Unsteady heat dissipation in accelerator superconducting cables insulated with polyimide insulation in normal and supercritical helium

Sławomir Pietrowicz[1,2], Nobuhiro Kimura[1], Bertrand Baudouy[2], Akira Yamamoto[1]

[1]High Energy Accelerator Research Organization, KEK, Tsukuba, Ibaraki 305-0801, Japan
[2]CEA Saclay, IRFU/ SACM, 91191 Gif-sur-Yvette, France

In order to predict the thermal characteristics of superconducting cables insulated with polyimide tapes dedicated for accelerator magnets, several unsteady heat transfer experiments were performed in different thermodynamic helium conditions. An experimental mock-up reproducing the heat transfer configuration of a stack of insulated Rutherford cables was used. Unsteady heat dissipations were performed at normal ($T = 4.23$ K and $p = 1$ bar) and supercritical helium conditions ($T = 4.23$ K and $p = 2.0$ to 3.75 bar) and temperatures in the cables were recorded. The values of localized heat load changed in a wide range from 0.1 kJ/m^3 per pulse up to 1.122 MJ/m^3 per pulse. The evolutions of temperature rise as function of time for short and “infinite” pulse duration representing time limited heat dissipation and a quench event are presented.

INTRODUCTION

In the present paper the experimental results obtained during transient heat dissipation process are presented. This research is a part of a study aiming at a general understanding on heat transfer in accelerators magnet coil cooled at helium temperature range. The steady-state conditions have been already investigated to model the quench event of a magnet [1]. In real magnet operation conditions, the dissipated energy from beam losses is delivered in a heat pulse manner. Therefore, transient heat dissipation investigations in magnet coils are necessary for the designing accelerators magnet and for improving our understanding of the heat transfer mechanisms.

For analyzing a pulse process in magnet it is useful to introduce a new parameter named localized heat load (J/m^3 per pulse) which is the product of the heating time, (*s*) and the unit heat load (*W/m*) divided by cross section of the cable (m^2) for example in the J-PARC magnets, the estimated value is about 20 kJ/m^3 per pulse [2].

The LHC superconducting magnets are operated in superfluid helium but some can be operated in pool boiling [3] or supercritical [2] helium conditions. For that reason the experiment was performed at normal (4.23 K and 1 bar) and supercritical helium ($T = 4.23$ K and $p = 2.0$ to 3.75 bar). The time of pulse heat load varied from 0.1 to 50 s and unit heat dissipated by Joule effect up to 1.4 W/m. The combination of time and unit heat load induced that localized heat load was ranging from 0.1 to 1122 kJ/m^3 per pulse.

EXPERIMENTAL SETUP

The experimental model reproduces the mechanical and thermal conditions of an accelerator magnet coil. The magnet coil is modeled by a stack of five stainless steel conductors of 150 x 17 x 2.56 mm^3 (LxWxH) dimensions. On the external surfaces of the steel conductors, special grooves imitating the geometrical structure of Rutherford cables were machined. The mock-up with assembled stack of samples was described in detail in [4].

The electrical insulation configuration of five conductors is exactly the same and is very similar to the one of the LHC magnets [3]. The electrical insulation consists in two wrapping layers. The first layer material is Kapton® 200 HN (50 μm x 11 mm) with an overlap of 50%. The second layer material is Kapton® 270 LCI (71 μm x 11 mm) with a 2 mm gap to create helium channels.

Additionally to capture the real conditions in magnet, one side is covered with a G-10 insulation called "fishbone" as it is done in the LHC magnet [3]. The opposite side was thermally blocked. This thermal configuration corresponds to the second layer of the LHC dipole coils [3]. The configuration of the stack is depicted in Figure 1 a.

During the experiment the localized heat load with rectangular shape was generated in the central conductor (Figure 1 b). The three central conductors of the stack are instrumented with Allan–Bradley temperature sensors called T_{II}, T_{III} and T_{IV} (Figure 1 c). The measurement and control systems consist of a wave generator connected to a power supply; an analog-digital converter used for recording voltages across a shunt resistor with known linear characteristics to determinate the power dissipated and across the Allen-Bradley resistance to determinate the temperature, (Figure 1). During the tests, two CERNOX™ temperature sensors placed at the bottom and top of the holder were used for temperature sensors calibration and monitoring the temperature inside the measurement chamber. Totally eight signals were recorded at a frequency probe of 1 kHz.

