New FRESCA sample holder for cable stability experiments

G. Willering, C. Denarié, S. Geminian, A. Verweij – AT/MAS
Summary

For the reception tests of superconducting cables at CERN, the test station called FRESCA is used. About a year ago it has been decided to modify FRESCA in such a way that also stability measurements can be performed. For a stability measurement we would like to give a short heat pulse to a single strand and measure voltages, temperatures and current redistribution close to the heated area. In order to do so, a new sample holder design is made. This report will describe the new sample holder and technical details of the standard experiments that are foreseen. For stability experiments an electrical pulse is given to a resistor mounted on one of the strands, acting as a heater. As resistor both strain gages and graphite paste is used. The effectiveness of this method and the difference between these resistances will be discussed in this paper. To measure the self field of the cable, two Hall probe arrays are placed in the magnetic field at the position where the heat pulses are given. The current distribution can be extracted from this Hall probe array measurement. Measurement results will follow in a next paper.

1.- Introduction and objective

For superconducting magnets, like LHC, a good understanding of stability is needed for optimal operation of the magnets and to better predict the effect of beam losses. For the design of future applications of superconductors a stable conductor is needed and for this purpose we need to extend our knowledge of the stability of superconducting cables.

Stability measurements on superconductors are performed on different levels. A lot of data is known about stability of superconducting strands, for example [1], but there is a lack of experimental data and theoretical modelling on stability of superconducting cables. Some Minimum Quench Energy (M.Q.E.) measurements on Rutherford Nb-Ti cables are done [2, 3] and rough calculations are made [4] predicting M.Q.E. versus I/Ic curves for bare and soldered Rutherford cables. Also some three strand cable models are made with a network model [5,6].

The FRESCA test station, see figure 2, is in the past years mainly used for reception tests of superconducting cables used for LHC magnets. For this purpose several sample holders for testing the cables of different types are available. In all these sample holders the two cables are assembled in a bi-filary geometry and separated by two 25 µm thick layers of kapton and pressed together. Two Hall probe arrays of 26 Hall probes are placed parallel to the two cables on the top part of the cables, outside of the magnetic field. These Hall probe arrays are mounted to measure the self field and hence determine the current distribution in the cable at the position of the array. Research for boundary induced coupling currents and measurements of time constants of current distribution in the cable are done.
Figure 1. Example of a Nb-Ti Rutherford type superconducting cable.

<table>
<thead>
<tr>
<th>CABLE</th>
<th>Type 01</th>
<th>Type 02 and 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of strands</td>
<td>28</td>
<td>36</td>
</tr>
<tr>
<td>Width</td>
<td>15.1 mm</td>
<td>15.1 mm</td>
</tr>
<tr>
<td>Mid-thickness @ 50 MPa</td>
<td>1.900 mm</td>
<td>1.480 mm</td>
</tr>
<tr>
<td>Keystone angle</td>
<td>1.25 deg</td>
<td>0.90 deg</td>
</tr>
<tr>
<td>Cable transposition pitch</td>
<td>115 mm</td>
<td>100 mm</td>
</tr>
<tr>
<td>Min. $I_c$ @ 1.9 K</td>
<td>$13750$ A @ 10T</td>
<td>$12960$ A @ 9T</td>
</tr>
</tbody>
</table>

Table 1. Main Characteristics of LHC Cables

We would like to investigate the stability of Rutherford type superconducting cables, see figure 1, as a function of several design parameters, especially the following:
- effect of Helium content in the voids of the cable
- effect of $R_c$ and $R_a$, the contact resistances between strands
- effect of the RRR-value of the used copper
- effect of oxidization of the cables
- local effects, due to cable geometry like the keystone angle

We will mainly use the LHC type 01 cable for our experiments, which is used for the inner layer of the LHC main dipoles. This 28 strand Nb-Ti cable has a keystone angle of 1.25°, see table 1 for some data. By giving a point-like disturbance to one of the strands the mechanisms that affect stability are studied. The main mechanisms are current (re)distribution and heat transfer between strands and to the surrounding Helium I or II. Main instrumentation is formed by Hall probe arrays, temperature sensors and voltage taps, all mounted close to the disturbed area. Especially disturbances just above and just below minimum quench energy (MQE) are of interest. MQE will be determined to give insight of the stability of the cable for changing applied magnetic field, $I/I_c$ and temperature. Performing detailed study on local differences in the cable, the thin and thick side caused by the keystone angle, should give information about the stability improving mechanisms.
2.- Technical details of the sample holder

