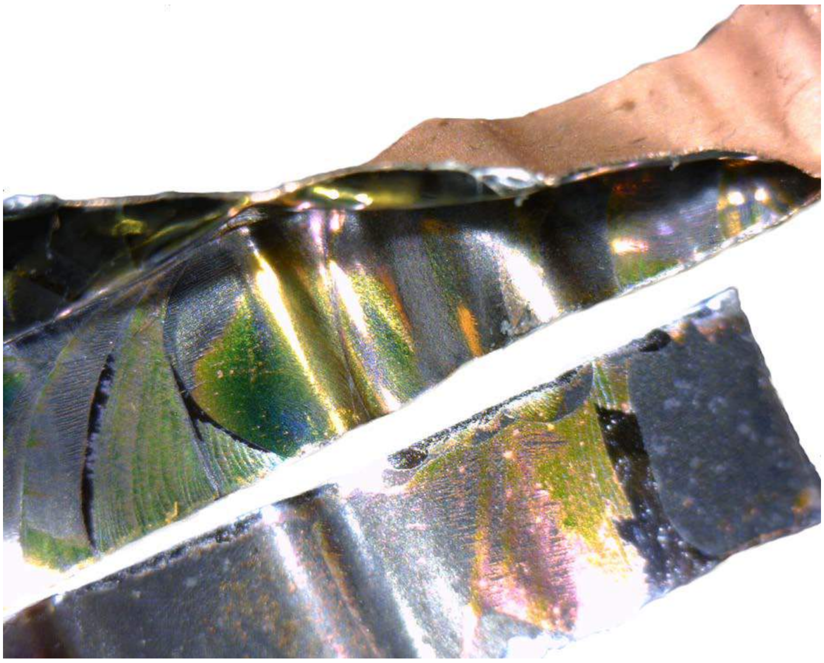
MASTER THESIS

NORMAL ZONE PROPAGATION IN A YBCO SUPERCONDUCTOR AT 4.2 K AND ABOVE



A.R. Hesselink

FACULTY OF SCIENCE AND TECHNOLOGY
ENERGY, MATERIALS AND SYSTEMS GROUP

EXAMINTATION COMMITTEE
Dr. M.M.J. Dhallé
Prof. Dr. Ir. H.J.W. Zandvliet
Prof. Dr. Ir. H.J.M. ter Brake

UNIVERSITY OF TWENTE.

04-03-2015

Abstract

The normal zone propagation velocity and minimum quench energy of a 2-mm wide YBCO superconductin 'coated conductor' tape are investigated at temperatures between 4.2 and 29 K, at three different magnetic field strengths and at varying operating currents. Confirming earlier observations on a wider tape at higher temperatures and in contrast to the simplest and most widely used theoretical model, it was found that the normal zone propagation velocity predominately depends on the current and hardly so on temperature or magnetic field. In agreement with theoretical predictions, the minimum quench energy was found to depend on both temperature and current, while the collected data do not allow to make a reliable conclusion about its magnetic field dependence. A more sophisticated analytical and a numerical model confirm the temperature independence of the normal zone propagation velocity for temperatures below 25 K. Comparison between the absolute value of the normal zone propagation velocity show a quantitative difference of 50% between the 2-mm and 4-mm wide sample. Although several likely causes were investigated, this difference remains as yet unexplained.

Contents

Chapter 1 Introduction

This report describes the continuation of measurements performed on the thermal behavior of a second generation high temperature superconductor wire. Superconductors are used in magnets, for they can handle very high current densities, required to create strong magnetic fields. In the last decade the HTS is available as a practical conductor in the form of tapes. HTS can handle higher temperatures, currents and magnetic fields than LTS. Therefore they are the future for high field magnet systems. But the properties of HTS are less understood. The understanding of the thermal behavior of HTS is important for its protection. When a part of a superconducting magnet transitions to a normal, resistive state during operation, a 'quench', the magnet has to be shut down or it can be damaged or even destroyed. So a quench has to be detected as fast as possible. The occurrence of a quench depends on the minimum quench energy and its detection on normal zone propagation velocity.

1.1 Superconductivity and the critical surface

Superconductivity has been around for more than a century now, though the phenomenon of losing electrical resistance, is still unfamiliar to many people. The discovery was made by Heike Kamerlingh Onnes [1] in 1911, who cooled mercury to a temperature of 4.2 Kelvin in liquid helium. At room temperature a bad conductor (for a metal), mercury became a superconductor. Since then many superconducting materials have been discovered and a fundamental theory has been developed. Below a certain temperature the materials lose their resistance: the critical temperature (T_c). The first class of superconductors (LTS) were metals, metal-alloys and compounds, with critical temperatures varying from below 4.2 K to 30 K. Niobium Titanium ($NbTi$)and niobium tin (Nb_3Sn) are now used commercially. In 1986, a new family of superconductors was found: ceramic copper oxide materials with unpredicted high critical temperatures [2]. Many of these copper oxides had a T_c above 77 K, the temperature of boiling nitrogen. They were called high temperature superconductors (HTS). Practical HTS materials are bismuth strontium calcium copper oxide (BiSCCO) [3] and yttrium barium copper oxide [4] (YBCO, see figure 1.1).

Temperature is not the only parameter which is of importance for a superconductor. When transporting a current through the conductor, it will induce a magnetic field (self field). Superconductors have a special interaction with a magnetic field. At first, the magnetic field is expelled from the interior of the material by inducing surface currents. Beyond a first critical field point, B_{c1}, the 'type I'-superconductors (mostly the pure elements) lose their superconductivity. 'Type II'-superconductors (including all HTS) allow the magnetic field to penetrate the material, as vortices of supercurrent with a normal core, enclosing a single magnetic flux

The picture on the titlepage shows the wire, unfolded at the YBCO layer. The two pieces come from the remainder of a sample after a dramatic quench.

quantum. There are Lorentz forces that work on these vortices as well as repelling forces between them. When the current is increased, more vortices move into the conductor from the outside. But the movement of the vortices causes an electric resistance, like friction. This is problematic, but defects in the crystal lattice can pin the vortices and so hinder their movement. With the increasing current, the vortices are compressed in the superconductor until the Lorentz force are larger than the pinning forces at the critical current (I_c). The second, upper critical field (B_{c2}) is reached when, without a transport current, the vortices are compressed in the superconductor until their normal cores overlap and no superconducting part is left [5] [6].

These three critical parameters are interdependent and can be combined in a graph, creating the so called (material-specific) critical surface. The critical surface of YBCO is shown in figure 1.2. The surface shows the interface between the superconducting state and the non-superconducting (normal) state. A transition will occur when one passes from a point 'below' the surface to a point 'above'. The critical surface of HTS materials is much higher than that of LTS materials. Of course there is a downside to the newer superconductor. HTS materials are ceramic and therefore fragile. Even more troublesome is the anisotropy of the superconductor properties: it is orientation dependent. The material has to be monocrystalline (green surface in figure 1.2) or the crystals have to be aligned with respect to each other a very small angle. Otherwise the current can not cross the interfaces between the crystals and the effectiveness of the conductor is compromised. Wires with YBCO or REBCO (RE stands for Rare Earth) as the HTS component are made commercially as tapes or 'coated conductors'. By using thin film technology to grow the HTS epitaxially on meter-long substrates, the problem of anisotropy is overcome.

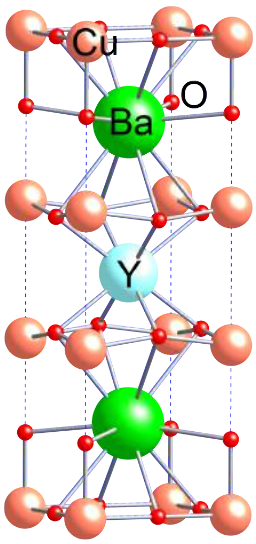


Figure 1.1: The unit cell of YBCO

1.2 Applications

Superconductors can transport current densities in the order of 100-100 A/mm^2 without any loss. The main application for superconductors are electromagnets, to build them into magnets. Using superconductors instead of copper, smaller and more powerful magnets can be made. Modern medical Magnetic Resonance Imaging (MRI) would not be possible without the use of superconductors, nor could the larger particle accelerators operate with only normal conductors.

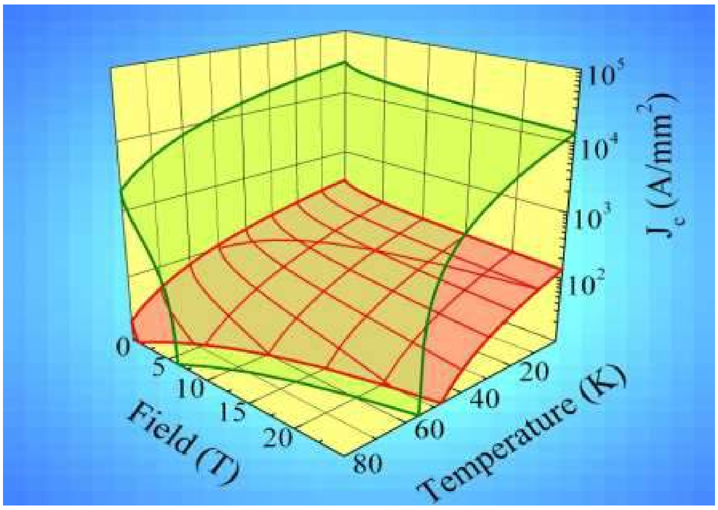


Figure 1.2: The critical surface of YBCO. The green top surface is for a perfect sample. The red surface is the practical engineering current density.

CERN in Geneva, Switzerland, is developing the successor of the Large Hadron Collider (LHC). To increase the resolution of these devices, stronger magnets are needed and HTS are the future conductor materials to build these. In the ITER project, superconductors are used to power and control the plasma in the world's first energy producing fusion plant. The potential in the energy sector for superconductors is big, but material costs and the requirement of cryogenic temperatures is slowing down the commercialization. HTS may operate with liquid nitrogen, which is much more practical than liquid helium, but the costs of HTS wires are still relatively high. Although HTS can work at relatively high temperature, often they will still operate at 4.2 K in hybrid systems together will LTS materials.

1.3 Minimum quench energy and stability

Superconductors are often used submerged in a bath of liquid cryogen during operation. Nevertheless they may heat up locally under influence of an external disturbance. Especially at temperatures below 100 K, there is a chance that this will happen, because the heat capacity of materials drops rapidly (figure 1.3). A minimal amount of energy is needed to heat up the material: the movement of a strand due to Lorentz forces, cracking of the impregnation of a magnet or the impact of high energetic particle in case of an accelerator magnet. When a small area of wire has a transition to the normal state, Ohmic heating occurs in this local zone. If the 'normal' zone is small enough and the cooling is sufficient, the current can sort of bypass the normal zone and the zone collapses. If the zone is big enough, a chain reaction commences, where the size of the normal zone increases, generating more heat. This is called a 'quench'. The least amount of energy required to cause a quench, is called the minimum quench energy (MQE), see equation 1.1. If no countermeasures are taken, the temperature of the wire will become too high, eventually destroying it. To raise the minimum quench energy, a stabilizer material is used, such as copper or aluminum. The stabilizer has a higher thermal and electrical conductivity when the superconductor turns normal. It can adsorb heat and redirect the current, preventing an immediate temperature rise.

$$MQE = \ell_{MPZ} \int_{T_0}^{T_t} C(T) dT \qquad (1.1)$$

The temperature of a minimum length of the normal zone (ℓ_{MPZ}) with a certain heat capacity ($C(T)$), has to be raised from the operating temperature (T_0) above the transition temperature (T_t). The minimum length of the normal zone to cause a quench is called the 'minimum propagation zone', see equation 1.2:

$$\ell_{MPZ} = \left\{ \frac{2k(T_t - T_0)}{\rho I^2} \right\}^{1/2} \tag{1.2}$$

with k the thermal conductivity and ρ the resistivity of non-superconducting material. I is the operating current. The difference between T_0 and T_t is called the thermal margin.

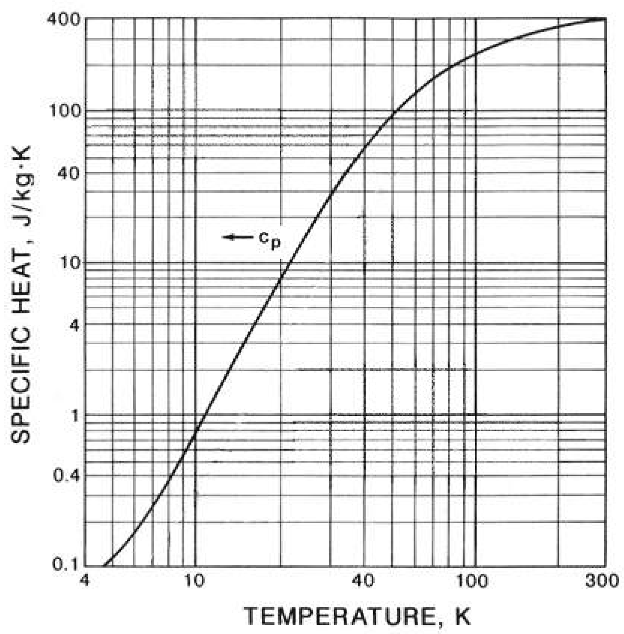


Figure 1.3: Specific heat of copper. Below the 100 K, the specific heat drops rapidly.

1.4 Normal zone propagation velocity

To create a high current density magnet, only a limited amount of stabilizer can be used. So quenches cannot be prevented and therefore a magnet has to be designed to allow quenches. During a quench, the magnet has to be protected against energy buildups, which cause high temperatures. The current has to interrupted and the energy stored in the magnet has to be dumped. This energy dump can be done in external resistors or in the cold mass of the magnet, by firing quench heaters. The quench heater create artificial normal zones and in this way the energy is smeared out. Before the quench protection can be initiated, it has to be detected. And within a very small time frame. A simple and fast method is using voltage taps connected to the conductor, indirectly measuring a resistance. Before the voltage taps can detect a quench, the normal zone has to reach them. The 'normal zone propagation velocity' (V_{nzp}) is the speed with which the superconducting-to-normal-transition front travels. It is shown for several superconductors in figure 1.1 as U_l. Looking at the HTS materials, the propagation is very slow. For the protection, this is problematic. Especially for the expensive HTS materials.

Table 1.1: Typical literature values for the normal zone propagation velocities (U_l) in several superconductors at depicted circumstances.[7]

Superconductor	Environment	T_{op} [K]	B_{ex} [T]	J [A/mm^2]	U_ℓ [mm/s]
NbTi (multifilamentary composite)	Liquid helium	4.2	0	420	"Recovery"
				840	6800
			4	420	4660
				840	18600
Nb_3Sn (multifilamentary composite)	Adiabatic	4.2	0	630	1830
			6	315	1490
				630	3720
Nb_3Sn (tape)	Quasi-adiabatic	12	0	700	510
		5.5	5	470	525
Bi2223-Ag	Quasi-adiabatic	40	0	230	2
YBCO (coated)	Adiabatic	46	0	10–15	2–8
	Adiabatic	77	0	3–15	3–10
	Adiabatic	77	0	65 115	2.5 9
		40	0	115	38
MgB_2 (single strand; iron matrix)	Quasi-adiabatic	4.2	4	26	No NZP
				78	930
				212	6000

1.5 Previous work

The V_{nzp} has not been investigated extensively at low temperatures. Therefore the setup made by H. van Weeren [8] for measuring the V_{nzp} of MgB_2, was used by J. van Nugteren [9] for measurements on REBCO tape in the temperature range of 45 to 25 K. He found an exponential relation for the V_{nzp} depending on the sample current only (see figure 1.4). Due to limitations of the setup, the measurements could not be evaluated at lower temperatures.

1.6 Assignment and layout

The goal of the research presented in this thesis work is to extend earlier normal zone propagation measurements on REBCO HTS tapes to temperatures lower than 25 Kelvin, ideally all the way to 4.2 Kelvin. The measurements are done on a 2 mm wide HTS tape at varying magnetic fields strengths and currents. Specifically, the goal was to check whether the unexpected power-law dependence of V_{nzp} on current holds also in this temperature window, and to establish the influence of temperature and magnetic field in more detail.

After this introductory chapter, the report continues with four more chapters. Chapter 2 describes the setup, sample preparation and measurement procedures. The results of the measurements are presented in chapter 3. Results from previous research and new simulations are analyzed in chapter 4. In the last chapter, the outcome from measurements and simulations will be discussed and concluded.

