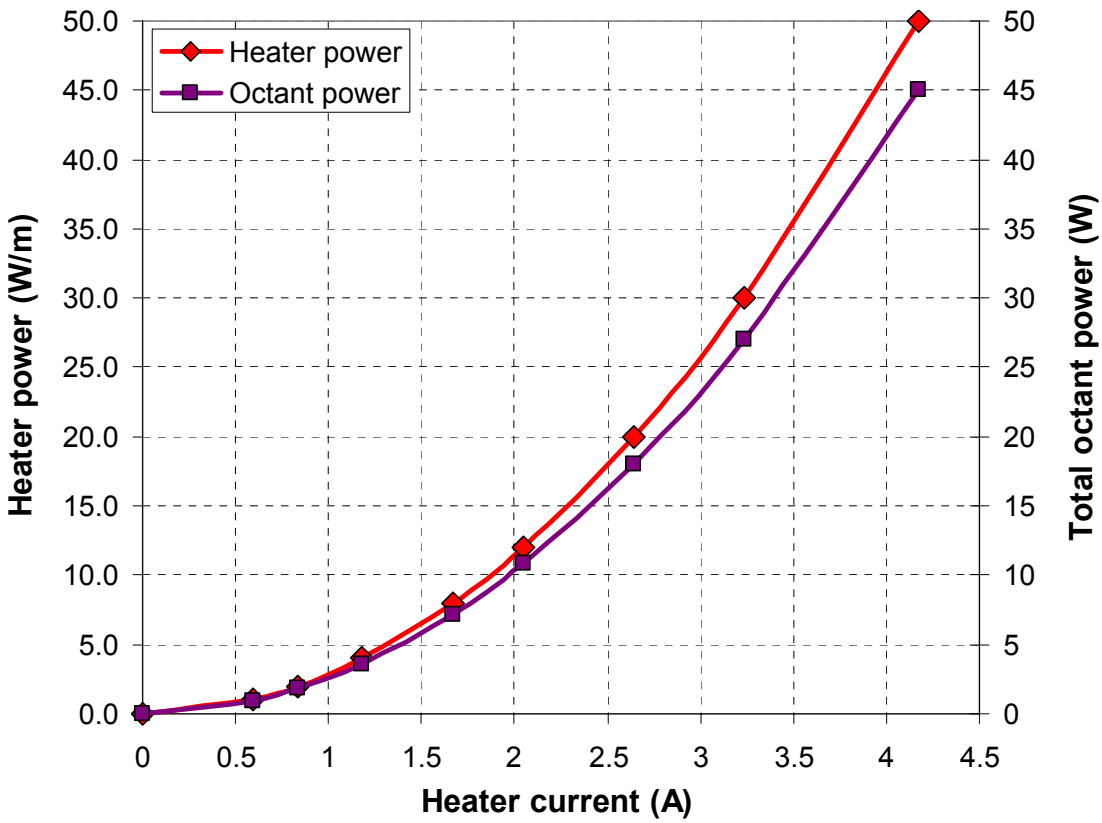

Figure 7. Heater power as function of the heater current.

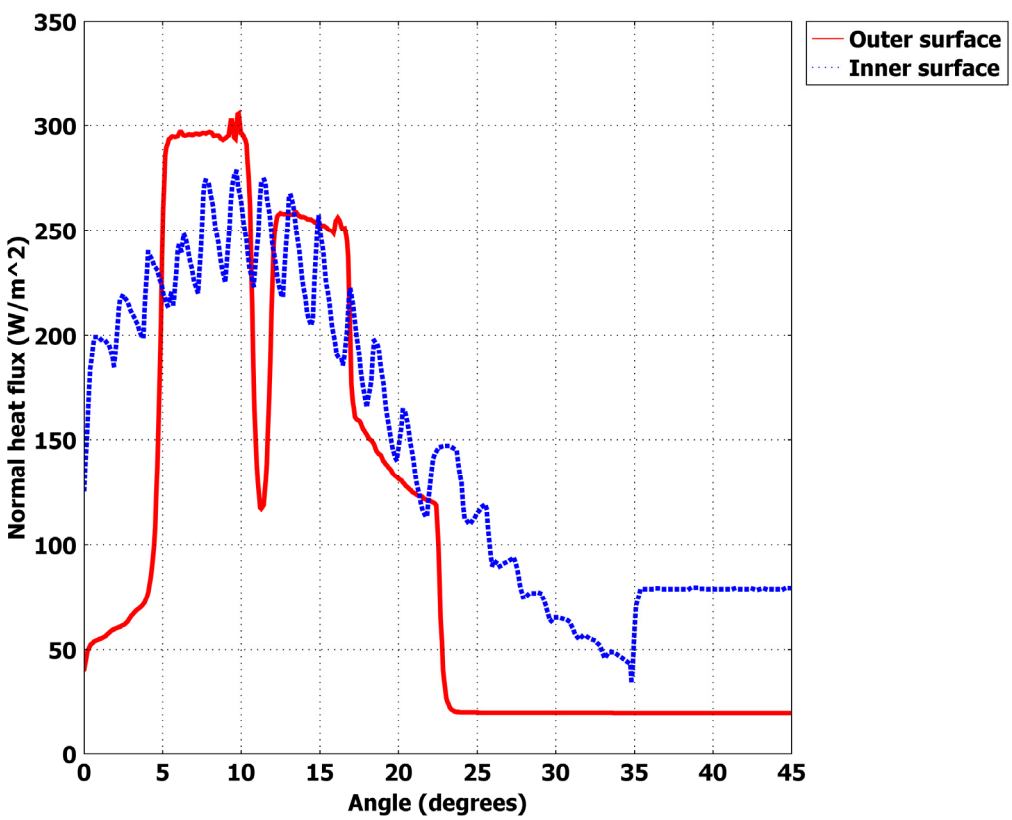

Figure 8. Surface heat flux as a function of angle (origin is in the coil midplane).

References:

1. E.D. Marquardt, J.P. Le, and Ray Radebaugh, "**Cryogenic Material Properties Database**", *Presented at the 11th International Cryocooler Conference June 20-22, 2000 Keystone, Co*.
2. G. Chlachidze, G. Ambrosio, N. Andreev, E. Barzi, R. Carcagno, V.V. Kashikhin, F. Lewis, F.Nobrega, I.Novitski, D. Orris, Y. Pischalnikov, D. Shpakov, C. Sylvester, M. Tartaglia, J.C. Tompkins, G. Velev, R.Yamada, A.V. Zlobin, **"LM02 Mirror Magnet Test Summary"**, *Fermilab Technical Division Note, TD-08-003, March 19, 2008*.