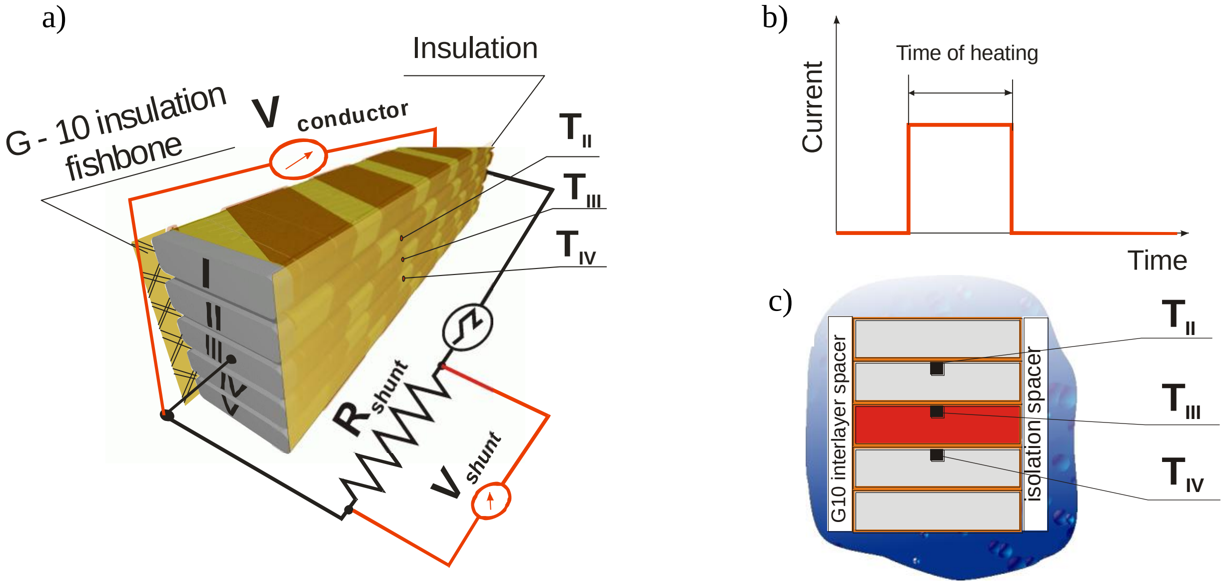

Figure 1 a) Configuration of the stack with the polyimide insulation b) shape of pulse, c) localization of temperature sensors

The holder with the conductors was mounted in the cryostat on a special frame (Figure 2 b). Its base and two sides in contact with the holder were perforated by making the grooves creating space and ensuring contact with helium.

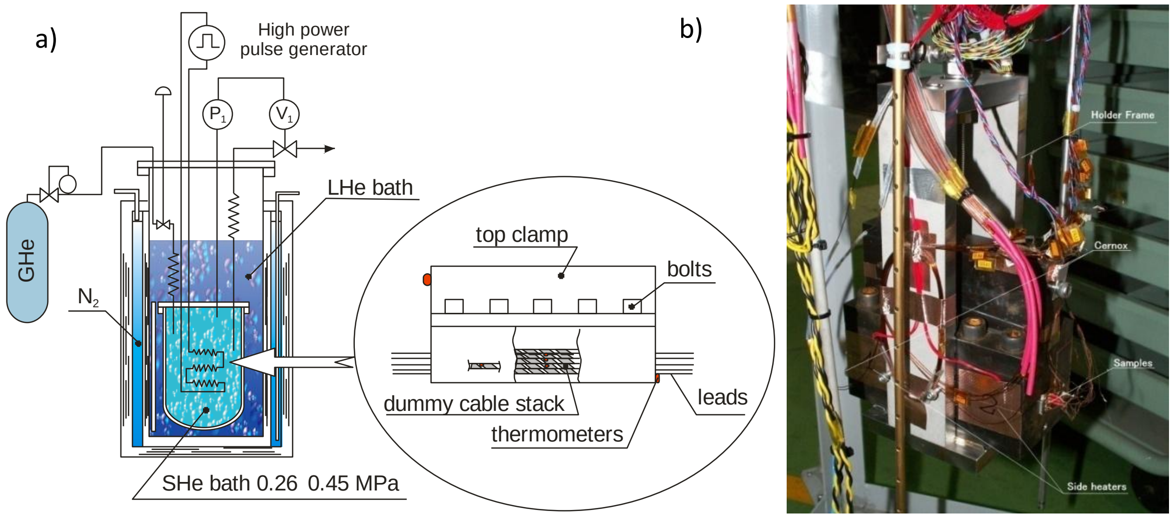

Figure 2 a) The cryostat with assembled holder, b) the picture of holder with instrumentation