2.1. Design criteria

For the aimed research a new sample holder is designed. The restrictions for the layout of the new sample holder are foremost given by geometrical limits, fitting in the actual setup of the inner cryostat [7]. The cross-surface available for the sample holder is 35 by 36 mm and is limited by the size of the stainless steel insert, as visualized in figure 3. In order to keep the two cables in position, preventing prequenches due to cable movement, a pressure of at least 30 MPa is applied on the stainless steel bars of the sample holder with the bolts of the insert. Special design conditions concern the two Hall probe arrays which are placed in the center of the field area, parallel to the length direction of the cable, located next to both cable samples. Each Hall probe array of 26 probes is connected by 54 wires. Together with wiring for heaters, thermometers and voltage taps more than 120 wires are used and to house them we need sufficient space. Besides that, the two cables have to be separated as much as possible, so the self field of one cable has only a small effect on the Hall probes of the other cable.
2.2 Sample configuration

The sample holder is designed to measure the LHC-cable types 01 and 02. The longitudinal configuration of the two cables is schematically presented in figure 4. There are always two cable samples needed to make a closed current loop. These two samples are in this case separated by 12 mm. This has the disadvantage that the sample holder can only be used with the field applied parallel to the cable, see figure 3, the so-called directions c and d, because the torque forces caused in perpendicular field would be too large.

They are caused by the Lorentz force, which has a linear relation with the distance between the cables. Note that in the original set-up, used for reception tests of the LHC cables, the two cable samples are separated by only 50 µm.
2.3 Sample holder

Figure 5 shows two cross-sections of the G10 and stainless steel sample holder, which was especially developed for the stability measurements. This 1.8 meter long sample holder consists of the 2 stainless steel bars of 1.8 meter and 6 pieces G10 of 30 cm. The bottom two and the upper three of the G10 pieces are identical and shown on the left.

The third piece from the bottom has the space for the Hall probe arrays and is shown on the right. This cross-section on the right is at the position of the Hall probe arrays, which are drawn in figure 4. The Hall probe array of the cable sample 2 is mounted on the left on the same height as this cable and the Hall probe array of cable sample 1 is mounted on the right on the same height as this cable. The other pieces, as shown on the left in figure 5, have to keep the cable and the G10 spacer in position and contain a free section of 36 mm$^2$ for the wiring, mainly the 56 wires connected to each Hall probe array. The width of the sample holder is 35 mm and the total height is 34 mm.
Figure 5. Cross-sections of the sample holder. On the left the cross-section of the main part of the insert is shown, with space for the wiring of the hall probe arrays and other instrumentation. On the right the cross-section at the level of the Hall probes, indicated by the small black rectangles. The heaters are mounted on top of cable 2.

2.4 Heater and heatpulse specifications

Theoretically a very short point-like heat pulse is required to determine MQE. For our test the following specifications regarding the heater and the heat pulse are needed.
- Power: 0-10 Watt
- Pulse duration: 30 - 1000 µs
- Heater size: < 1 mm²
- Ability to resist \( \geq 30 \text{ MPa} \)
- Resist thermal cycling

2.5 Heater 1: strain gage

Electrical resistors are chosen in order to give a well known and quantified heat pulse to the wire. Initially, strain gages are used, because they have the characteristic of being very flat, they are expected to resist the pressure on the sample and they are commercially available. The used strain gage (see table 2) has the effective dimensions 0.79*0.81 mm² and its physical dimensions are about 3*1 mm, so it can be put on top of one of the strands in the cable. The heater consists of a constantan resistance in an open faced configuration on a 30 µm thick kapton backing. Of the available gages, the 120 Ω version is used because it fits the needs for the pulse generator the best. For each applied field the resistance will be measured at helium temperature with a two point measurement.

The actual heat pulse entering the cable is closely related to the way of mounting the heater onto the cable. This is especially a challenge in the FRESCA setup where the gages are subject to a large pressure and have to be mounted in a limited space. In the measurements the strain gage was placed with the kapton backing on a strand of the cable (see appendix A). A one-dimensional heat flow model is made with an input pulse of 8 W for 100 µs, and the heat flow from the heater into the strand is calculated. This is illustrated in figure 6. Comparing the surfaces below the curves, one can calculate that 40 percent of the generated heat does not enter the strand. In order to reduce this percentage, an 8 micron kapton film was applied as separator and the strain gage was laid on it with the open face down. In this case about 20% of the generated heat does not enter the strand (see figure 6). The total loss factor is even more influenced by the pulse shape and the quench decision moment. The quench decision moments are roughly calculated with CUDI and respectively for 30 and 8 µm of kapton around 1.2 and 0.3 ms.
All the energy flowing in the cable after this point can also be counted for as a loss, where 30 µm provides a bigger loss than 8 µm of kapton. It can be concluded that the 8 µm layer of kapton has much better characteristics concerning pulse shape and effective energy transfer than the 30 µm layer. However, even for the 8 µm layer, the heat is flowing in a very indirect way to the strand and a proper MQE measurement will be impossible.