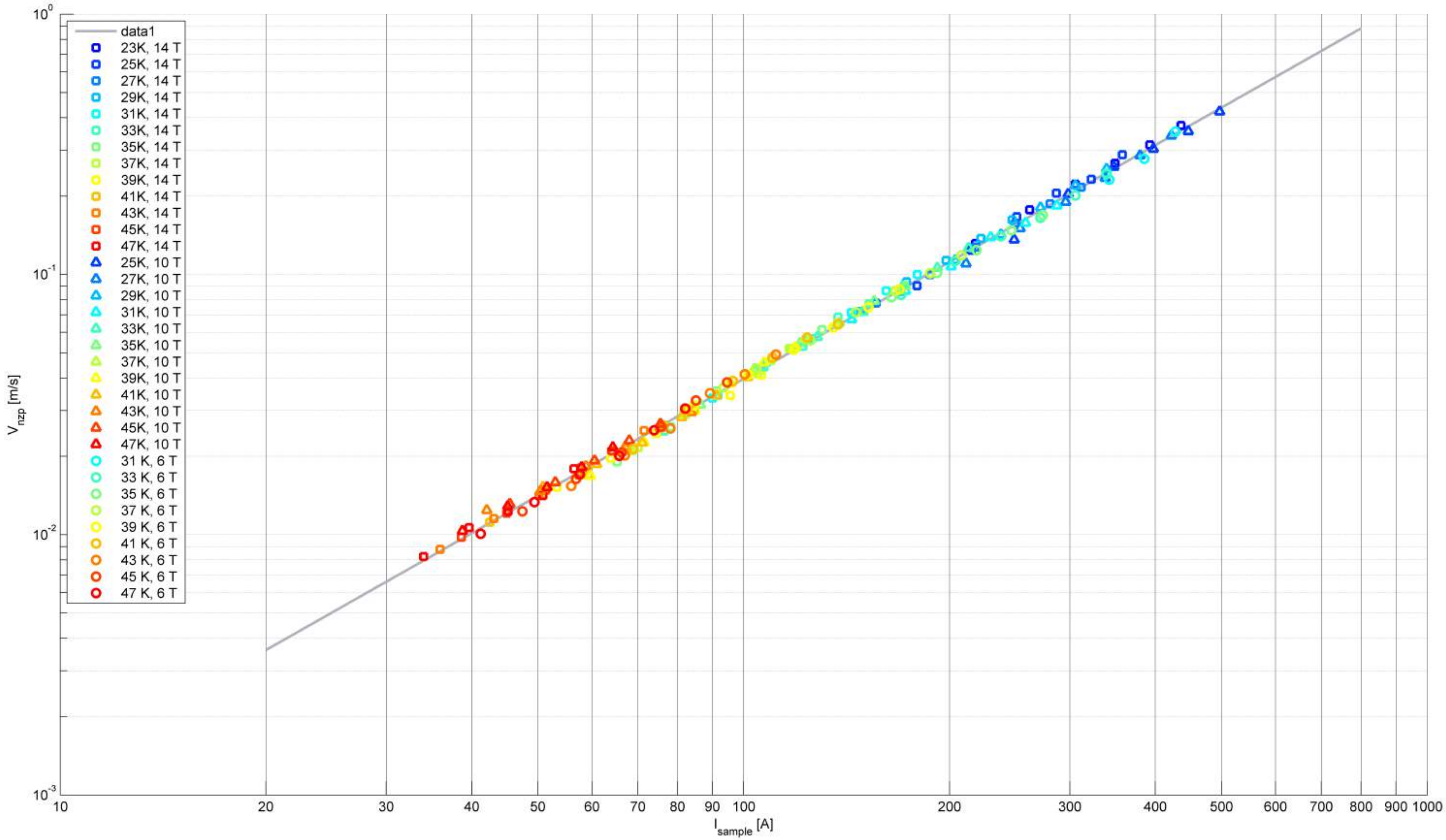


Figure 1.4: Logarithmic scaled graph of the normal zone propagation velocities found by J.van Nugteren [9]. The velocities are depend only on the current passing through the conductor.

Chapter 2 Experimental Aspects

In this chapter, various aspects of the measurements are clarified. The setup for measuring the MQE and V_{nzp}, is explained in section 1, including several modifications to the probe that were needed for this assignment. The instrumentation hardware and software is discussed in section 2. Then the experimental procedure for measuring the critical current and normal zone propagation is explained. In the last section, the signal analysis and accuracy procedure is discussed. For more information, a manual for the "NZP experiment 2014" is included in Appendix A.

2.1 Setup

The setup for measuring the MQE and V_{nzp} was designed and build in 2008 by H. van Weeren [8] for the characterisation of Magnesium Diboride (MgB_2 superconductors). J. van Nugteren [9] modified the probe and reassembled the setup for measurements on REBCO tapes. Also a new software environment was written to control the experiments, with additional protection measures.

The setup is a so-called "time-of-flight" experiment. The sample is placed in a controlled environment, in a stabilized temperature and magnetic field, transporting a stable current. A resistor is used as "quench heater" to create a normal zone. The heat pulse signal is registered to find the quench energy. In case of a quench, the normal zone expands and the resulting voltage signal is recorded with voltage taps soldered to the wire at known distances from the heater. The normal zone velocity is calculated from the time interval that it takes the normal zone to travel over the distance between two voltage pairs, i.e. the time taken to reach a matching voltage level over the next pair.

Challenging, but important in this kind of experiment is that it should be performed as adiabatic as possible. Ideally, all the heat generated in the sample should only be used to drive the propagating normal zone further. However, it is not possible to execute these experiments under fully adiabatic conditions. Heat will flow away from the zone to the environment. Several precautions are taken to keep the sample in a 'quasi-adiabatic' condition. First, it is held in a vacuum. Second, the electrical wiring to the voltage taps, heaters and temperature sensor consists of manganin, a copper alloy with a low thermal conductance. Third, ridges in the embedded heater structure ensure lower heat loss to the support underneath the sample. Heat loss from thermal radiation cannot be prevented. Also, the time scale of the experiment is relatively small and therefore losses to the sample holder are correspondingly small.

Sample description

The earlier NZP experiment on REBCO used standard-width 4 mm wide tape, but measurements could not be continued because the niobium tin current leads in the set-up could not handle the high currents that the HTS are able to conduct at temperatures below 25 K. The experiments were therefore conducted on a tape half the width: 2 mm. The critical current should depend linear on the width of the tape [10], so the conductive properties of the 4-mm and 2-mm tape should be comparable.

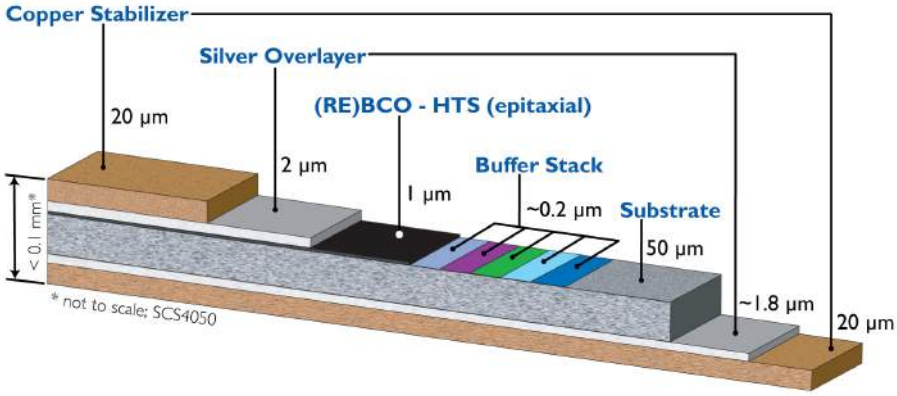


Figure 2.1: The buildup of the used REBCO tape manufactured by Superpower inc.

The sample is a so-called second generation HTS coated conductor provided by the company Superpower inc (see figure 2.1). On a flat substrate of non-magnetic high strength steel, REBCO is deposited with the use of metal organic chemical vapor deposition (MOCVD). An outer layer of copper stabilizer is applied by electroplating, about $20\mu m$ surrounding the tape. The conductor type used is SCS 2050 with batch number M3-1052D at conductor length 808.15-813.15. Its average dimensions are a width of 2 mm and a thickness of $96\mu m$.

Sample preparation

A 75 cm long piece of REBCO tape is used for the NZP measurements. The tape is marked with indications for the voltage taps, heaters and temperature sensors. It is then soldered to copper terminals with bismuth lead tin, a solder with a low melting temperature of $105°C$. Next, the voltage taps and the casing for the temperature sensors are soldered to the tape and heaters are glued on the sample with an alumina loaded epoxy (Stycast 1850FT). The result is shown in figure 2.2. Note that the sample shown in the photograph is dismounted after a measurement. The soldering and gluing is done after attaching the tape to the sample holder, to prevent stresses from bending the tape. During the first NZP measurements, the quench heater detached from the tape. Several attempt were done to glue it back on the tape, but these were unsuccessful. A new fixation method had to be used, as shown in figure 2.3. The quench heater was secured to the sample with nylon wire, adding thermal grease between the tape and the heater for improved thermal conductance. Stycast was used on the ends of the heater, to fix its lateral position. With this new fixation method, the quench heater no longer detached from the tape.

Figure 2.2: A tape sample with the voltage taps, heaters and temperature sensor housings.

Then the wiring of various elements (temperature sensors and heaters) was soldered to the contact pads located above the copper terminal and their connections were tested.

During measurements of the critical current values on the 2-mm wide tape, the sample was pulled off the copper terminals by Lorentz forces, i.e. the solder yielded. Note that - to prevent

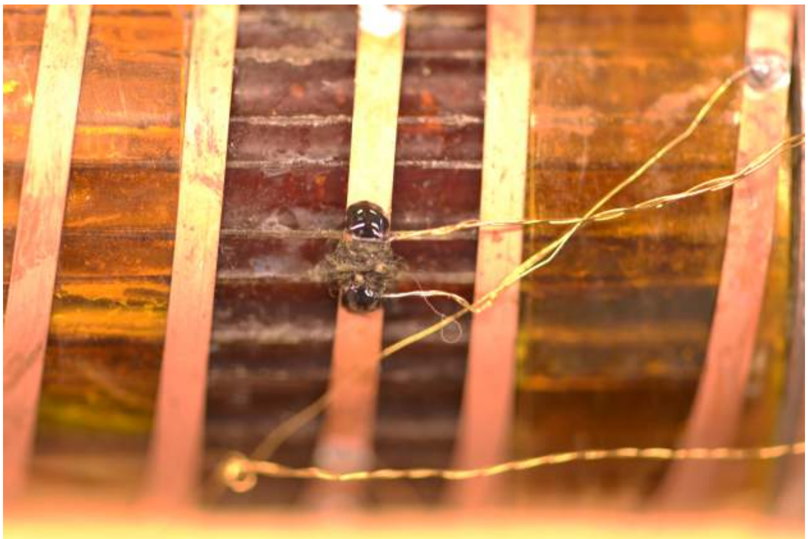


Figure 2.3: The quench heater, fixed to the tape with nylon wire. Thermal grease was applied between the tape and the heater. Epoxy secures it lateral position.

sample buckling - the current is injected in such a way that these forces (which were, at their maximum, about 4.4 kN/m). It was therefore decided to reinforce the attachment of the tape to the current leads by winding a few turns of single filament niobium titanium wire around the outside of the REBCO tape on the terminals and soldering it in place together with the sample.

The sensors and heaters on the 2-mm tape are positioned in the same manner as on the 4-mm tapes used in the earlier experiments, to keep the results comparable. Of course the dimensions of the heater elements had to be adapted. For the quench heater a SMD thick film resistor produced by the company TE connectivity with a resistance of 15Ω is used. It has a length, width and thickness of 3.1, 1.6 and 0.55 mm respectively. The quench heater is placed in the middle of the tape. All the other elements are placed symmetrically around the quench heater, for precision and redundancy. With 5 mm separation, the voltage taps V1 to V3 are connected to the sample 10 mm next to the quench heater. An extra tap (V4) is then placed, to be used during I_c-measurements. The copper housing for a calibrated Cernox temperature sensor is soldered on the tape. Thermal grease is applied for improved conductivity and the sensor is secured with a nylon thread in the casing. Next to the Cernox is the edge heater: a 20Ω SMD thick film resistor manufactured by Panasonic, which is 3.2 mm in length, 1.6 mm in width and 0.6 mm in thickness.

2.1.1 Probe

The insert consists of a G10 glass fiber epoxy tube through which run two copper current leads, a vacuum pumpline and a data cable tree (see figure 2.4). Two bridges made of niobium tin wire are connected from the copper current leads to the end of the sample holder (figure 2.5). The niobium tin bridges form a bottleneck because they have a critical current of only 440 A at magnetic field strength of 14 T. For efficient cooling of the copper current flanges the inside of the sample holder is hollow, forming a reservoir which is connected to the liquid helium bath. Surrounding the reservoir is a cylindrical laminated structure of copper foil (for circumferential heat conductivity), kapton (for radial thermal insulation)and resistive phosphor-bronze wire cast in epoxy. This sandwich forms the embedded heater and is the most important piece for controlling the temperature. The sample is spiraled around the embedded heater between the two copper current terminals. The spiraling will insure an even temperature profile.

Above the top copper terminal are 36 contact pads to which the wiring from the sample can be soldered. The sample holder is sealed inside an aluminum vacuum chamber that is screwed to the copper flange and made helium tight with an indium o-ring. The flange, vacuum chamber, copper terminals and contact pads are in contact with the liquid helium bath at 4.2 K.

The cable tree had to be replaced before the first experiments on the 2-mm tape could be started. The electrical connections from the sample went through the vacuum tube to a DIN-connector at the top of the insert. This implied that the sample was in direct thermal contact with the room temperature environment. After revision, the electrical wiring runs through the liquid helium and enters the vacuum chamber through a aluminum/steel plug sealed with epoxy. The copper wiring from the data cable is then soldered and secured to the contact pads. In this way, possible heat leakage from direct room temperature connections is prevented. The electrical connections for the quench heater still run through the vacuum tube to vacuum chamber. This heater circuit is separated from the data cable to prevent the distortion of the other signals by the quench heater pulse ('cross talk'). Through the G10 tube run two extra pairs of insulated wires from the top. One pair is soldered to the niobium tin current leads. It measures the overall voltage over the sample holder and is used for quench detection.

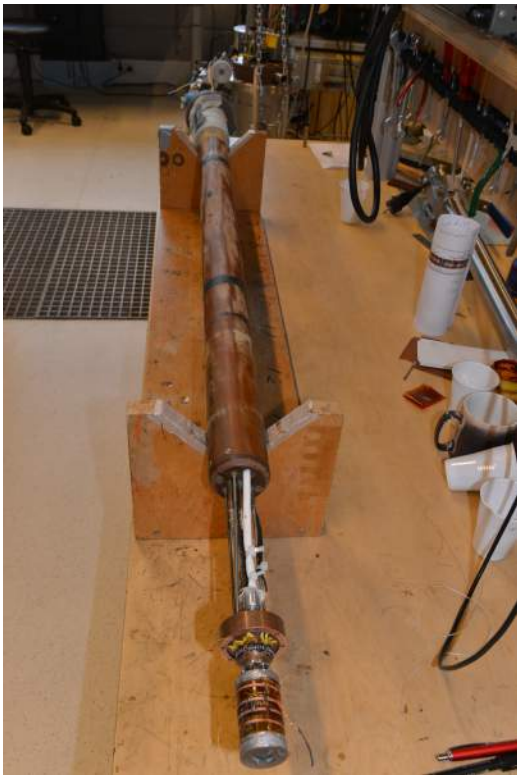


Figure 2.4: The low temperature insert

2.2 Changes in instrumentation

Although the main functionality of the instrumentation has not been altered since the previous NZP measurements, several adjustments had to be made. Figure 2.6 shows the grouping of the instruments in functional blocks. With the tape of 2 mm, the risk of sample damage due to overheating during a quench is more severe than with the 4 mm wide samples. Therefore an extra quench detector was placed in the setup. This 'primary' quench detector CTS 87/3

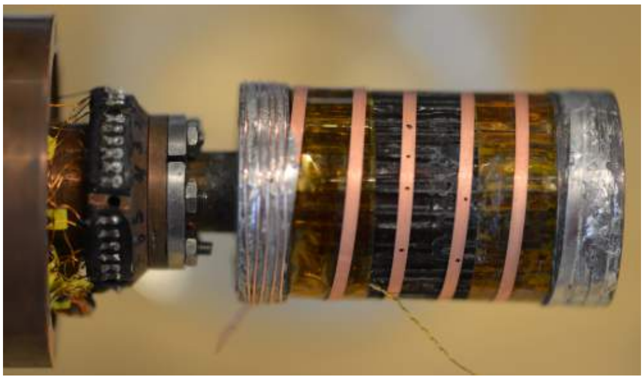


Figure 2.5: The sample holder, with a 2 mm tape soldered to copper terminals. On the left terminal a bare NbTi wire can be seen, used for reinforcement. Visible next to the left terminal, near the flange, are the contact pads for the electrical connections. The black underneath the tape is the embedded heater with its ribbed support structure.

is more sensitive and connected with a new voltage pair $V0$ placed on the sample ends near the copper terminals, so it measures over the whole tape length. In this way CTS 87/3 guards the tape specifically. During a quench, it intervenes the current control signal, setting it to zero. The niobium tin current leads are less sensitive, but are still protected by another quench detector CTS 87/6. This detector controls the quench detection port of the power supply, shutting down the power in case of a quench.