The experiment was performed for the different scenarios of energy dissipation. The heating time changed in the following steps: 0.01, 0.05, 0.1, 0.5, 1, 5, 10 and 50 seconds. For each value of heating time the pulse current values were: 3.74, 5.29, 6.48, 7.48 and 8.37 A. For the values mentioned above the localized energy load changed in the wide range from 0.1 to 1122 kJ/m^3 per pulse. For all pulses, the chamber temperature stayed constant around a value of 4.23 K. The value of the absolute pressure was automatically regulated by means of the V_1 valve conjugated with P_1 gauge pressure (Figure 2 a). The measurement was done for absolute pressure of 2.0, 2.5, 3.0, 3.5 and 3.75 bar.

Examples of the evolution of temperature in each conductor when the central conductor was heated alone with a unit heat load of 978.2 mW/m, a constant absolute pressure of 3.75 bar and a current of 8.37 A are shown in Figure 3. The pulse heating time varied from 0.5 to 50 s and the combination of heating time and the value of heat load leads to different localized energy load of 11.21, 112.16, 224.21 and 1122 kJ/m^3 per pulse, respectively. During the experiment the highest temperature rise (1.58 K) was observed in the heated conductor III (the central conductor) for the localized heat dissipation -1123.9 kJ/m^3/pulse (Figure 3 d). With decreasing localized heat load, the temperature rise was lower and for 11.2 kJ/m^3/pulse equal to 0.139 K (Figure 3 a).The evolutions of temperature rise in adjacent conductors (T_{II} and T_{IV}) are shown in Figure 3 as well.