Figure 6. The actual power flowing into the cable is calculated for different thicknesses of the kapton layer between the strain gage and the cable. The input pulse of 8 W has a width of 100 µs.

As current leads for the strain gages, small flat copper strips are used of 1 mm width and about 50 microns thick. These lead to the side of the cable, where a wire is attached to it. Appendix A shows a schematic drawing of heaters and voltage taps on the cable.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Vishay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>EA-006-031DE-120</td>
</tr>
<tr>
<td>$R(\Omega)$ at 300K</td>
<td>120</td>
</tr>
<tr>
<td>$R(\Omega)$ at 4K 0T</td>
<td>~ 109</td>
</tr>
<tr>
<td>$R(\Omega)$ at 4K 10T</td>
<td>~ 104</td>
</tr>
<tr>
<td>Gage length (mm)</td>
<td>0.79</td>
</tr>
<tr>
<td>Gage width (mm)</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Table 2. Specifications of the used strain gage.
2.6 Heater 2: Graphite paste heater

As shown in the previous section, the big disadvantage of the use of strain gages is the time delay and the heat loss of the heat pulse. Therefore graphite paste based heaters have been tried. This technique is already used before in several other experiments [2].

To produce a well defined graphite paste heater, first a layer of kapton tape is taped on the clean cable surface. With a small soldering tip at 450 °C a hole is melted in the kapton tape with a diameter of about 0.5 mm. The hole should be entirely positioned on the flat surface of the strand. A bit of graphite paste, Eccobond 60L, is put in the hole. A small copper strip with a width of 1 mm stretching out to the side of the cable is put on top of the paste. In order to produce a good bonding between the graphite paste and the copper, a homogeneous force is put on the strips with table clamps, while drying. Hardening of the paste takes about 4 hours at 25 °C. After this procedure, the force can be released and the wiring can be finished. For a picture see appendix A.

At low temperature with a pressure of about 50 MPa the heater resistance varies typically between 2 and 500 Ω. To get heaters with the same order of resistance a heater training should be performed. Consecutive increasing heat pulses are given to the heaters, causing the resistance to steadily decrease and stay at the low value, see figure 7. After training the heater resistance varies typically between 1.5 and 8 Ω. A possible explanation for this training behaviour is that the graphite paste will be smeared out with high temperatures during pulses and they will get a better contact with the copper surfaces. Caution should be taken, because a change in heater resistance causes a change in quench energy. That is why training is necessary.

Measurements showed that the graphite paste heaters have a quench energy that is much lower than the strain gages with 30 microns of kapton. In future measurements the graphite paste heaters will be used.

![Figure 7. Typical behaviour of a graphite paste heater during training. Consecutive increasing heat pulses are given resulting in a decreasing resistance. After this training, decreasing heat pulses are given showing that the heater will remain at its lowest reached resistance value.](image_url)
2.7 Pulse generator

To induce a pulse to the resistance (strain gage or graphite paste) an electrical pulse generator designed by Maccaferri is used. This pulse generator is already used by Bauer [1] for strand stability measurements and is now upgraded to higher voltages for cable stability measurements. This generator gives a rectangular pulse with a width between 10 µs and 32 ms and with a voltage up to 55 V. Measurement of the pulse is done internally by the pulse generator as well as by a Nicolet Vision data acquisition system with a sampling rate of 100 kHz.

2.8 Voltage taps

To measure the voltage on the cable, normally voltage taps over 60 cm of the cable are used, positioned a-symmetrically around our prepared area inside the magnetic field. With these voltage taps the overall quench velocity and the U-I curves are determined. For more detailed measurement at the position of the quench, also voltage taps are positioned around the heaters on the same strand. The graphite paste heaters can also be used as a voltagetap, because of their low-resistive connection to the cable.

2.9 Hall probe arrays

To measure the self field of the cable, Hall probe arrays are used. Figure 8 shows the concept of these arrays and table 3 gives the main specifications of the Hall probes. Also a photograph of the array is shown in figure 9. The 26 Hall probes per array measure the field next to the cable, composed of the (constant) applied field and the self-field generated by the current in the cable. For homogeneous current distribution, all Hall probes are in the same magnetic field. For inhomogeneous distribution of current, the Hall probes are in an inhomogeneous magnetic field, caused by the combination of the twisting of the strands and the inhomogeneous current distribution. The current distribution can therefore be deduced by analysis of the variations of the Hall probe signals.

Figure 8. Schematic drawing of the Hall probe array located next to a cable. Suppose that the dark strand has a higher current than the other strands. The darker Hall probes will then have higher signals. On the right the direction of the self field of the cable is shown in relation to the Hall probes.