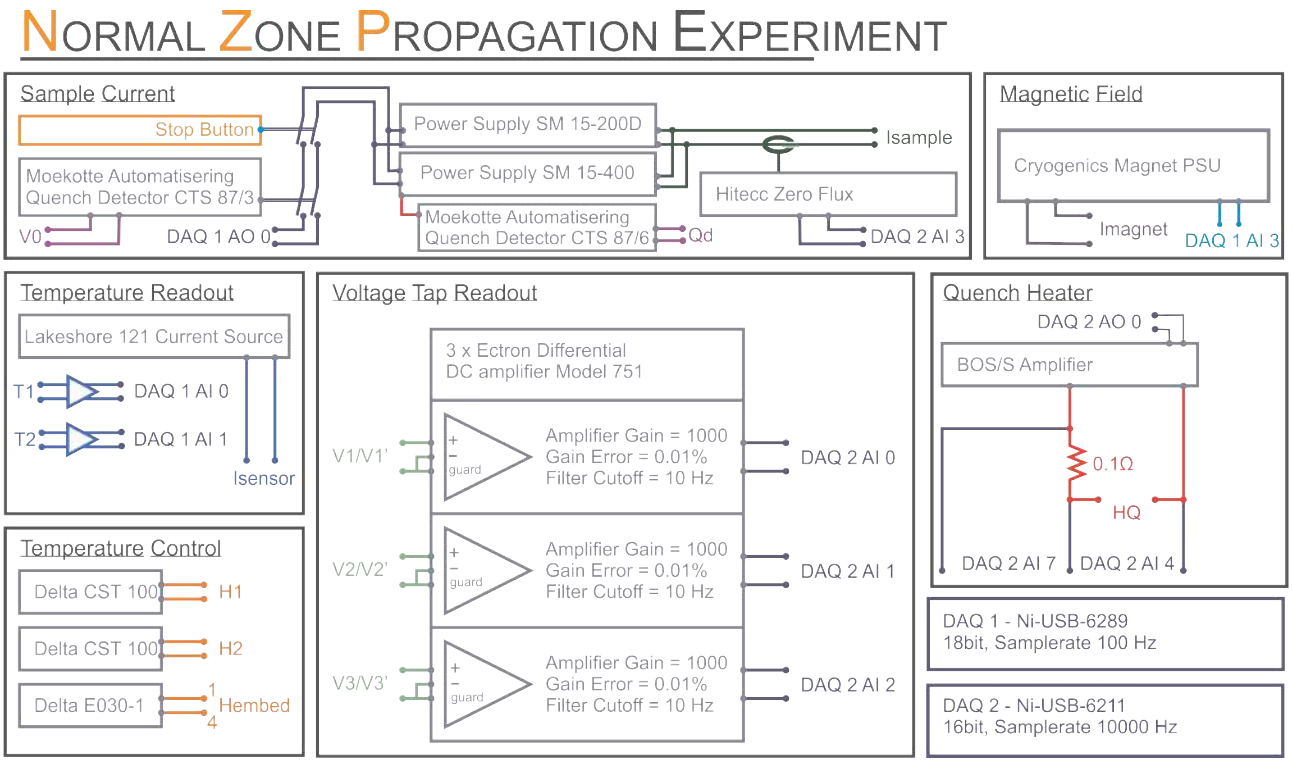


Figure 2.6: Scheme of the setup configuration and connections

During measurements it was also noted that the voltages were not very stable, it seemed that the Ectron amplifiers were malfunctioning. During inspection of the amplifier's signal, it turned out there was a voltage buildup of 300 V between the amplifier output and the ground. After consultation with the manufacturer, a 10 $k\Omega$ resistance was placed between the signal input and amplified signal output to level the voltages, (figure 2.7). The grounding of the DAQ 2 device was disconnected to prevent an ground loop. Not shown in figure 2.7, the current readout was connected to the ground connection on the DAQ 2 device, to get a more stable current readout signal.

There were some problems with the stability of the current control signal. This was in all likelihood caused by the output impedence of the DAQ device, which could not source sufficient signal current. To overcome this problem, an in-house made instrumental amplifier with gain 1x was used.

The measuring current for the Cernox thermometers was raised from 10 μA to 300 μA [9], so that the temperature signals could be read directly by the data acquisition card without the need for pre-amplification. However, at temperature measurements in liquid helium at 4.2 K, the thermometers seemed to heat themselves, influencing the temperature. The measuring current was therefore set back to the recommended 10 μA and an instrumental pre-amplifier was used at gain 100x.

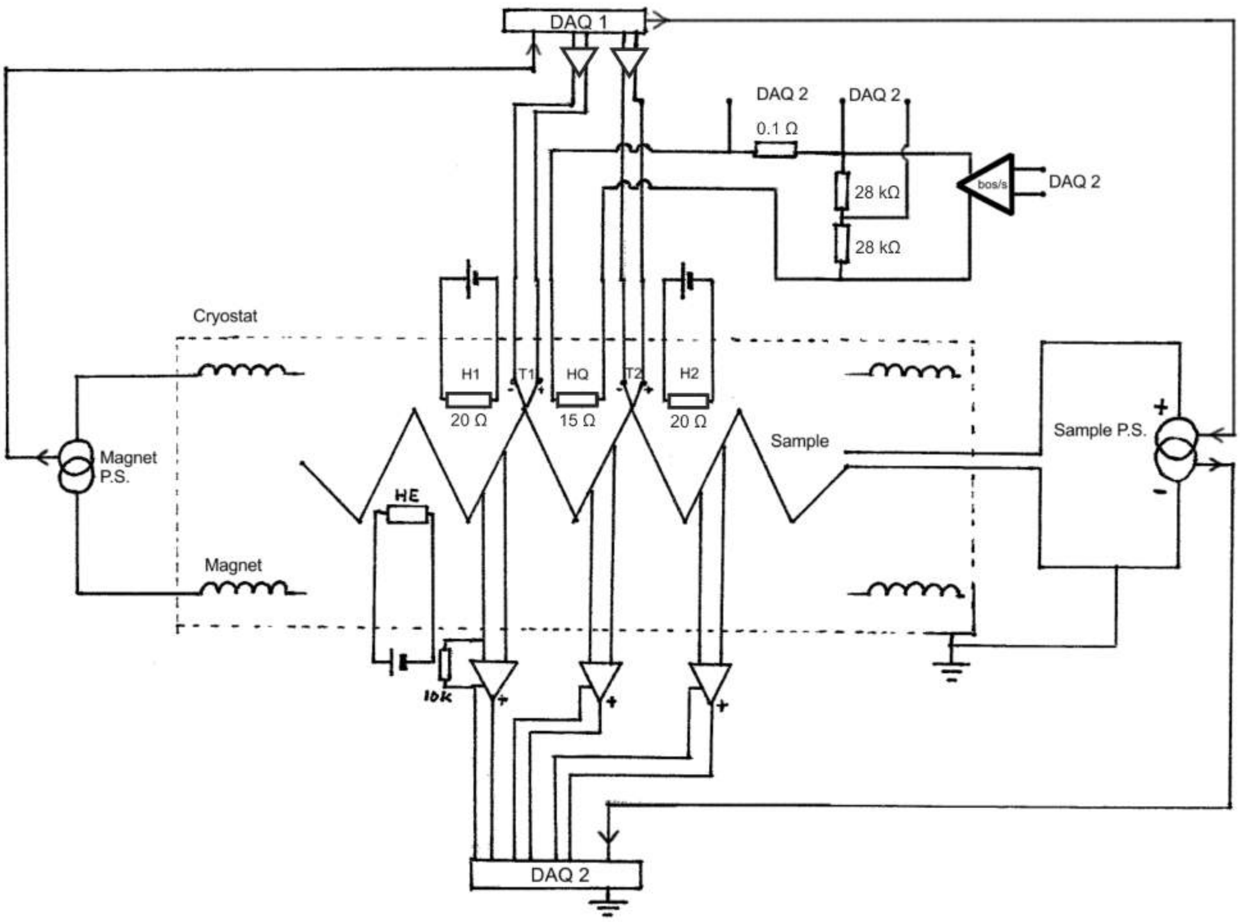


Figure 2.7: The electrical schematic of the NZP-experiment. A connection between the amplifier input and output is established to prevent a voltage buildup with the ground. The grounding of DAQ 2 was disconnected.

2.3 Measurements Ic

To characterize the quality of the 2-mm wide sample and to be able to compare it to the 4-mm wide tape, critical current measurements were conducted using the same setup and Labview software as the normal zone propagation experiment. The voltage taps used for these measurements were spaced least 50 mm apart to optimize sensitivity. During the first measurements on

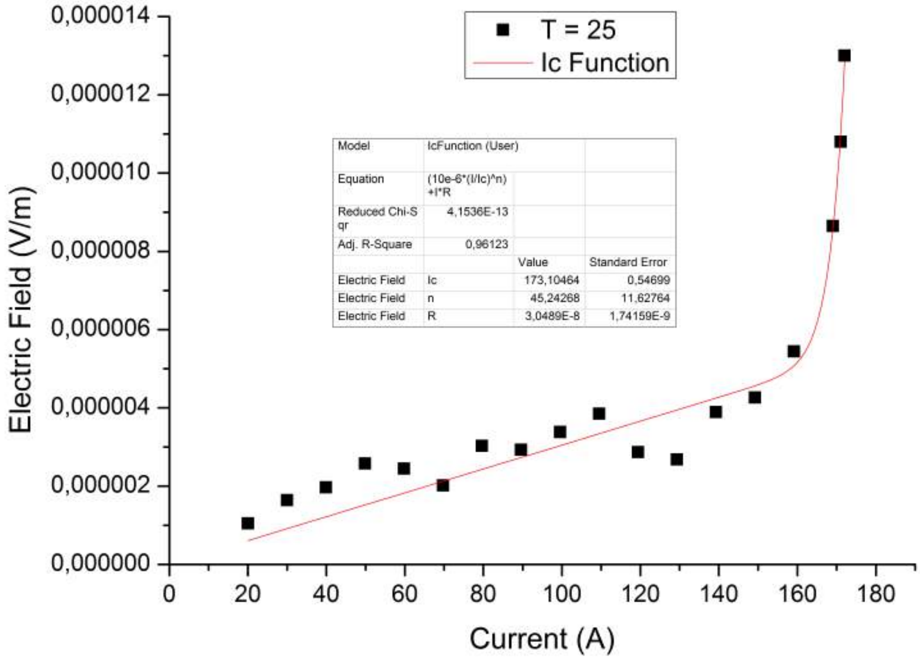


Figure 2.8: Graph of a critical current measurement at T = 25 K and B = 14 T.

the 2 mm wide tape, the sample got damaged. It must be noted that REBCO coated conductors are relatively fragile and still in development: the quality of the REBCO is not uniform along its length. The tape was damaged at a weak point outside the zone monitored by the voltage taps. Also the temperature could not be controlled during the ramping of the current towards the critical point.

It was therefore decided to conduct the measurements of the critical current with a standard I_c-setup available in the superconductivity lab. This setup uses a simple custom-made program called 'VI', which monitors several volt meters. Also the current and magnetic field can be controlled from this program. Three voltage pairs soldered on the tape, measuring over the whole tape length, over a length outside the heaters and inside the heaters. Also a Cryocon temperature controller can be used with this setup. The controller monitors the thermometers and control the edge heaters to tune the temperature. Especially near the critical current, maintaining the temperature is of importance, since ohmic heating at the soldered current leads can raise the temperature of the whole sample. The temperature controller also has internal relays that can be used to interrupt the current control signal. These relays can be set to open the circuit at a maximum temperature. In this way there is another safety measure.

In spite of all the safety measures, the measurements of the critical current were difficult. The tape has a fast increasing critical current at temperatures lower than 23 K, even at the highest magnetic field of 14 T. After the measurements on the 4-mm wide tape, the Lorentz forces were directed outwards. As discussed above, when these forces point inwards, the tape could buckle when it is not tightly wound around the structure or kink between the ridges. But in this configuration, with the Lorentz forces pointing outward, the hoop stresses became too high. The data that could be collected are represented in table 2.1. Figure 2.8 shows the current-electric field curve registered during a critical current measurement at T = 25 K and B = 14 T. In appendix B, all the graphs of I_c-measurements can be found.

After several unsuccessful attempts to complete the line of I_c-values all the way to T = 4.2 K,

Table 2.1: Critical current values found at a background magnetic field of 14 T.

T [K]	Ic (average) [A]	n-value
25	173	45
23	197	18
21	221	18
19	249	16
17	278	6
15	310	31

the I_c-measurements were considered too risky. The values are not of main importance for the analysis of the MQE and V_{nzp} and could be determined after the NZP measurements. More discussion about I_c-values of the 2- and 4-mm wide tapes can be found in the Analysis, chapter 4 on page 26.

2.4 Measurements Vnzp

In this section, the different functional elements of the equipment schematically shown in figure 2.6 are discussed.

Current and magnetic field control The experiment starts with the creation of a controlled environment. The EMS-laboratory has a 60 mm bore diameter, helium-cooled Nb_3Sn magnet able to generate a maximum magnetic field with a strength of 14 Tesla, powered by a Cryogenics power supply and controlled remotely with the 'VI'-program. The current through the sample is provided by a Delta SM 15-400 power supply able to deliver currents up to 400 A. Another supply was available capable of delivering 200 A, the Delta SM 15-200D. The sample current is measured with a Hitec Zero Flux probe, giving a signal of 0.005 V/A and able to measure currents up to 2000 A. The current is directly controlled by the DAQ 1 device. To stabilize the current control signal, a instrument amplifier is used between the DAQ and the quench detector. The sample current is monitored with an accurate micro-volt meter to verify the correct registration by the DAQ 2 device. The critical current of the Nb_3Sn current leads is 440 A. As discussed earlier, because of this limit, it was decided to use a REBCO tape of 2 mm width.

Temperature control An important part is the control of the temperature. The experiment has to be performed as adiabatic as possible. The sample holder is lowered in a liquid helium bath of 4.2 K. The sample environment is vacuum-pumped to prevent unwanted heat loss to the bath by conduction or convection. It is pumped for at least two nights to a pressure below 0.01 Pa, using a Pfeiffer Hi-Cube pump. To check for leaks, the pressure is verified to increase no more than 1.8 Pa/h, presumably mainly due to out-gassing. When lowered in the liquid helium bath, any residual gas will freeze to the wall. This cryo-pumping ensures a good vacuum: in between measurements at room temperature, a small leak was discovered, but lowered in the cryostat the pressure in the vacuum chamber did not increase. To thermally insulate from the sample further, all electrical wiring is made of manganin wire with a diameter of 0.1 mm. There are three parts of thermal loss which cannot be prevented:

1. Thermal conduction to the nylon ridges on the sample support structure (figure 2.3 and 2.5)
2. Thermal radiation from the tape to the outer wall of the vacuum chamber, cooled to

T=4.2K

3. Thermal radiation from the tape to the support structure with the embedded heater

The temperature is raised by three elements. In the support structure of the tape is the embedded heater. A resistive phosphor bronze heater wire runs along its whole length and thereby ensures an even spread of the heat. Its current is provided by a Delta E030-1 power supply in voltage mode. After adjusting the output of this embedded heater, it takes quite a long time for the temperature to stabilize, typically more than 240 seconds. This confirms the heat is spread gradually and that heat from the sample will not flow fast to the support structure when the temperature of the sample is raised during a quench. Most heat is conducted longitudinal through the tape towards the copper terminals of 4.2 K. Because of that, there are two edge heaters. These thick film SMD resistors of 20Ω are attached at the ends of the tape and isolate the measured zone from the heat sink. The edge heaters allow accurate adjustment of the temperature and are powered by two Delta CST 100 current sources. The temperature is monitored with calibrated Cernox temperature sensors from Lake Shore Inc. and their power is supplied by a Lake Shore 121 current source. For all experiments, the X31553 and X78396 thermometers were used. The registration of the temperature is done by the DAQ 1 device, which features 18-bit input sampling and is thus more accurate than DAQ 2.

Quench initiation and registration When the temperature-, magnetic field- and current environment of the sample is controlled and stabilized, the quench can be initiated. The heat is applied by a SMD resistor of 15Ω attached to the tape, as shown in figure 2.3. The current is supplied by a Bipolar Operational Source / Sink (BOS/S) amplifier. This supply is set to amplify the controlling signal voltage from the DAQ 2 device by a factor of two. The maximum output of the amplifier is 20 V and 20 A. The quench heater signal is a single square pulse, with a maximum height and width that can be adjusted in the Labview environment. The signal-registering device DAQ 1 has a voltage limit of only 10 V. To be able to measure a full signal, the voltage is divided with two 28 $k\Omega$ resistances in series and later multiplied again in the software environment. When the quench heater warms up, its resistance will change. So the current through the quench heater is monitored separately by measuring the voltage over an accurate 0.1 Ω shunt resistor. The energy of the pulse through the heater is then determined by the integral of the voltage and current over the time length of the pulse:

$$E_{pulse} = \int_0^\infty U \cdot I dt, \tag{2.1}$$

where U is the voltage over the heater and I is the current through it.

When the heat pulse is triggered, also the possible normal zone propagation is registered by the monitoring voltage taps on one side of the quench heater. The signal has to be measured fast and accurately, so each voltage pair signal is pre-amplified by an Ectron 751ELN DC-Amplifier. The amplifiers are set on a gain of 1000x and a low-pass filter bandwidth of 10 Hz. A smaller bandwidth (1 Hz) would slow down the signal-processing too much. The DAQ 2 device is used for the registration of the voltages. It has a sample rate of 10 kHz divided over three channels, which is higher than the DAQ 1 device. The voltage signal measured by the data acquisition card is divided by the voltage tap distance in the software, to produce the electric field. The energy of the pulse then gradually increased until a quench occurs. A clear trace of measured voltage response during a quench is shown in figure 2.9.

Quench detection The most delicate part of the experiment is the recording of the quench itself. The current has to be shut down within a small time frame after its detection, to avoid damaging the tape by overheating. For this, a "Moekotte Automatisering" DC Quench detector is used. This hardware trips when an input signal reaches a pre-set alarm level, interrupting the current control signal or enabling the quench detection port of the power supplies. As discussed earlier, also the current leads of the insert are protected with this method. Besides the quench detection hardware, a software-based quench detection method is implemented for redundancy: if the signal of the voltage taps exceeds a certain trigger level, the current is set to zero. The current is also disabled automatically when a certain interval after a heat pulse has past. The quench detection has to respond quickly. Hardware detection is the most direct method and therefore, most of the time, the first one to trigger. The device needs to be 'tuned' carefully: if the current is shut off too soon, the voltage signal of the quench is too small and unstable and the data are useless. After a first sample burned out despite these redundant safety measures, a second quench detector was added to the setup to have more control.