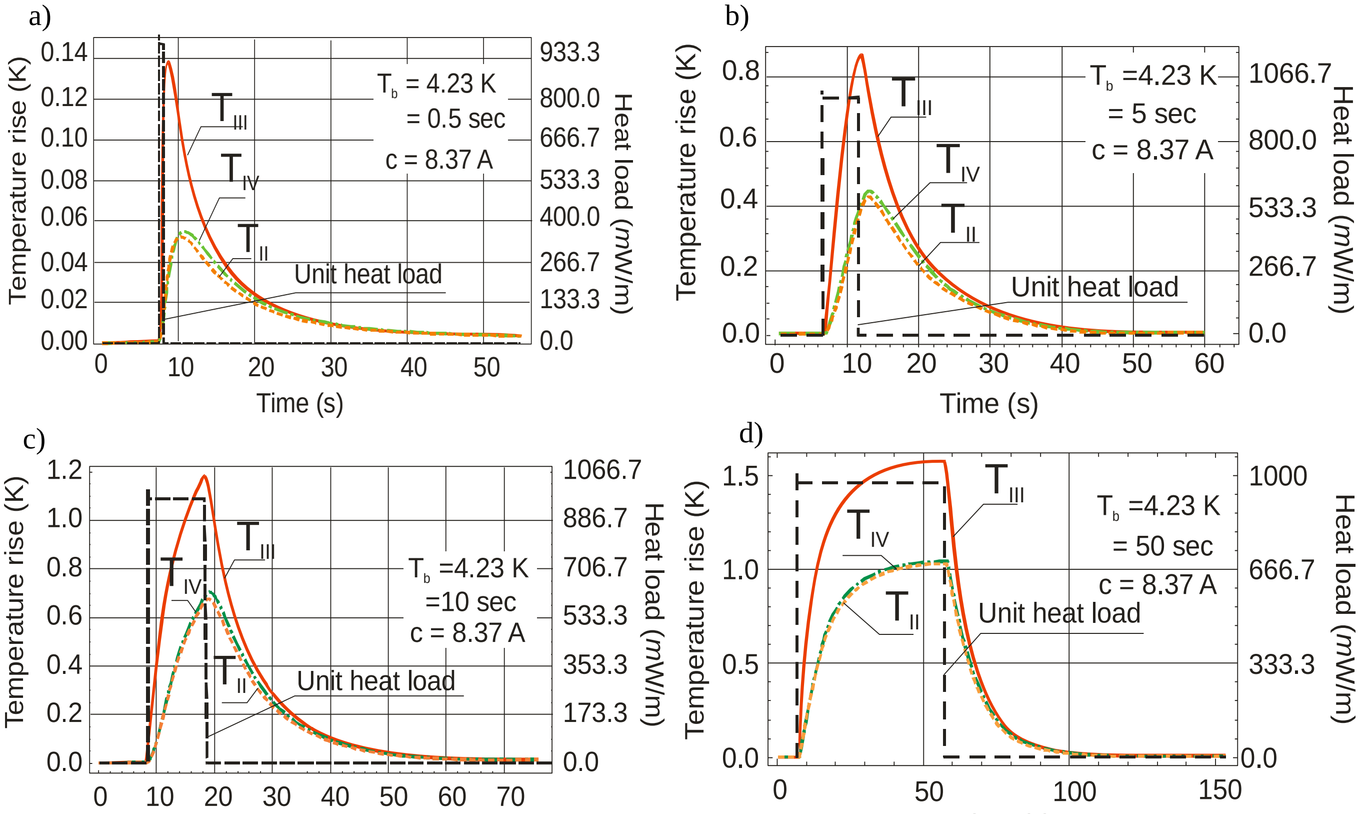

Figure 3 Temperature rise in each conductor as a function of the heating time for a constant current of 8.37 A and an absolute pressure of 3.75 bar, a) heating time: 0.5 s and localized energy load 11.21 kJ/m^3/pulse, b) 5 s and 112.16 kJ/m^3/pulse, c) 10 s and 224.21 kJ/m^3/pulse, d) 50 s and 1122 kJ/m^3/pulse

The maximum temperature rises at the end of heating process versus localized heat load are presented in Figure 4. Each series of experiment was performed for a constant unit heat load in the central conductor and different values of the heating time steps: 0.01, 0.05, 0.1, 0.5, 1, 5, 10 and 50 seconds. These procedures were repeated for each value of unit heat load: 194.7, 587.7, 784.1, and 978.2 mW/m.

It can be seen, especially for the central conductor, (Fig. 4 b), that for a value up to 6 kJ/m^3/pulse (region 1) the obtained results are collected around two parallel slopes. The highest slope is characterized by lower value of unit heat load and the lowest slope is obtained for the highest value of unit heat load. The explanation of that difference can be due to different mechanism of heat transfer from heated conductor to surrounded helium. As it was mentioned in [5] for the lower values of heat load the dominating mechanism of heat transfer can be natural convection and for higher heat load values nucleate boiling heat transfer. From the specification of cable and value of unit heat load, the heat flux from the cable for highest values of temperature rises is 4.9 W/m^2 and 14.8 W/m^2 and for lower values of temperature rise is 19.8 W/m^2 and 24.6 W/m^2. These values are in very good agreement with the values characterizing a transient boiling heat transfer. For the value higher than 6 kJ/m^3/pulse, (region 2), the tendency of the higher slope changed which suggests that the mechanism of heat transfer is changing from natural convection to nucleate boiling.

It can be also observed that the temperature rises in conductor II and IV are different which is the consequence of unsymmetrical placements of the temperature sensor in the stack (Figure 1c), some amount of heat is transferred through flanks of conductor II.

For the high values of localized heat load the temperature rises achieved the values obtained during steady state process [1], which means that stationary condition is achieved after 50 s.