Figure 9. Photograph of a part of a Hall probe array in position next to the thin edge of the cable sample. The black squares are the Hall probes.
HP model | Lakeshore HGT-2100
---|---
Approximate active area | 0.13 mm x 0.13 mm
Magnetic sensitivity at operating current | 44 to 112 mV/T
Maximum linearity error (sensitivity versus field) | ± 1% RDG (-1 to +1 T)
Zero field offset voltage | ± 2.8 mV (max)
Operating current | 400 µA

Table 3. Specifications of the used Hall Probes at 300 K.

### 2.10 Temperature sensors

To determine the temperature of the cable during and after a quench, RuO$_x$ resistors are used. These 10 kΩ resistances (at 300 K) are very sensitive to temperatures below 40 K and hardly sensitive to magnetic field. They are fed by a 1 µA battery current source and have a sensitivity of -1600 Ω/K at 4.2 K and -7000 Ω/K at 1.9 K. A good knowledge can be obtained of the overall temperature of the cable before and after a quench. Depending on the response time due to the insulation between cable and resistor, also a fast response temperature change at the position of the quench can be detected.

### 2.11 Data acquisition

For measuring data at high sampling rate, the 16 bit data acquisition system Nicolet Vision is used with a rate of 100 kHz per channel. The following channels are recorded during each test: I, $B_{appl}$, $V_{pulse}$, some Hall probes, some Temperature sensors and some of the voltage taps.

### 3.- Typical stability measurements

#### 3.1 Measurement operation

The sample holder described in this note is only used in situation where the field is parallel to the cable, because the distance between the cable samples gives rise to a large torque force in perpendicular field. Before measuring, the magnetic field is set at the desired field. A measurement cycle starts with a current ramp from 0 A to a plateau current with a ramp rate of 800 A/s. After reaching the plateau current, this current is then kept constant for 15 s. Immediately after this waiting time, a heat pulse is given to the cable. If a quench is provoked the current ramps down and a new measurement cycle can be started. If the cable does not quench, the current will be ramped up to quench, to prevent that the next measurement is influenced by current distribution processes during the previous heat pulse. Due to the quench, the temperature of the cable will increase, depending on the sample current, to about 20-60 K. It takes about 25 s before the cable has again cooled-down to bath temperature. The next run will only be started after complete homogenization of the temperature.

For determining the quench energy a trial and error method is used. Firstly one energy is chosen where a quench occurs, $E_q$, and another energy where no quench occurs, $E_{nq}$. Every next pulse is determined by $(E_q+E_{nq})/2$. In this way the error is every step divided in half. This method is repeated until an accuracy of 2% is reached. The Quench Energy is now taken as the smallest energy at which the cable quenches.
3.2 (Minimum) Quench Energy

For characterizing the stability of superconducting cables or strands, the most used parameter is the Minimum Quench Energy. This is the smallest amount of energy needed to provoke a quench or to set up a Minimum Propagating Zone (MPZ). We need to be careful when speaking about this MQE. In first measurements it showed to be strongly influenced by the pulse length and pulse shape. Shown in the section about heaters and in figure 6 is that the total loss factor is strongly influenced by the pulse shape and duration. Because of all the described effects, we will use the term Quench Energy, which refers to the energy of the input pulse.

4.- Conclusions

A new sample holder for the FRESCA test station has been designed and built in order to make stability measurements on Rutherford cables. With the new sample holder short heat pulses can be given on one or several strands. The effect in terms of voltages, temperatures and current distribution can be measured. The first experiments are done with the described new sample holder.

Giving heat pulses using strain gages has the drawback that an electrical insulating material should separate it from the cable, with a thermal insulation as small as possible. It can be concluded from the first measurements that the 30 micron backing of the strain gage gives rise to an unacceptably long delay of the heat pulse. For physically more useful results, the thin 8 micron kapton foil should be used. However, the thin kapton foil turned out to be very fragile and during the experiments 8 of the 9 heaters where damaged or the connection with the voltage taps failed.

The use of graphite paste heaters seems to be a good alternative, with very good heat contact with the cable and being less sensible to damage.

In a following note the measurement results will be discussed.

Acknowledgements

A special word of thanks we would like to give to Remo Maccaferri, who upgraded the pulse generator and Remy Rota for his assistance with the sample preparations and his technical support.
References


Appendix A: Sample configuration.

In the figure on the left, schematically a configuration of the sample preparation of heaters is given. On the top part of the cable 4 strain gage type heaters are located on one strand, with their connecting copper strips.

On the bottom part 4 graphite paste heaters are put on one strand. Because the graphite paste heaters are in contact with the cable, they can also act as voltagetaps.

The picture below shows a schematical drawing of the cross-section of the graphite paste heater lay-out.