Based on his experience with 4-mm wide tapes, J. van Nugteren [9] recommended to set the alarm level of the quench detector in such a way, that after a quench the temperature will not rise above 70 K at T1 and T2. For measurements on the 2-mm wide tape, this limit implied an alarm level of the quench detector which was too low for acquiring a clear voltage signal, i.e. the quench detector responded too quickly. The alarm level was raised until a usable voltage development could be measured. The corresponding maximum temperatures during a quench now lie around 110 K.

Software The NZP-experiment is mainly controlled with a Labview by written by J. van Nugteren [9]. Labview is a graphical programming environment developed by National Instruments. The Labview environment for NZP-experiment consists of several functional sections:

1. Environment control; monitor temperature and magnetic field.
2. I_c-measurement and current control; monitor and control the sample current, ramp rate and the voltages. An I_c-measurement can be started, slowly ramping from a starting current and measuring the voltage until a certain level has been reached. Then the I_c-measurement is terminated and the current is shut down.
3. Pulse response; set the pulse energy and monitor the outcome after a pulse.
4. Quench detection; settings for the software quench detection.
5. Data I/O; export the data from the last action (I_c-measurement or pulse response) as a matlab-file.
6. Settings; indicators and controls of e.g. sampling frequencies, time, amplification, scaling and offsets for components.

2.5 Signal analysis

The result from a measurement is exported to Matlab and analyzed. As discussed in section 2.1, the normal zone propagation velocity is determined from the time delay between the voltage signals of different taps. The voltages rapidly increase when the front of the normal zone reaches the voltage taps. The signature of a quench can be clearly seen in figure 2.9. The first part is noise, mainly due to 50 Hz pick-up. Then the front of the zone reaches the first voltage tap and around 10 mV the quench detector triggers and shuts down the current. Due to the self-inductance of the sample, the voltages become negative and the measurement ends. Ideally, the voltage profiles recorded with successive pairs should have the exact same shape, though this is not fully the case. Measures have been taken to minimize the influence of anomalous signals. Still noise can not fully be prevented. Also, some cross-talk remains between the wires, although they are twisted separately in the cable tree.

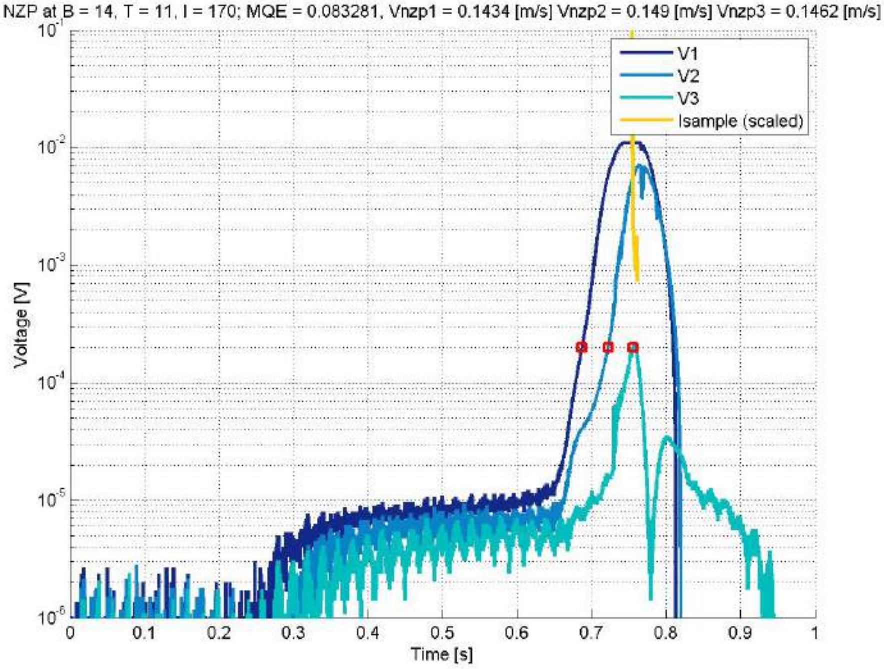


Figure 2.9: A clear voltage signal from a quench event.

A quench is recognized as an exponential voltage level growth, which is shifted in time for the subsequent voltage pairs. Disturbances in the voltage profile are seen in figure 2.9, after t = 0.65 s at V2 and after t = 0.7 s at V3. These disturbances are seen in almost every measurement on 2-mm tape, in contrary to measurements on 4-mm tape. Because of these irregularities, the value of V_{nzp} is harder to determine. Therefore, of every measurement, $(V_{nzp}, V_{threshold})$a profile like the one in figure 2.10 was determined by calculating V_{nzp} at different threshold voltages. With such profiles, a threshold voltage could be determined at which the propagation velocities are most stable and comparable with each other. This general threshold voltage was set at 0.2 mV. For a few measurements, the threshold voltages had to be adjusted slightly. The general threshold voltage used for 4-mm tape results was 0.1 mV, so the results stay comparable. The profiles are also used to estimate uncertainties on the normal zone propagation velocities.

A further possible source of errors is the influence of the solder of the voltage taps. The voltage taps need to be soldered to the tape, as shown in figure 2.11. Care was taken to do this as 'cleanly' as possible, but a minimum amount of solder is needed for good contact. This solder adds material and thus heat capacity locally. The increase of heat capacity lowers the V_{nzp}, see equation 4.2 on page 26.

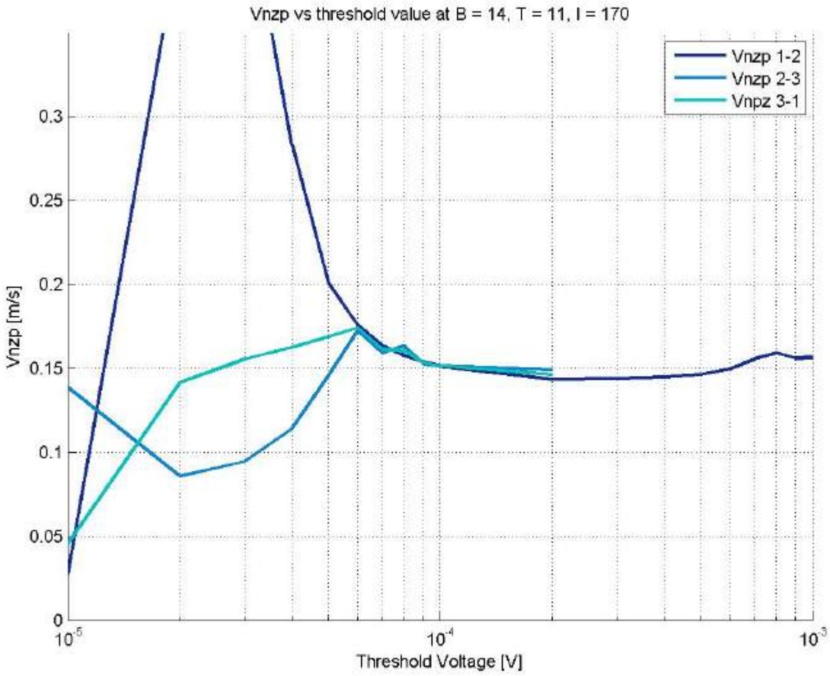


Figure 2.10: A profile of figure 2.9 with V_{nzp} versus threshold voltage. At a threshold voltage of 200 μV, the signals are stable and the velocities of all taps are comparable.

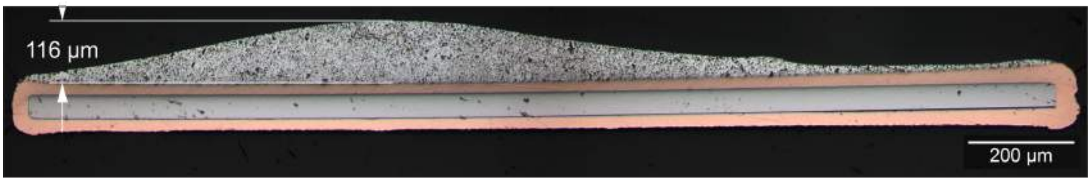


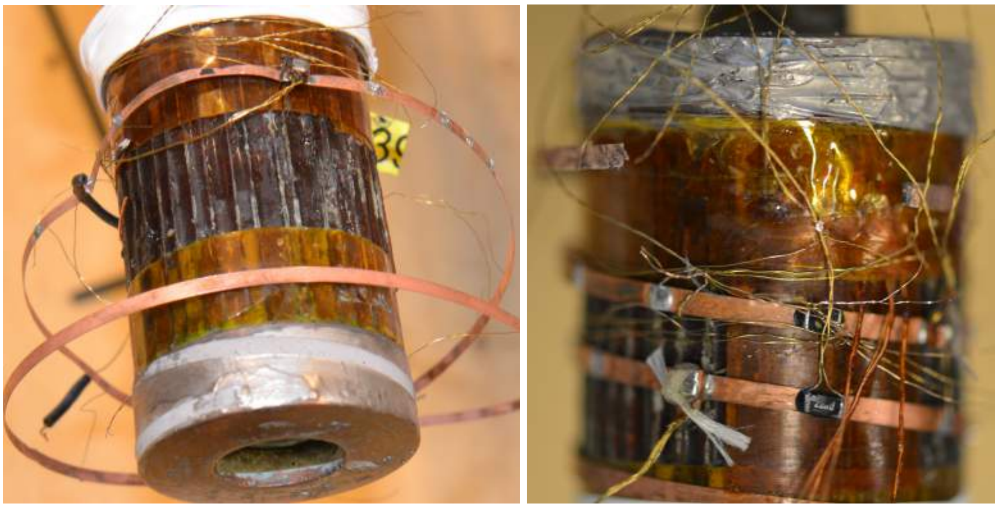
Figure 2.11: Crossection of the 2-mm wide tape with solder of a voltage tap.

Chapter 3 Results

In this chapter the results of the measurements on the 2-mm REBCO tapes are presented. The chapter starts with an overview of the experimental campaign. Next, the results of the minimum quench energy are presented as functions of temperature and current. Finally, also the normal zone propagation velocities are shown at various magnetic fields, temperatures and current levels.

3.1 Overview

At the start of the assignment to measure MQE and V_{nzp} on 2-mm tapes and as discussed in chapter 2, the electrical wiring was replaced. To test the modified set-up and to gain experience with the experiments, a new 4-mm REBCO tape was mounted. During a first test run with this new 4-mm tape in the 15 T magnet, the embedded heater leads burned out and needed to be replaced with slightly thicker manganin wire. A successful set of experiments was then performed on the 4-mm tape, reproducibly yielding comparable I_c, MQE and V_{nzp} data as those reported previously by J. van Nugteren [9]. During on of the I_c-measurements, the sample broke at the quench heater, outside the monitored area. An extra voltage tap across the whole tape was added from this moment onward. Enough experience with the setup and the instrumentation was gained after this test run to commence the measurements on the 2-mm tapes. The heater elements were replaced with smaller versions from the same manufacturer and type. A Cryocon temperature controller was used to maintain a constant temperature during the I_c-measurement. A set of successful I_c-measurements was conducted for temperatures between 25 K to 19 K. At 19 K, the tape quenched and was damaged. Subsequent inspection revealed an overheated spot, once more outside the sample length monitored by the voltage taps. A new tape was prepared and three new voltage taps were added for I_c-measurements. Apart from an initial (solved) grounding problem with a temperature sensor, the second I_c-measurement run gave good results. The addition of three voltage taps (V0,V4,V5) for measuring I_c proved valuable. Six I_c-values were acquired at a magnetic field strength of 14 T within the temperature range of 25 K and 15 K. Unfortunately however, at T = 13 K, the tape was pulled from the bottom terminal by the outward pointing Lorentz forces and the sample was destroyed. A picture of this tape can be seen in figure 3.1. Therefore, the third sample was reinforced with niobium titanium wire around the terminals. The outcome of the measurement can also be seen in figure 3.1: this time the sample burned through after one I_c-value measurement, outside of the zone heated by the edge heaters. After this failed attempt to collect further I_c values at lower temperatures, it was decided to start the NZP measurements and postpone the I_c-measurements, to minimize the risk of damaging the tape. It was reasoned that previous measurements could be used as a first indication and after a successful NZP measurement run, the I_c could still be determined. The fourth 2-mm wide sample burned right through during the first NZP measurement, because the alarm level of the quench detector was set too high. With the addition of another quench detector and a much more cautious tuning approach, the fifth sample finally gave adequate MQE and V_{nzp} results. These are presented in the following sections.



(a) The second 2 mm wide sample **(b)** The third, burned out sample

Figure 3.1: Photographs of the sample after failed experiments. **(a)** This sample was electromagnetically pulled from one of the soldered current terminals. **(b)** The tape burned out between the edge heater and the corresponding current terminal.

3.2 Mimimum Quench Energy

Although the focus of this assignment was on the determination of the normal propagation velocity, the experiments also yielded an estimate of the MQE-value under various operational parameters. As shown in figures 3.2 and 3.3, the MQE decreases with increasing temperature and current. Referring to equation 1.1, the temperature dependence of MQE is determined by two effects. A higher operating temperature T_0 implies that the sample needs to be heated less to reach the transition temperature T_t, so MQE goes down. The difference $T_t - T_0$ is called the thermal margin. On the other hand, the heat capacity $C(T)$ is a strongly increasing function of temperature. Based on this observation, MQE might be expected to go up with temperature. In the dissertation of H. van Weeren [8], it is mentioned that in MgB_2 wires, for which the set-up was originally designed and used, there is a competition between these two effects, leading to a non-monotonic temperature dependence of MQE. The thermal margin clearly has more influence here in these REBCO tapes. Concerning the current dependence of MQE (figure 3.3), for a given magnetic field, a higher sample current implies a lower T_t. So also the observed decrease of MQE with increasing sample current can be interpreted as a decrease of the thermal margin. The dependence of MQE on magnetic field, however, is anomalous. It may be expected that MQE decreases with increasing magnetic fields: for a given current T_t and hence also the thermal margin will go down as the field goes up. The measurements at a magnetic field of 10 T from 15 K and lower temperatures, and the measurements at a magnetic field of 14 T were made with a different quench heater fixation. As discussed in section 2.1, the quench heater was glued to the tape with aluminum loaded epoxy, but detached several times and the fixation had to be replaced. Therefore it is rather difficult to make conclusions on the dependence of the MQE on the magnetic field.

Adding to this, there is in general a rather large uncertainty on the measured value of the minimum quench energy, related to uncertainties in heater efficiency. Part of the deposited

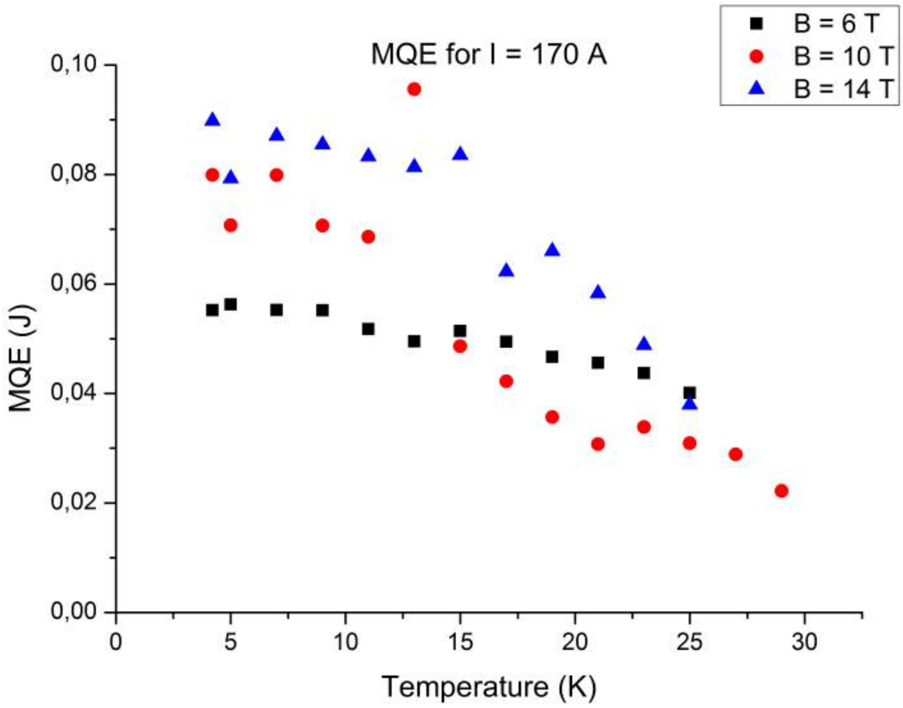


Figure 3.2: The dependence of the MQE on temperature and magnetic field, measured at a constant current of 170 A. The numbers are not adjusted for heater inefficiency.

energy simply heats up the heater-leads. Moreover, the heater itself has a finite heat capacity and its thermal connection to the tape has a finite thermal impedance. This implies that when the heater and the thermal connection warms up, energy only gradually seeps in the sample. As a consequence, before the quench, some heat already can be lost to the environment because of radiation and the electrical connections of the heater. As a further complication, when the sample becomes normal, ohmic heat increases the samples temperature and part of this ohmic heating can flow back into the heater. All these effects make MQE measurements notoriously difficult to interpret [9].

3.3 Normal zone propagation velocity

In this section, we turn our attention to the measured normal zone propagation velocity (V_{nzp}). The main goal of this assignment was to asses whether the conclusion of earlier work in the temperature range 25-45 K (i.e. the observation that V_{nzp} hardly depends on magnetic field or temperature) also extends to lower temperatures.