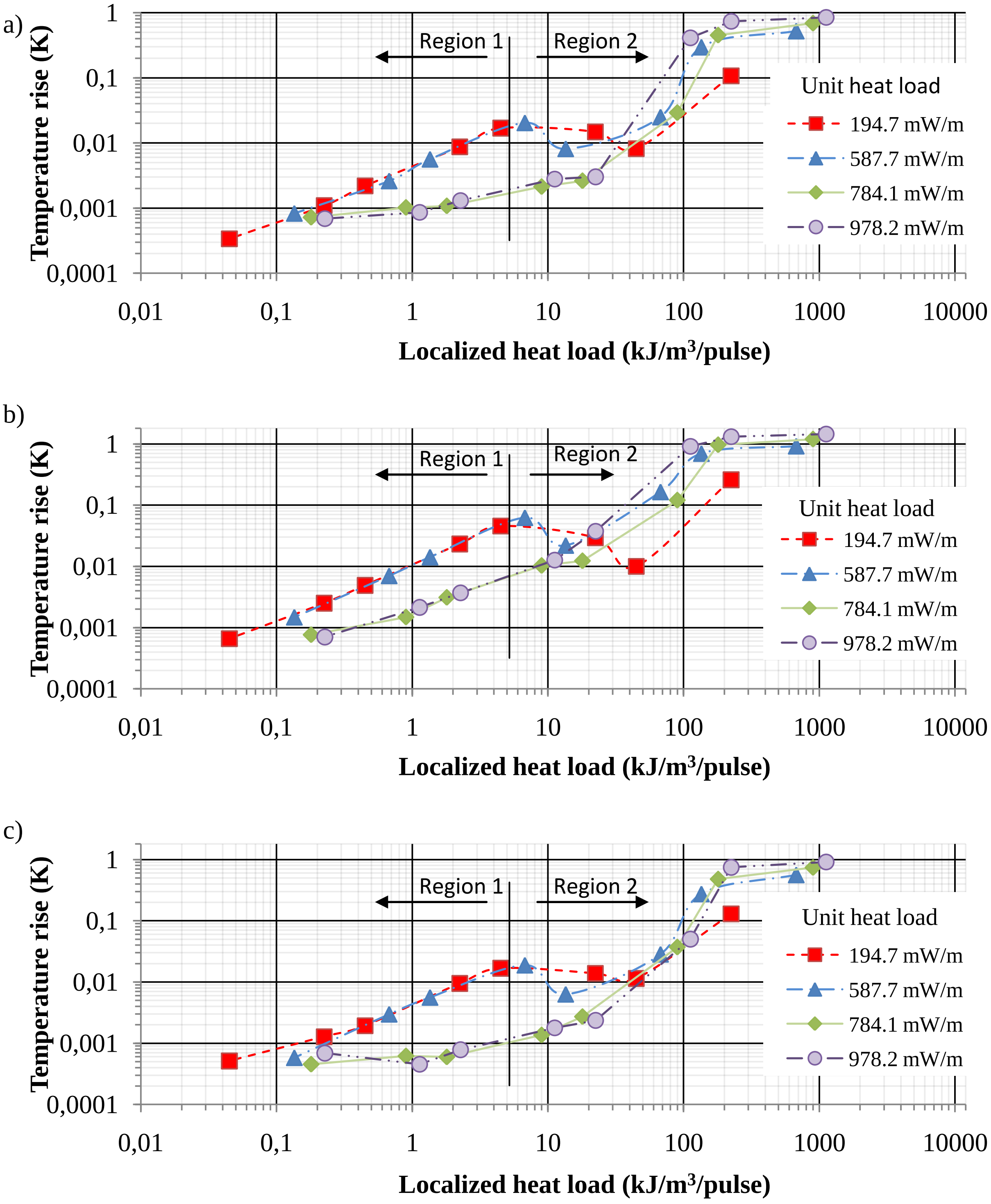

Figure 4 Temperature rise as the function of localized heat load for each conductor: a) conductor II, b) conductor III (heated), c) conductor IV

EXPERIMENT AT SUPERCRITICAL HELIUM

Very similar experiments were done for supercritical helium conditions. The temperature in the experimental chamber was constant and equal to 4.23 K, the absolute pressure was fixed for 2.0, 2.5, 3.0, 3.5 bar. The values of localized heat load varied from 0.2 to 1123.9 kJ/m^3 per pulse. The evolutions of the maximum temperature rise in each conductor are presented in Figure 5.