Figure 3.4 shows a total of 38 points measured at temperatures varying between 4.2 and 29 K, at a constant current of 170 A and at three different magnetic field strengths (6, 10 and 14 T). Clearly the variation of the normal zone propagation velocity in this temperature- and field range is hardly significant. Several velocities, measured at the same temperature, but different magnetic field strenghts, show an overlap. Note that the error estimates indicated in the figure were determined from the analysis of the threshold voltages, see section 2.5. A linear fit through the points (figure 3.5) gives a slope of $(5.3 \pm 1.7) \times 10^{-4}$ m/s per Kelvin in the temperature range of 4.2 K to 29 K, i.e. the fitted V_{nzp} variation over this range (~ 1 cm/s) is of the same order as the typical uncertainty estimate on the V_{nzp} values ($\sim 1 - 2$ cm/s). Four points were excluded at magnetic field strength B = 6 T, for temperatures 7, 9, 11 and 13 K.

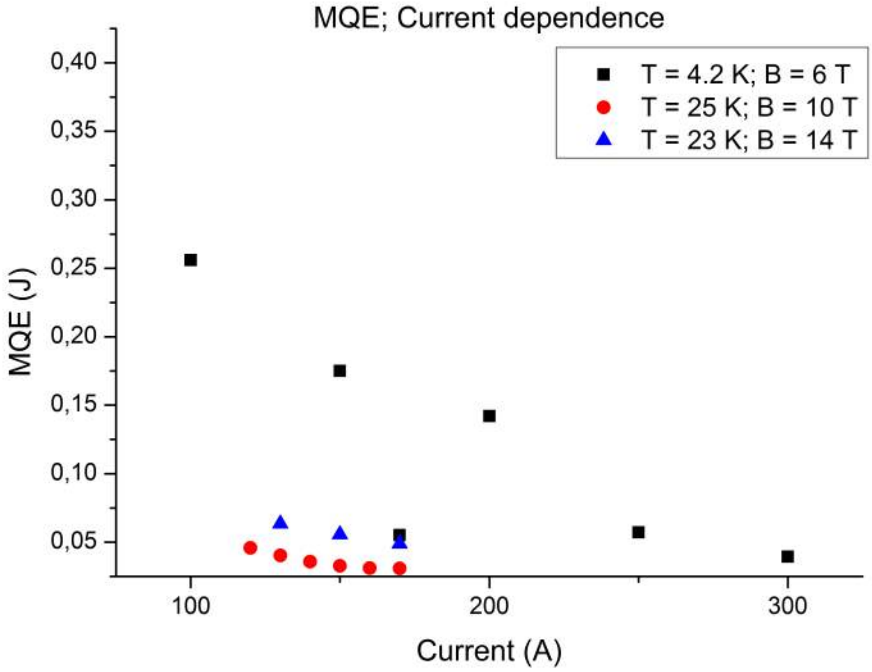


Figure 3.3: MQE versus sample current. The values of MQE are not compensated for any heater inefficiencies.

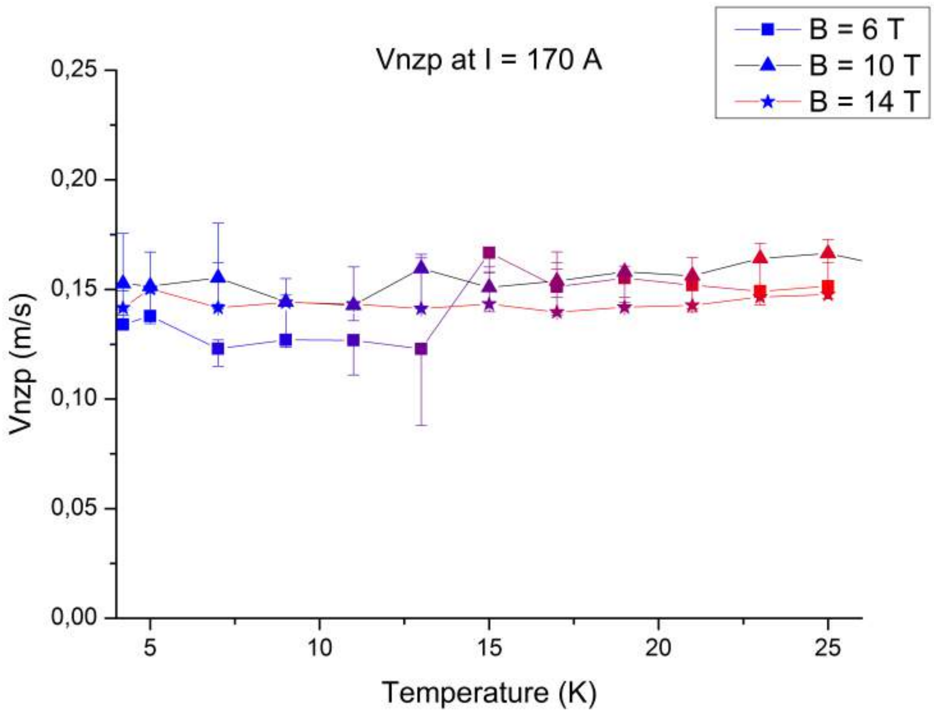


Figure 3.4: Vnzp versus temperature. The velocity changes with 9 percent between 4.2 and 29 K. At several temperatures, the velocity at different magnetic field strenghts show an overlap. The error was determined by analysing the threshold voltage (section 2.5)

.

These measurements were conducted in the beginning of the measurement period, at the start of the 'learning curve' described by the overview in section 3.1. The threshold voltages of the measurements were too low, because of a too tightly set quench detector. The quench detector cut off the current before a usable signal could develop.

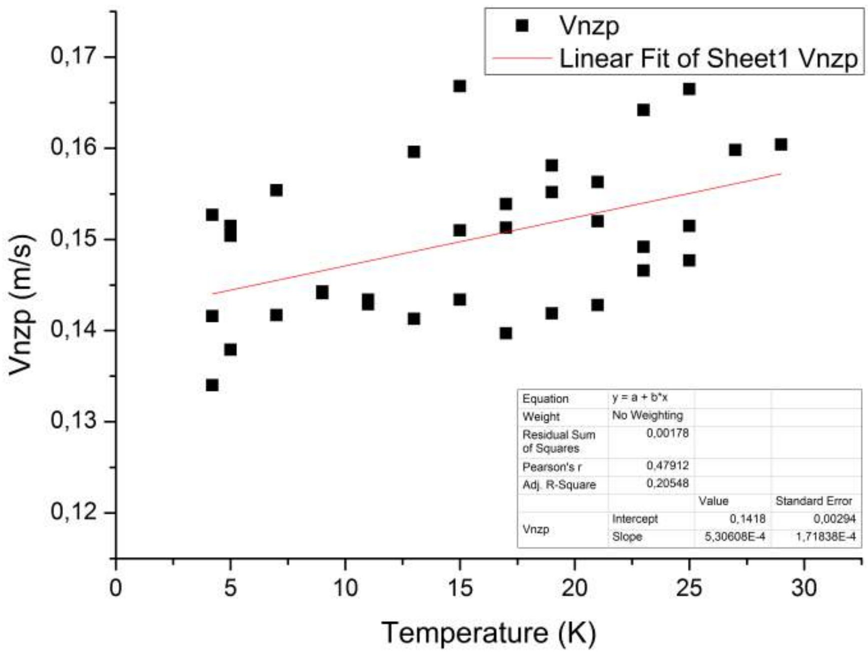


Figure 3.5: The temperature dependence of Vnzp at a constant current of 170 A. A fitted linear trend line is added, with a slope of $(5.3 \pm 1.7) \times 10^{-4}$ m/s per Kelvin. Four points fell out of the error margin and were excluded.

The normal zone propagation velocity was also measured with varying currents, in the range of 100 A to 300 A. These measurements are used to check whether the power law reported by [9] for 4 mm wide tape also holds for this 2 mm wide sample and whether it extends to lower temperatures. They were executed at several magnetic field strengths and different temperatures. Also here it can be seen that the normal zone propagation velocity is quite independent of field and temperature. The linear trend on this double-logarithmic plot indicates also for this tape a power-law type dependence on the current passing through the sample. Sadly, only 15 points could be taken to underline the current dependence, since the sample degraded after the measurement at I = 300 A. The next chapter, section 4.3 will further elaborate on the current dependence of the normal zone propagation.

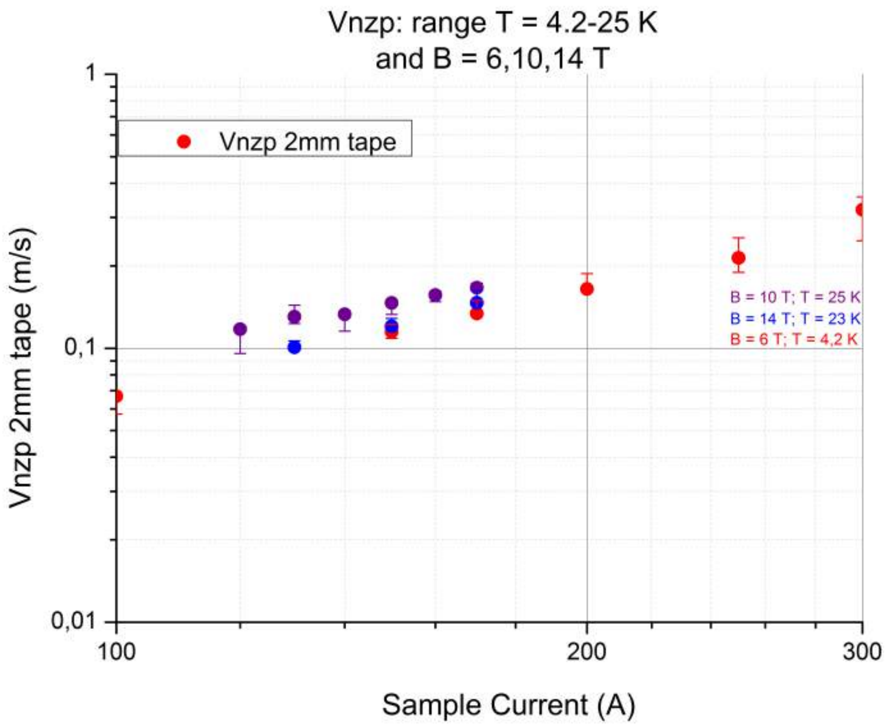


Figure 3.6: V_{nzp} measured versus sample current at three different combinations of magnetic field and temperature.

Chapter 4 Analysis

The theoretical description of normal zone propagation in low-temperature superconductors is based on the analysis of the heat balance equation, as described in of this chapter. Whether or not this 'classical' model can just as well be used for the REBCO HTS, is also explored in this first section. In parallel with the experiments, numerical simulations were executed. The main conclusions of these simulations are summarized in section two. In the final section, the data for the 2 mm wide tapes are compared with the previous observations on 4-mm REBCO tape.

4.1 Analytical model

The model of normal zone behavior is based on the heat balance equation. The one-dimensional version of this heat balance equation is given below (Eqn. 4.1).

$$C(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right] + P_\Omega + P_i - P_c \tag{4.1}$$

Here $C(T)$ is the temperature-dependent heat capacity in J/mK, $k(T)$ the temperature dependent thermal conductivity in Wm/K and T the temperature. The power terms P_Ω, P_i and P_c represent the Ohmic power dissipation in the tape, the initial disturbance and the cooling to the environment respectively, all given in W/m. Assuming an adiabatic environment and a steady-state propagation of the normal zone (i.e. its propagation once transients due to the initial disturbance have died out), P_c and P_i are neglected, respectively. The difficulty in solving the resulting differential equation lies in the non-linear character of the remaining power term P_Ω, which is caused by the non-linear electric field - current density relation (see section 2.3). However, under some simplifying assumptions, the equation may be solved analytically at the interface between the normal zone and the superconducting parts of the sample to yield equation 4.2 for V_{nzp}. For the full derivation, see [7] or [9].

$$V_{nzp} = \frac{I_{op}}{C(\tilde{T})}\sqrt{\frac{\rho(\tilde{T})k(\tilde{T})}{(T_t - T_{op})}}. \tag{4.2}$$

In this analytic expression of V_{nzp}, I_{op} is the current in the sample, C its heat capacity (averaged over all constituent materials), ρ its average electrical resistivity in the normal state, k its average thermal conductivity, T_t the transition temperature and T_{op} the operational base temperature. With the simplifications commonly made, the material-dependent properties are usually evaluated at an average temperature: $\tilde{T} = (T_t + T_{op})/2$.

Clearly this analytic model prediction equation 4.2 is temperature dependent, while this is not seen (or hardly, see figure 3.4) in the results. The model approximations that were made for LTS materials and that give good results there, apparently do not hold for HTS materials at low temperatures. As a first observation, the temperature range under consideration with HTS is obviously larger than for LTS. For the latter materials, the transition temperature T_t (depending on current and magnetic field) typically lies below 10 K while their operational temperature typically is 4.2 K. Here, T_t may be as high as 40 K and considering the material properties to be constant is a crude approximation. The temperature dependence of the material properties is shown in figure 4.1. Crudely speaking all values drop with temperature, with the electrical resistivity becoming almost constant below 25 K and the heat capacity below 15 K. The thermal conductivity becomes linear below 15 K.

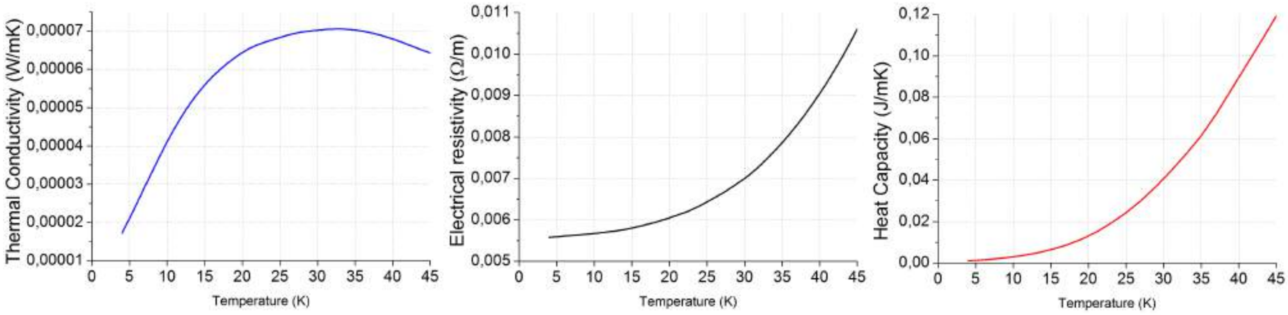


Figure 4.1: Calculated average material properties for the 2-mm wide REBCO tape [9]. Plotted against temperature are the electrical resistivity 'ρ', the thermal conductivity 'k' and the heat capacity 'C'.

In the book on superconducting magnet design by Iwasa [7], it is argued that the approximation of $\tilde{T}$ should only be used if $(T_t - T_{op})/T_{op} \ll 1$. This is generally more or less applicable for LTS materials, but in general not for HTS. Instead of equation 4.2, Iwasa suggests using a more exact version with temperature dependent material properties, proposed by Whetstone and Roos [11]:

$$V_{nzp} = I\sqrt{\frac{\rho(T_t)k(T_t)}{\left[C(T_t) - \frac{1}{k(T_t)}\frac{dk}{dT}\bigg|_{T_t}\int_{T_{op}}^{T_t} C(T)dT\right]\int_{T_{op}}^{T_t} C(T)dT}} \tag{4.3}$$

We will refer to the prediction Eqn. 4.2 as the 'short model' and to Eqn. 4.3 as the 'long model'. The short model evaluates the material properties at a temperature which is too high, yielding temperature dependent V_{nzp} values. The long model considers the full temperature range for the material properties and yields a V_{nzp} that is nearly temperature independent below 25 K, confirming the experimental observations on the 2- and 4-mm wide REBCO tapes. Quantitatively, the long model prediction deviates about 15% from the 4 mm data and 33% from the 2 mm data. It should be noted, however, that the long model considers a fully adiabatic system, whereas the experiments are performed quasi-adiabatic (see section 2.4). Equation 4.3 shows that the predicted influence of the current is seems to be linear, in contrast to the power close to 1.5 observed experimentally. We will refer further discussion of this discrepancy to the next section, where more precise theoretical predictions will be made based on a purely numerical model.

The last parameter that remains is the applied magnetic field. An applied field will mostly influence the electrical resistivity, raising it. However, below 25 K the electrical resistivity is small and constant, so a magnetic field is not expected to change the value of V_{nzp} to a great extent.

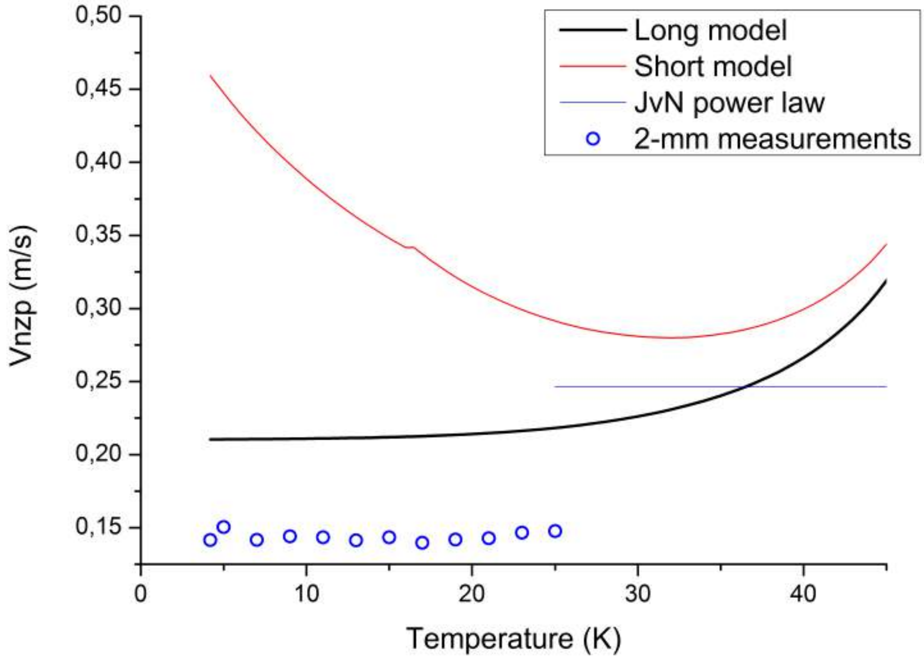


Figure 4.2: Comparison of the 'short model' prediction Eqn. 4.2, the 'long model' prediction Eqn. 4.3, the 'power law' behavior observed in the 4 mm tapes [JvN] and the present data on the 2-mm tape. The models are considered at an operating current of 173 A and a magnetic field of 14 T.

Another important analytical approximation which requires a closer look, is the choice of the transition temperature. It is defined as

$$T_t = (T_{cs} + T_c)/2 \tag{4.4}$$

with T_{cs} the 'current sharing' temperature, i.e. the temperature at which the sample current becomes equal to the (temperature dependent) critical current and the first ohmic dissipation sets in. The choice of T_t midway the current sharing- and critical temerature was proposed by Dresner [12]. It is based on a piece-wise solution of the heat balance equation to simplify the treatment of the current sharing regime. To clarify this concept, we consider the example in figure 4.3, where we indicate which fraction of the current is carried by the REBCO layer of the tape and which fraction flows in the copper stabilizer (see also figure 2.1). Three regions are distinguished:

- Fully superconducting - In figure 4.3, below T_{cs} = 30 K. All current is flowing through the superconductor and there is no Ohmic heating.
- Current sharing - In figure 4.3, between T_{cs} K and T_c = 68 K. The I_c drops below the operating current, forcing a part of it through the normal conductor, generating heat.
- Fully normal - In figure 4.3, above $T_c = 68$, all superconductivity is lost.

Matching the solutions for all three regimes at the boundaries, creates an implicit equation which can not be written in a closed analytic form. Therefore, Dresner proposed to treat current sharing with the more simple step function of equation 4.4, which does lead to a closed analytic expression. By doing this, he assumes that below T_t all current flows loss-less in the superconductor, while above T_t the full current flows in the stabilizer. However, the transitions regime is larger for HTS materials than LTS materials, making this approximation cruder. Constructing an alternative analytical prediction that avoids this central current sharing simplification is a task that was considered to lie outside the scope of this MSc assignment, especially since nowadays relatively straightforward numerical models can be constructed and evaluated. Such a model is the topic of the next section.

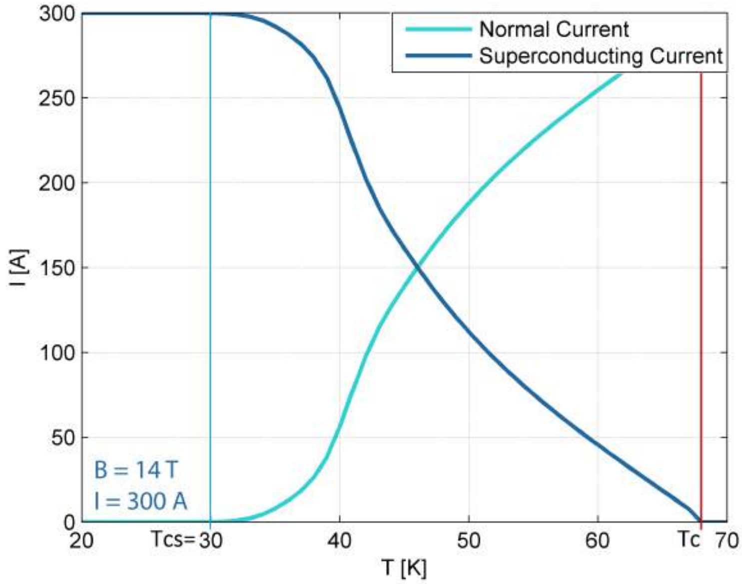


Figure 4.3: Example of current sharing in the 4-mm tape. T_{cs} is at T = 30 K. T_c is at T = 68 K.

4.2 Simulations

In parallel with the NZP experiments on the 2-mm wide HTS tape, simulations were conducted to support the findings of the experiments, in the same manner as was done for the 4-mm tape. The simulations for the 2-mm tape were executed by Remco Timmer in the frame of his BSc assignment and solves of the discrete heat balance equation in a one-dimensional lumped system.

$$C(T_i)\frac{dT_i}{dt} = \frac{k(T_i)(2T_i - T_{i-1} - T_{i+1})}{dx_i} + I_{nc}^2\rho(T_i)dx_i + P_i(x_i,t) - h(T_i - T_{op})dx_i. \tag{4.5}$$

Once more $C(T)$ is the temperature-dependent heat capacity in J/mK, $k(T)$ the temperature-dependent thermal conductivity Wm/K, $\rho(T)$ the temperature-dependent electrical resistivity in Ω/m and dx_i the length of the node with index i.

Solving the heat equation numerically, the slow transition of the HTS shown in figure 4.3 can be fully incorporated. Also the temperature dependence of the material properties can be fully taken into account. The discrete form of the heat equation is solved using Matlab ode15s differential equation solver. A sample length of 0.2 m is divided in a number of nodes and all nodes are attributed the same temperature T_{op} at the start. The quench is initiated at the center node by the disturbance term P_i. An example of the resulting evolution of the temperature profile is shown in figure 4.4.

For the description of the current sharing regime (4.3) and the corresponding calculation of the power dissipation term P_Ω, the temperature- and magnetic field dependent critical current values of the tape are required. However, a full description of the critical surface (see 1.2) of these tapes was not available and the experimental campaign to determine I_c below 25 K proved to be cumbersome (section 2.3), so an estimation was made for the critical current values in

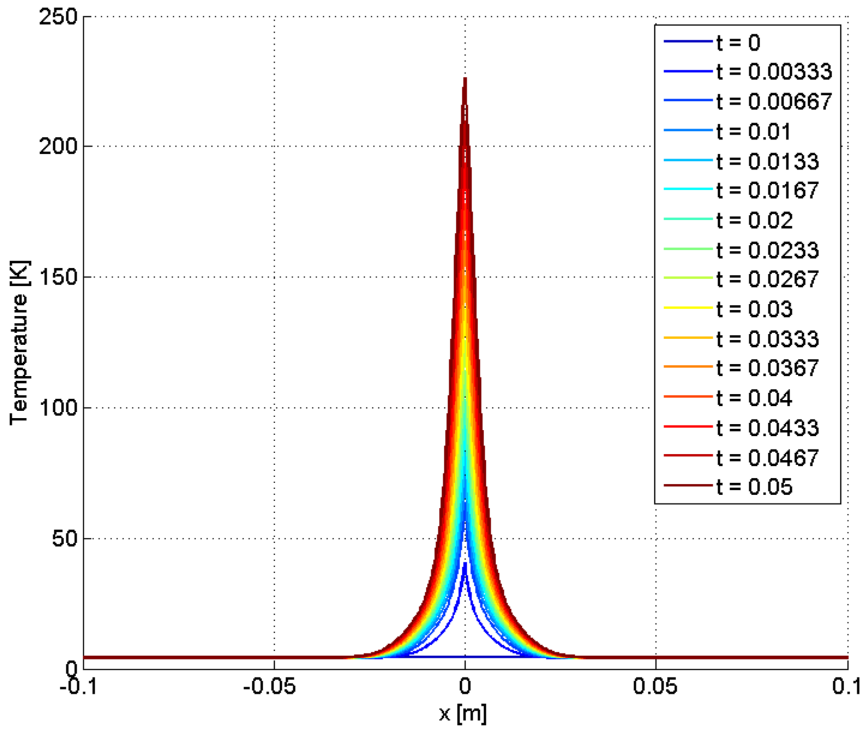


Figure 4.4: Temperature development of a simulated quench, with B = 14T at T = 4.2 K and I = 170 A.

this lowest temperature range. Two types of scaling relations were investigated: an exponential scaling relation, proposed by C. Senatore [13] and a bi-linear scaling. Earlier measurements of V. Lombardo [14] and J. van Nugteren indicate a bi-linear relation, i.e. scaling with two seperate linear fittings with a transition from one to the other between 30 K and 40 K. In figure 4.5, the measured I_c values and the investigated scaling relations are shown. Both scaling relations approach the available measurements fairly well.

With these extrapolated critical current values, simulations were performed and the results were compared with the measurements. The results for the temperature dependence of V_{nzp} is presented in figure 4.6 and the current dependence in figure 4.7. The temperature-independent value for the 4 mm wide tape [9] is shown together with the measurements done on the 2-mm wide tape.

All solutions of the simulation lie below the power law and above the measurements on the 2 mm wide sample. Though the values differ from the measurements, the simulations confirm the limited dependence of V_{nzp} on magnetic field and temperature. The simulations with the bi-linear current-temperature relation yield values that are about 25% higher than the points calculated using the exponential scaling relation. The bi-linear scaling is more realistic because the I_c values do not 'explode' at low temperatures. However, the exponential readings are more near the measured 2-mm tape values. If we are looking for a model which is closer to the measurements, then the exponential scaling is the most appropriate. As a general conclusion, it is clear that this simple 1D-model can be used to produce reasonable data.

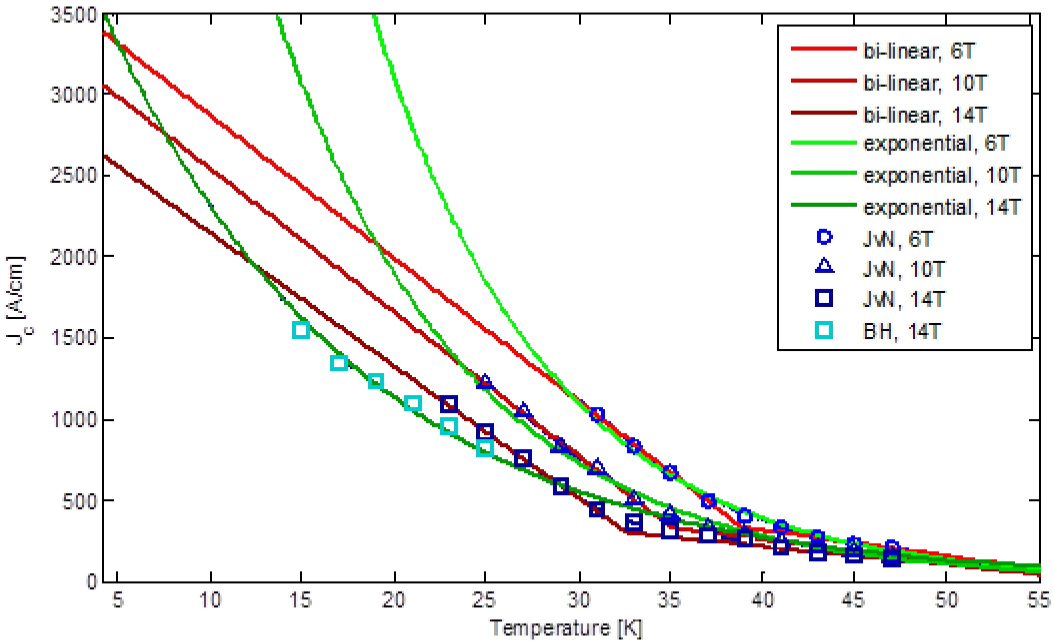


Figure 4.5: Critical current density values at different magnetic field strengths, used for the simulations. The points represent the measured values, the lines show the values using the fitted scaling relations. JvN stands for the measurements of the 4-mm wide tape, BH for the 2-mm wide tape data collected in this work. Behind the name in the legend the value of the magnetic background field is indicated.

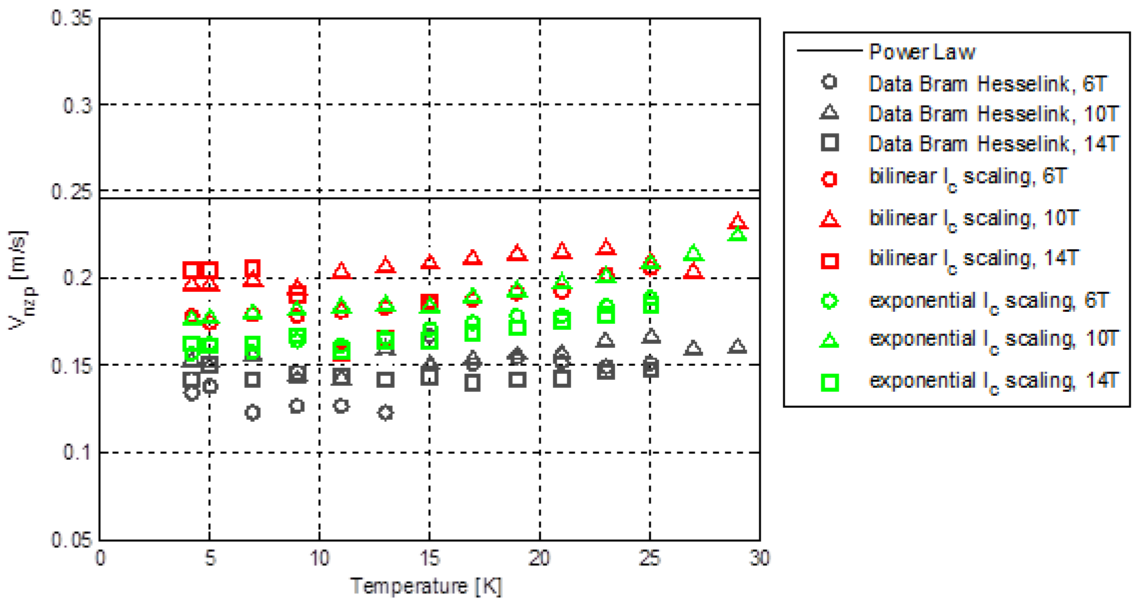


Figure 4.6: Results from the simulation of temperature dependence of V_{nzp}, at a constant current of I = 85 A/mm width.

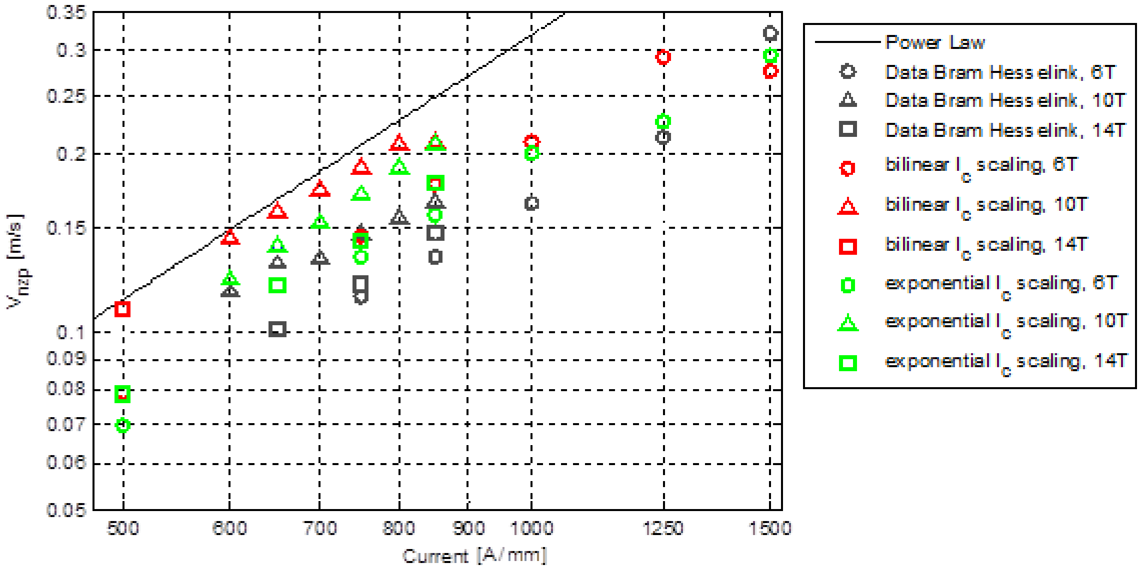


Figure 4.7: Results from the simulation of current dependent V_{nzp}. For T = 4.2 K at B = 6 T; T = 25 K at B = 10 T and T = 23 K at B = 14 T.

4.3 Comparison of normal zone propagation in the 2 - and 4 mm wide tapes

One of the goals of the research in this report was to verify the power-law dependence of the normal zone propagation velocity on the sample operating current. In figure 4.8, the normal zone propagation velocity against the current is fitted with a exponential function:

$$V_{nzp} = 10^{P_2} I^{P_1} \tag{4.6}$$

The power-law behavior found by J. van Nugteren [9] is also drawn as a solid light grey line. Comparison of the fitted power-law Eqn. 4.6 shows a great similarity in the slope, but there is a rather large difference in V_{nzp} values, with the propagation in the 2 mm wide tape $40 - 50$ % lower than in the 4 mm wide one. In table 4.1 the coefficients P_1 and P_2 are summarized.

Table 4.1: Fitting coefficients P1 and P2 of equation 4.6 for the two HTS samples

Type measurement	P_1	P_2
4 mm @T = 25 – 45 K	1,490855124	-4,38271618
2 mm @T = 4.2 – 25 K	1,4331	-4,46418

4.3.1 Possible causes for the differences between the 2-mm and 4-mm tape

Although the temperature-, magnetic field - and current dependence of V_{nzp} is similar for both tape widths, the absolute difference between the V_{nzp} values measured in both tapes is relatively large. In the following subsection probable causes for this difference are further explored.