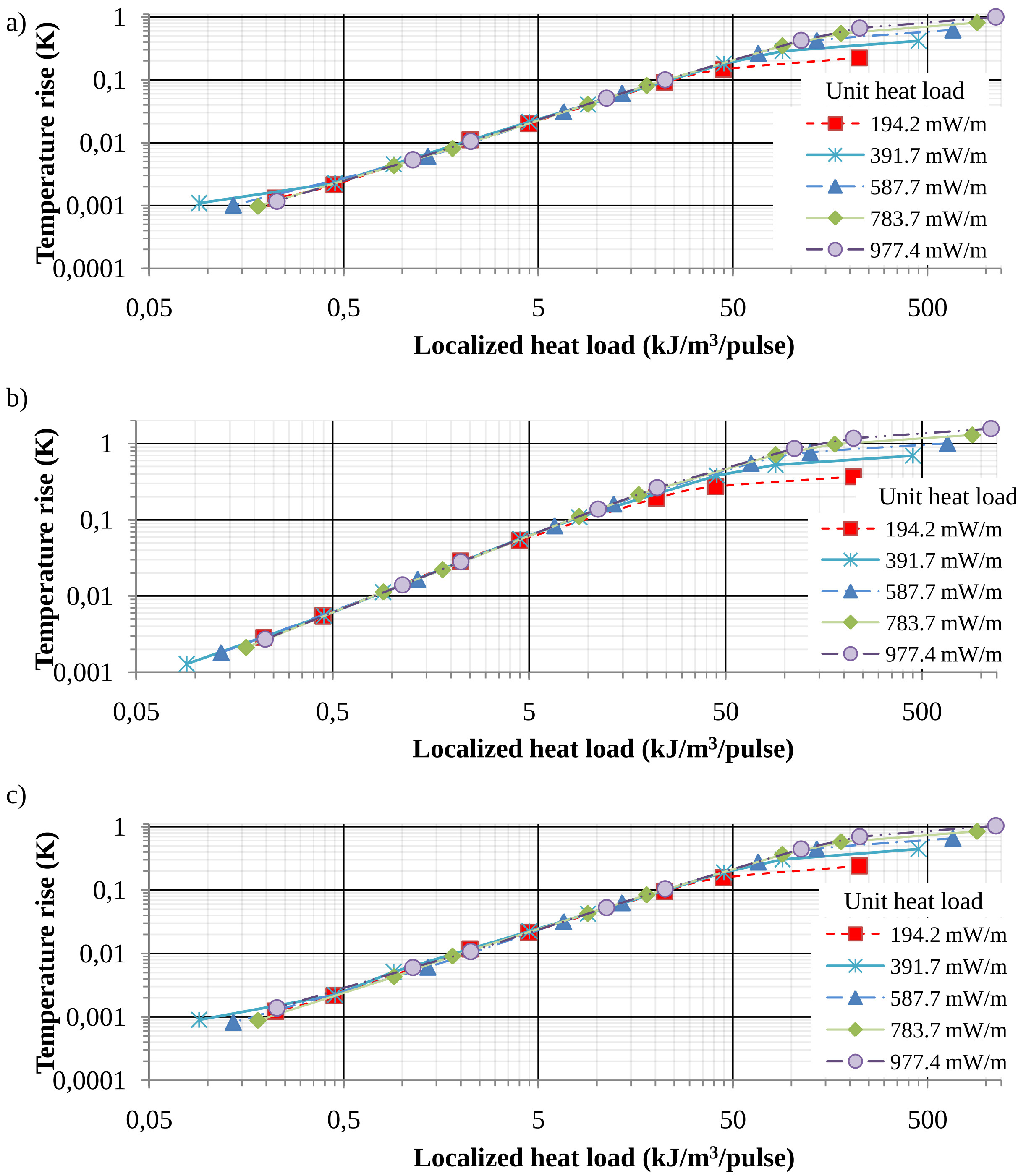

Figure 5 Evolution of temperature rise vs. localized heat load for absolute pressure 3.75 bar a) conductor II, b) conductor III (heated), c) conductor IV

When the value of localized heat load increased the temperature rise enlarged as well. In the double logarithms coordinates, obtained data up to 15 kJ/m^3/ pulse were assembled around straight line which means that during the process only one mechanism of heat transfer occurs. For the highest value of localized heat load the temperature rises reached the values obtained during steady state heat load (after 50 seconds). The example of experimental results for absolute pressure 3.75 bar with plotted value of temperature rises obtained during steady state is shown in Figure 6.