Copper layer thickness As discussed in section 2.1, a large part of the REBCO tape consists of copper stabilizer. According to equation 4.2, the copper influences the value of V_{nzp} directly by increasing the heat capacity and the thermal conductivity and by lowering the electrical resistivity of the tape. A change in thickness of the other layers will not contribute as much to

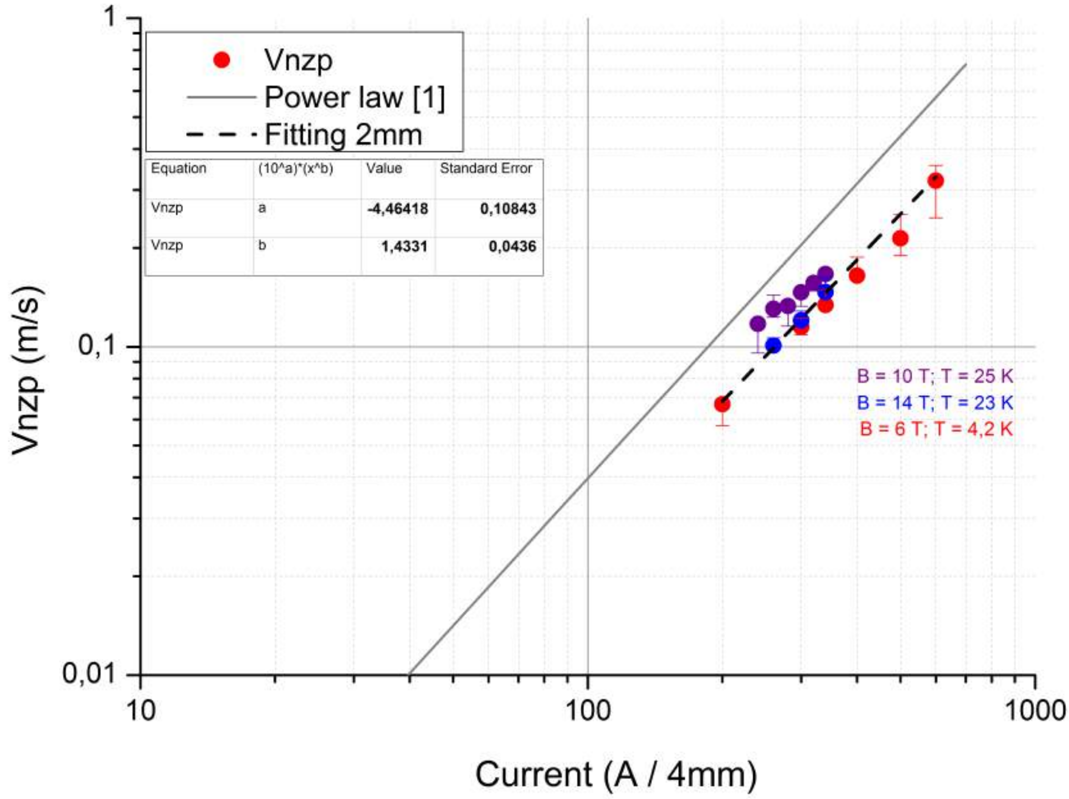


Figure 4.8: Measured V_{nzp} compared with the earlier found current dependence

the thermal and electrical properties of the tape. Moreover, the copper layer is electroplated and its thickness is less controlled than the other material layers. Cross-sections of the 4-mm and 2-mm wide tape were polished and images were taken, as shown in figure 4.9 and 4.10. Due to electrostatic edge effects during the copper deposition, a buildup of copper is seen near the edges of both tapes, a phenomenon that in the community is commonly called 'dogbone shape'. This thickness inaccuracy is inherent with the electroplating technique. Because of its smaller dimensions, the influence of this copper accumulation at the edges might have a relatively large effect on the properties of the 2-mm tape. To check whether the conductors have a significantly different relative amount of copper, these cross-sectional images were analyzed in detail. The conclusion is that the 2-mm wide tape has $(7 \pm 1)\%$ more copper than the 4-mm wide tape. With the numerical model described in section 4.2, it was concluded that this leads to a decrease of V_{nzp} with almost the same percentage: $(8 \pm 1)\%$.

Figure 4.9: Cross section of the 2-mm tape. Notice 'dog bone' shape of the tape, i.e. the increased amount of copper at the edges.

Figure 4.10: Crossection of the 4-mm tape used for measurements executed by J. van Nugteren [9].

Width of the tape To compare the 2-mm to the 4-mm tape, the values of the I_c, V_{nzp} and MQE are scaled by their width, so a factor 2. To be certain, these nominal dimensions of the tapes need to be measured accurately. Once more using the cross-sectional images in figure 4.9 and 4.10, the widths of the tape were determined with a higher precision. The widths were found to be (2.01 ± 0.01) mm and (4.02 ± 0.01) mm respectively. These values includes the irregular shaped copper layer. The width of the REBCO layer itself is (1.93 ± 0.01) mm and (3.97 ± 0.01). The scaling factor should therefore be 2.06. This would imply the current densities would go up by 3%, in the comparison to the I_c values reported in figure 4.5. Assuming that the 2-mm tape has a comparable quality as the 4-mm tape. The rescaling of values would imply a lower V_{nzp} with the same factor as the current. In other words, the 2-mm values would fall an extra 3% with respect to the 4 mm ones. This correction is minor and, moreover, in the wrong direction to explain the observed V_{nzp} difference.

Minimum propagation zone To register a steady-state propagation velocity, the voltage taps need to be located sufficiently far from the quench starting point. A crude first estimate indicates that the minimum distance is about equal to the minimum propagation zone length ℓ_{MPZ} (see section 1.3). V_{nzp} is supposed to become stable once it has propagated beyond the MPZ. Using equation 1.1 on page 4, the ℓ_{MPZ} is calculated. At 25 K, the MPZ is estimated to have a length of 0.47 mm and at 4.2 K it has an even smaller length of 0.26 mm. So V_{nzp} should be stable at the voltage taps, which are placed 10, 15 and 20 mm away from the quench initiation heater.

Cooling term The heat balance equation 4.1 contains a cooling term P_c, which takes into account heat leaking away from the normal zone to the environment and consists of a radiation part and a conduction part to the support structure. The cooling term could give an indication for difference between the two tapes. Increased cooling during a quench results in a lower amount of heat available to drive the superconducting-to-normal front forwards and hence to a lower propagation velocity. Estimating the radiation part yields 0.012 W/m, which is negligible compared to conduction losses. Analyzing the conduction term at 25 K and 4.2 K for the 2-mm tape gives a cooling factor of 2.3 W/m at 25 K and 1.8 W/m at 4.2 K, respectively. These values are smaller for the 2-mm than the 4-mm, so they cannot explain the lower V_{nzp} value in the narrower tape.

The most plausible causes for the observed V_{nzp} differences between the 2-mm and 4-mm wide tape were investigated and cannot explain the 40-50% difference. There could be more reasons, like increased heat leak through the quench heater or voltage taps, temperature fluctuations in the measured zone or residual gasses in the vacuum chamber. Since care was taken to reduce these effects to a minimum, we deem it unlikely that they are responsible. At the writing of this report, the deviations between the two tapes are therefore still an open question.

Chapter 5 Discussion and conclusion

The normal zone propagation velocity and minimum quench energy of a 2 mm wide REBCO coated conductor tape were measured at magnetic field strengths of 6, 10 and 14 Tesla. The measurements were successfully conducted as a function of temperature in the range of 4.2 K to 25 K at a constant current of 170 A. The velocity and quench energy were also investigated as a function of current with the temperature held constant at 4.2 K, 23 K and 25 K.

The minimum quench energy was found to decrease with increasing sample current, as might be expected from theory: when the current is raised the transition temperature goes down and the thermal margin, that needs to be overcome to turn the sample normal, becomes smaller. A similar effect was found in the temperature dependence of MQE. Raising the temperature at fixed current also decreases the thermal margin and hence reduces the amount of heat needed to drive the tape into the normal state. Note that - unlike the current dependence - this conclusion for the temperature dependence of MQE is non-trivial. Theory as well as earlier observations on MgB_2 wires show that the reduced thermal margin needs to be balanced against an increased heat capacity, which might induce the opposite temperature dependence. However, just like in earlier observations on 4-mm wide tapes, the data on the 2-mm wide samples show that the effect of thermal margin reduction dominates. Unfortunately, after a first measurement series at relatively high temperature in a magnetic field of 6 T, problems with the quench heater required a different way of attaching it to the tape, influencing the measurements of MQE at the lower temperatures of 14 T and 10 T. Therefore, no hard conclusions can be drawn on the magnetic field dependence of the MQE.

It was shown that the normal zone propagation velocity is almost independent of the temperature, with a barely significant increase of 9% between 4.2 K and 29 K. Also the magnetic field strength hardly seems to have an influence on the V_{nzp} at fixed temperature and current for fields between 6 T and 14 T.

The analytic model based on the heat balance equation with the approximation of Dresner was compared to the measured data. The model predicts a temperature dependence of V_{nzp} due to the temperature dependence of the materials properties: heat conduction, electrical resistivity and heat capacity. For low temperature superconductors, these can be evaluated at an average temperature. However, as pointed out by Iwasa, this type of averaging becomes incorrect for high temperature superconductors and a more exact model was used, which integrates the full temperature dependence of the material properties over the whole temperature range of interest. It was shown this type of model indeed predicts the observed temperature independence of V_{nzp} below T = 25 K.

To obtain a more detailed comparison with theory, numerical simulations were executed and their results were compared to the data. A scaling relation had to used for the critical current, because reliable I_c-values not could be obtained below T = 15 K for the 2-mm wide tape. The I_c-values that were found at higher temperatures, are in good agreement with the I_c-values found earlier in a similar 4-mm tape, when taking into account the difference in width. So the tape should be of similar quality. The simulations of the normal zone propagation using different scaling relations show some spread, but lie below the V_{nzp} values measured in the 4-mm tape and above those of the 2-mm tape. Both mainly depend on the operating current and only slightly on temperature. The magnetic field seems to have more influence in the simulations than in the measurements. Although the results are not fully comparable, the simple and computationally efficient numerical 1D-model gives a good insight in the V_{nzp} behavior.

One of the main goals of the assignment was to verify the dependence of the normal zone propagation velocity on the sample operating current. Earlier work on a 4 mm wide tape reported a power-law relationship between both, but could not be extended to lower temperature due to prohibitively large critical currents and associated high MQE values. Extending the measurements of the 4-mm tape at temperatures above 25 K to temperatures below 25 K, a good qualitative agreement was found between the current-dependence in both temperature regions. The power-law exponent is almost the same, but there is a 50% difference in the absolute value of V_{nzp} observed in both tapes. At the writing of this report, the cause of the difference in velocities remains uncertain. The different tapes have been examined for the thickness of the copper layer, for the REBCO width, for the size of the minimum propagation zone and for the cooling term. None of these likely culprits gave a justification for the observed difference.

In summary, the present work allows to extend the main conclusion of earlier experiments to lower temperatures, i.e. the normal zone propagation velocity in REBCO coated conductor tapes below T = 50 K appears to depend mainly on the sample current and - in contrast to 'classical' superconductors - hardly on temperature or magnetic field.

Recommendations

The main goals of this master assignment are achieved, but some subjects can be investigated further. Also a lot of experience was gained during this measurement campaign. Therefore, some recommendation are given for improvements and future research.

- The 'RRR'-value of the copper layer was not determined accurately. Comparison of the RRR-value of the 2-mm and 4-mm wide samples, could give further explanation for the quantitative differences of their V_{nzp}-values.
- There were big differences between the MQE value of the 2-mm and 4-mm wide samples. The QE could influence the V_{nzp}. Registration of quenches at higher QE values is advised.
- The exact analytic equation 4.3 was only investigated qualitatively for the 2-mm wide sample. Introducing a cooling factor make the model quantitatively more comparable.
- HTS coated conductors of other manufacturers exist. The NZP behavior of these tapes can also be investigated and could give further insight in their behavior.
- When the NZP-experiments are continued using the existing setup, it is advised to upgrade the current leads with HTS to handle higher currents and temperatures.
- During this measurement campaign, the results from the third voltage pair could not used, because of an unclear signal. In this case, the first two of the redundant voltage pairs should be used. Or all voltage pairs should be placed closer to the quench heater.
- The voltage taps for registering the V_{nzp} are not used for I_c-measurements. The second end of the V_{nzp} pairs should be placed at one point.
- During I_c-measurements, the sample should be fully wrapped with, for example kapton, as support against outward pointing Lorentz forces. This should be removed for NZP-measurements.

Acknowledgements

First, I would like to thank those who were directly involved with the work outlined in this thesis. Marc Dhallé, whom without this thesis wouldn't be as it is now, he has my full respect. For all the help in the lab, which was a lot, I would like to thank Sander Wessels. My gratitude goes Marcel ter Brake, the professor of the EMS group where I am involved since my bachelor assignment. And Harold Zandvliet, as external committee member, being there at the last moments of me being a student. Now I am sounding melancholic, however I am only grateful. There are so many I would like to thank for so many experiences during the years at this university. My family, for always being there and never giving me any doubt. My flatmates, for lifting me up and putting me down. Friends and acquaintances at many places, like the study association Arago, sport association, the big band and so many in between. I would like to thank my colleagues at EMS for the nice conversations and everything I can't think of. Thank you all for being there. Just let me finish with the words:

Thanks for the tales!

Nomenclature

This list gives a description of all symbols used in the report.

Symbol	Description	Unit
B	Magnetic field	$[T]$
B_{c1}	First critical field	$[T]$
B_{c2}	Second or upper critical field	$[T]$
C	One dimensional heat capacity	$[J/mK]$
C_0	Geometric average one dimensional heat capacity	$[J/mK]$
E	Electric field	$[V/m]$
E_0	Electric field used in the definition of the critical current	$[V/m]$
E_{pulse}	Energy contained in a heater pulse	$[J]$
h	Heat transfer coefficient for cooling to the environment	$[W/mK]$
h_{cu}	Thickness (height) of the copper layer	$[m]$
i	Index of Node	N.A.
J_c	Critical current density	$[A/mm^2$
I	Electrical current	$[A]$
I_{op}	Sample current	$[A]$
I_{sample}	Sample current	$[A]$
I_{nc}	Electrical current in the normal conducting parts of the sample	$[A]$
I_{sc}	Electrical current in the superconducting parts of the sample	$[A]$
k	One dimensional thermal conductivity	$[Wm/K]$
MQE	Minimal quench energy	$[J]$
n_{nodes}	Total number of nodes	N.A.
N	N-value of a superconductor	N.A.
P_Ω	Ohmic heating power	$[J/sm]$
P_i	Quench initialisation power	$[J/sm]$
P_c	Cooling power	$[J/sm]$
QE	Quench energy	$[J]$
R	Electrical resistance	$[\Omega]$
t	Time	$[s]$
t_{pulse}	Duration of a heat pulse	$[s]$
T	Temperature	$[K]$
T_{cs}	Current sharing temperature	$[K]$
T_c	Critical temperature	$[K]$
T_t	Transition temperature	$[K]$
T_{op}	Operating temperature	$[K]$
T_i	Temperature of the node at index i	$[K]$
$\tilde{T}$	Average temperature between T_t and T_{op}	$[K]$
U	Voltage	$[V]$

Symbol	Description	Unit
V_{nzp}	Normal zone propagation velocity	$[m/s]$
U_ℓ	Normal zone propagation velocity	$[m/s]$
w_{sample}	Sample width	$[m]$
x	Spacial coordinate	$[m]$
x_i	position of the node at index i	$[m]$
ρ	One dimensional electrical resistivity	$[\Omega/m]$
ℓ_{mpz}	Length of the minimal propagation zone	$[m]$

Bibliography

[1] H. Kamerlingh Onnes. Sur les Résistances Électriques. *Communications from the Physical Laboratory of the University of Leiden*, pages 1–11, 1911. Supplement 29.

[2] J.G. Bednorz and K.A. Müller. Possible high TC superconductivity in the Ba-La-Cu-O system. *Zeitschrift für Physik B*, 64(2):189–193, 1986.

[3] H. Maeda, Y. Tanaka, M. Fukutumi, and T. Asano. A New High-Tc Oxide Superconductor Without a Rare Earth Element. *Japanese Journal of Applied Physics*, 27(2):L209–L210, 1988.

[4] M.K. Wu, J.R. Ashburn, C.J. Torng, et al. Superconductivity at 93 K in a New Mixed-Phase Y-Ba-Cu-O Compound System at Ambient Pressure. *Physical Review Letters*, 58(9):908–910, 1987.

[5] V.L. Ginzburg and E.A. Andryushin. *Superconductivity.* World Scientific, revised edition, 2004.

[6] M. Tinkham. *Introduction to Superconductivity.* Dover, second edition, 2004.

[7] Y. Iwasa. *Case Studies in Superconducting Magnets.* Springer Science, 2nd edition, 2009.

[8] H. van Weeren. *Magnesium Diboride Superconductors for Magnet Applications.* PhD thesis, University of Twente, 2007.

[9] J. van Nugteren. Normal Zone Propagation in a YBCO Superconducting Tape. Master's thesis, Twente University, 2012.

[10] D. Uglietti, H. Kitaguchi, S. Choi, and T. Kiyoshi. Angular Dependence of Critical Current in Coated Conductors at 4.2 K and Magnet Design. *IEEE Transactions on Applied Superconductivity*, 19(3):2909–2912, 2009.

[11] C.N. Whetstone and C.E. Roos. Thermal Phase Transitions in Superconducting Nb-Zr Alloys. *Journal of Applied Physics*, 36(3):783–791, 1965.