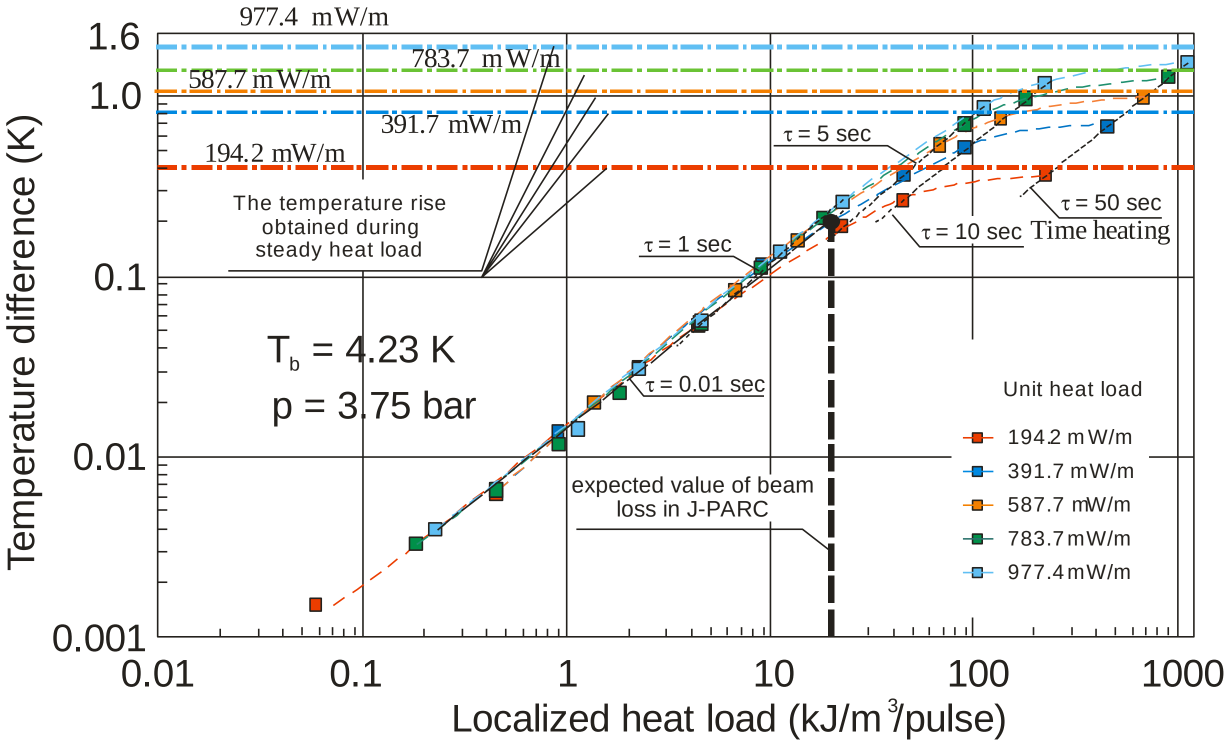

Figure 6 The comparison of temperature rise in the heated sample for steady and unsteady pulse heat load

It is worth mentioning that for the highest values of absolute pressure the temperature rise is higher, for example for 2.00 bar, ΔT=1.48 K, for 3.75 bar ΔT=1.58 K for the same value of localized heat load equaled 1123.9 kJ/m^3/pulse.

CONCLUSION

The unsteady heat dissipation in mock-up of superconducting stack of cables has been experimentally investigated at saturated and supercritical helium conditions. The experiment showed different mechanism of heat transfer during the dissipation of heat up to 6 kJ/m^3/pulse in saturated helium. In supercritical helium for testing range of localized heat load up to 25 kJ/m^3/pulse the results gathered around the straight line in the double logarithm coordinates, finally after 50 s temperature rise reached the values obtained during steady heat load conditions.

REFERENCES

1. Pietrowicz S., Kimura N., Baudouy B., Polinski J., Yamamoto A., Thermal behaviors of Rutherford type stack of cables with polyimide isolation in normal and supercritical helium, International Cryogenic Engineering Conference – 12 , Seoul, Korea, (2008), 297 - 302
2. Iwamoto Y., Kimura N., Ogitsu T., Ohata H., Nakamoto T., Nabe K., Ichikawa A., Yamamoto A., Quench Stability Against Beam-Loss in Superconducting Magnets at the 50 GeV Proton Beam Line for the J-PARC Neutrino Experiment, IEEE Transactions on Applied Superconductivity (2004) 2 592 -595.
3. Bruning O., Collier P., Lebrun P., Myers S., Ostojic R., Polle J., Proudlock P., LHC Design Report, Volume I The LHC Main Ring, Geneva 2004
4. Meuris C., Baudouy B., Leroy D.; Szeless B., Heat transfer in electrical insulation of LHC cables cooled with superfluid helium, Cryogenics (1999) 39 921 – 931
5. Steward W. G., Transient helium heat transfer phase-1-static coolant, Int. J. Heat Mass Transfer (1978) 21, No. 7, 863–874.