[12] L. Dresner. Analytic Solution for the Propagation Velocity in Superconducting Composites. *IEEE Transactions on Magnetics*, 15(1):328–330, January 1979.

[13] C. Senatore. Overview of the critical surface of industrial CC for EuCARD-2, 21-23 May 2014. 1st Workshop on Accelerator Magnets in HTS, Desy Hamburg.

[14] V. Lombardo, E. Barzi, D. Turrioni, and A.V. Zlobin. Critical Currents of Tapes and Wires at Different Temperatures and Magnetic Fields. *IEEE Transactions on Applied Superconductivity*, 21(3):3247–3250, June 2011.

Appendix A Manual NZP experiment

Manual

of the

Normal Zone Propagation experiment 2014

By A.R. Hesselink, October 2014

Contents

1. Introduction

This manual is made to provide a insight into the Normal Zone Propagation experiment and create an overview of all experimental aspects there are for determining the minimum quench energy and normal zone propagation velocity[1].

NZP and MQE

By a temperature anomaly, a zone with resistance can arise in a superconductor: the normal zone. This local rise above the critical temperature can be caused by a shift of the wires or high energy particles impacting the conductor, but also a lack of cooling by the existence a helium bubble. If the conduction of heat is sufficient and exceeds the heat generation, the normal zone will collapse. If this is not the case, the normal zone will expand and cause a so-called quench.

The speed at which the normal zone expands is the normal zone propagation velocity (NZP). It determines the detection delay and how evenly the spreading of the heat is. To create an expanding normal zone, a minimal quench energy (MQE) is required.

A quench needs to be detected as soon as possible, to avoid damage of the conductor due to the temperature rise. After the detection measures can be taken, like lowering of supply current or firing quench heaters to develop more normal zone which even out the heat and prevent local extremes of temperature.

Setup

The setup used for the NZP experiment has evolved over a number of Phd and MSc assignments. It was made by H. van Weeren in 2008 for measurements on MgB_2. After this J. van Nugteren measured a 4-mm HTS ReBCO tape in 2013 and measurements on a 2-mm HTS ReBCO tape were conducted in 2014 by B. Hesselink. The present manual describes the set-up at the end of this last experimental campaign.

Design

The NZP probe consists of an insert piece made of G10 glass fiber epoxy. Two niobium tin bridges are soldered with high temperature solder to copper current leads and the sample holder.

[1] **The master thesis of J. van Nugteren can provide additional information on the experiment.**

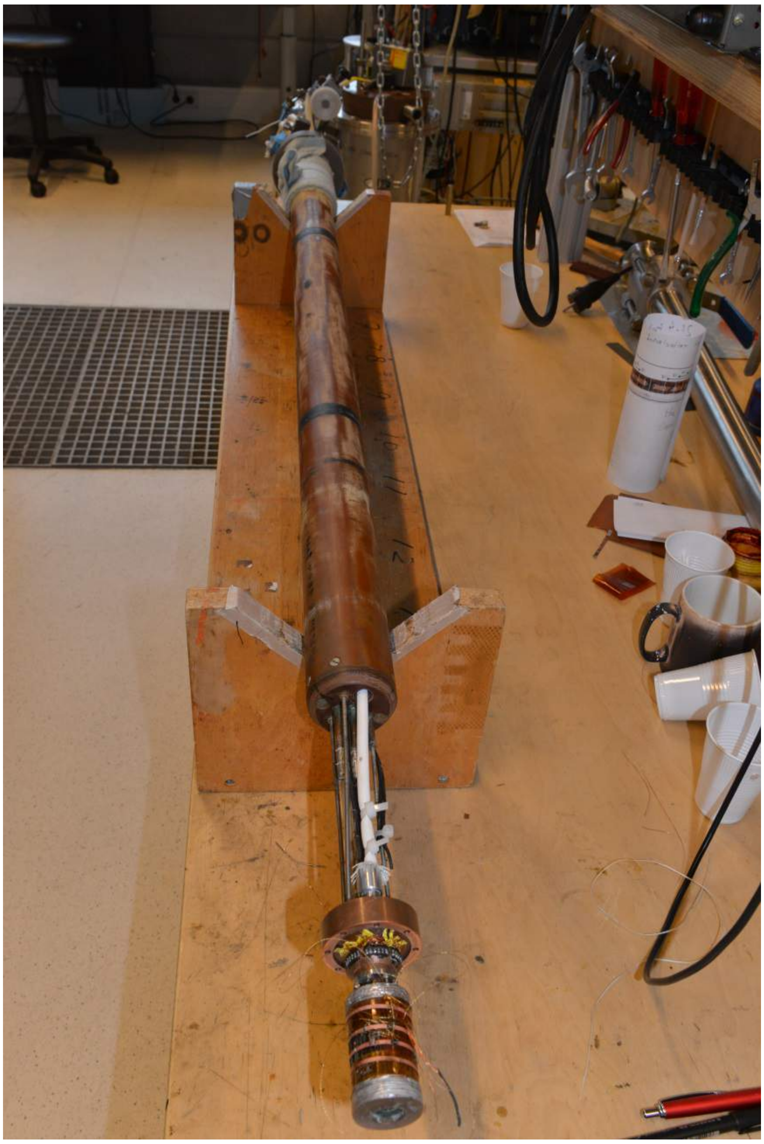


Figure 1: The NZP probe.

Insert wiring

Through the insert several pipes lead towards the sample holder. One holds the cable tree with 16 pairs of 0.22 mm copper wires. The cable tree is in direct contact with liquid helium and leads into the vacuum chamber through a stainless steel plug filled with alumina loaded epoxy (stycast).

Another two pair of wiring runs through the vacuum tube. They are in direct contact with room temperature and thus one pair is made of 0.15 mm manganin wire and one pair is a Phosphor Bronze wire, to insure the sample stays thermally isolated.

Two isolated wire pairs running through another pipe, are available as taps for quench detection.

All wires lead to contact pads attached to the copper terminals with stycast, connecting the wires thermally to 4.2 K.

Sample holder

The most intricate piece of the probe is the sample holder. The hollow holder consists of two electrically isolated copper terminals and the embedded heater. The sample holder is surrounded by a vacuum chamber.

Figure 2: Real time view of the sample holder.

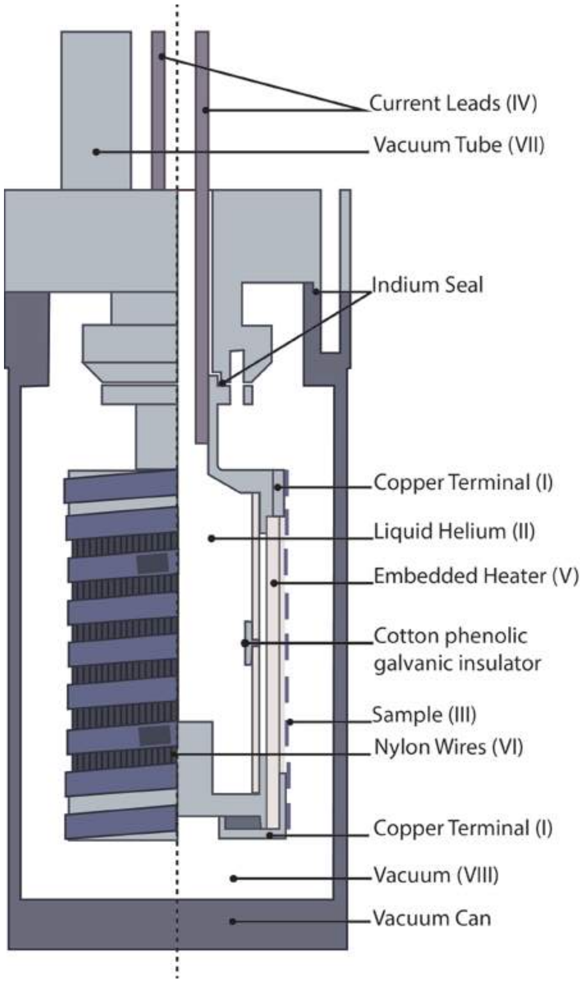


Figure 3: Schematic of the sample holder.

2. Instrumentation

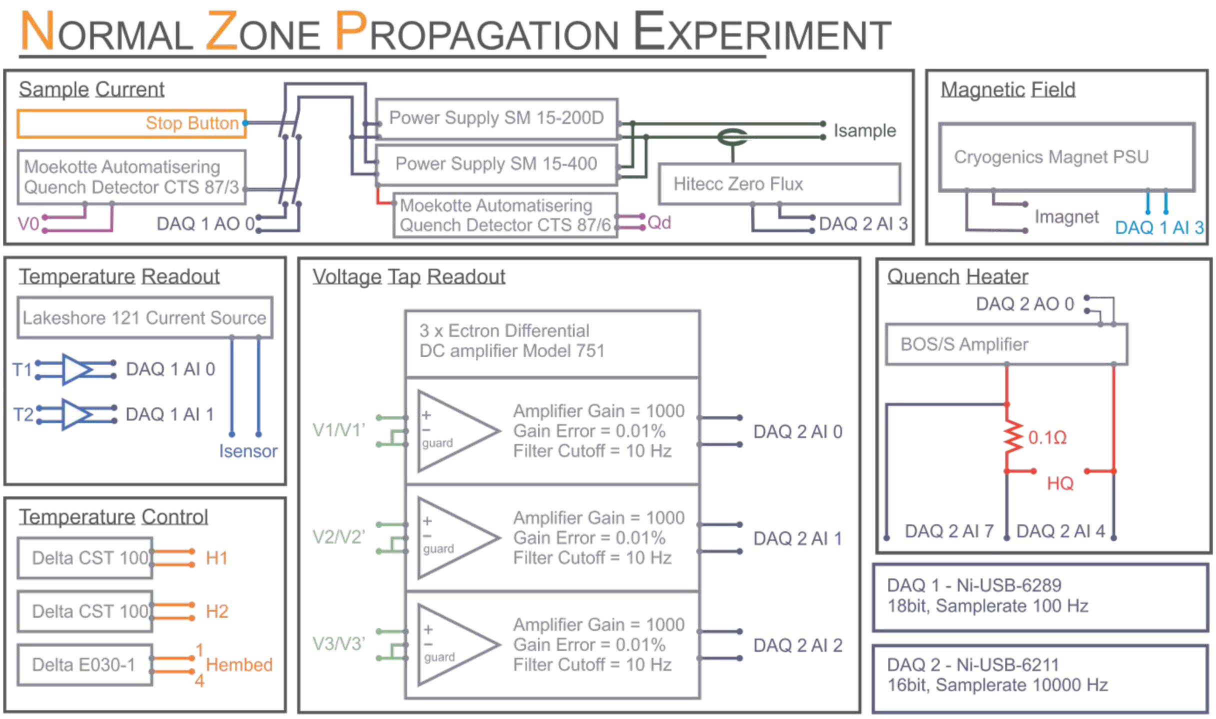


Figure 4: Schematic overview of the instrumentation and its connections.

Abbreviation	Type number sensor
T1	X31553
T2	X78396

Table 1: Description of the used Cernox temperature sensor for the HTS NZP experiments.

Abbreviation	Type SMD resistor	Style	Manufacturer
HQ	15Ω thick film	3216 Metric	TE Connectivity
H_1/H_2	20Ω thick film	3216 Metric	Panasonic

Table 2: Description of the resistors used as heaters.

Figure 4 shows the different functional blocks involved in a typical 'time-of-flight' NZP experiment. The sequence starts by setting:

- The background magnetic field B
- The temperature T
- The sample current I

Then a heat pulse is applied by the quench heater, the voltage traces are recorded and in case of a quench, the detector kills the sample current power supply.

The hardware that implements the functional blocks of figure 4 is electrically interconnected. Figure 5 shows a schematic of these electrical connections. DAQ 1 senses the thermometers T1 en T2, controls the current and registers the main magnet current. DAQ 2 controls the quench heater HQ, records all the voltages and reads the sample current.

Figure 6 shows the actual layout of the instruments, together with a description of their function and installment.

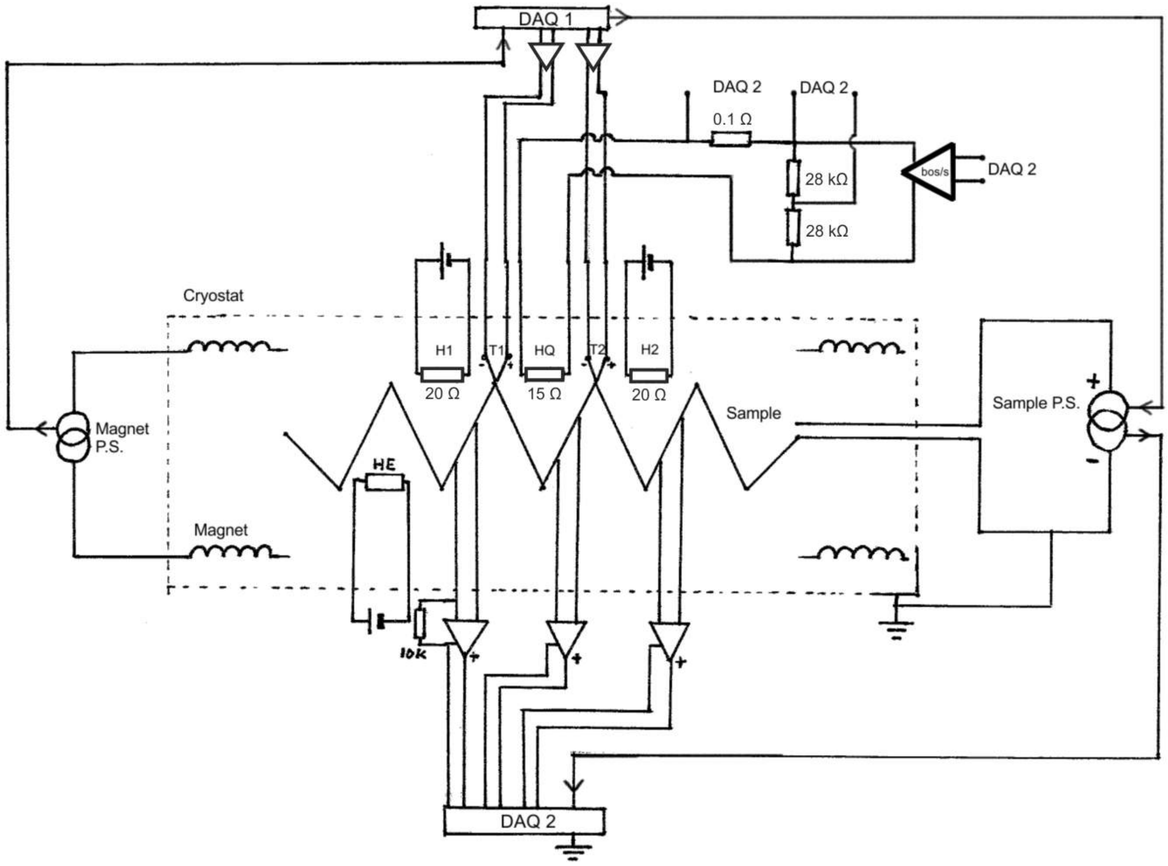


Figure 5: Electrical scheme of the setup. To overcome grounding problems, the DAQ 2 was disconnected from ground.

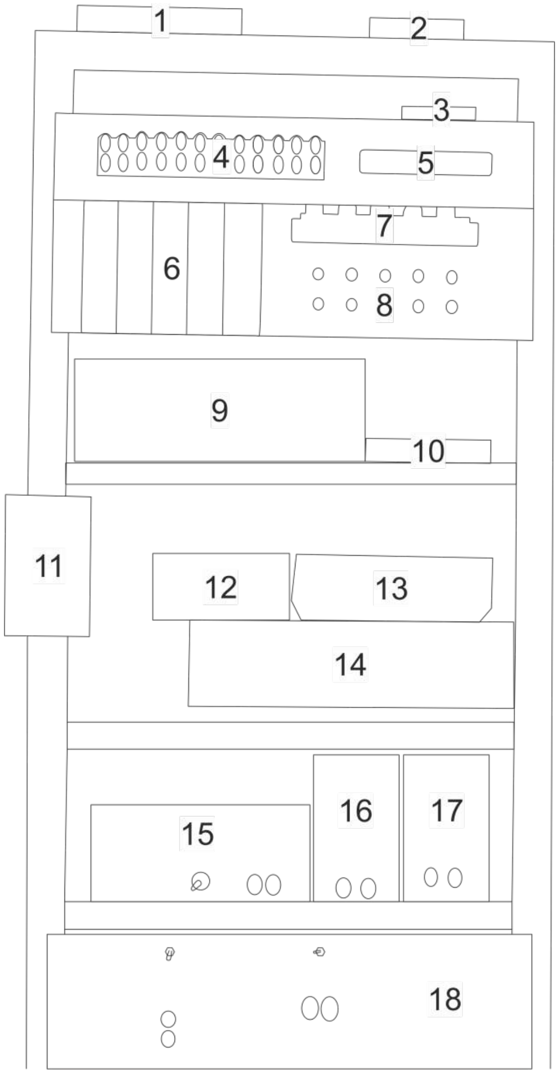


Figure 6: Front of the instrumentation rack.

Figure 7: Overview of the instrumentation rack.

Connections

1. **NI DAQ 1 USB-6289**
   Temperatures sensor are connected to this device, just as the readout of the magnet and the current control output. It is more accurate (18-bit) than DAQ 2.

2. **NI DAQ 2 USB-6211**
   The amplified voltages from the taps are connected to this device, together with the current readout from the zeroflux, the in- and output signals of the quench heater.

3. **Lakeshore 120/121 current source**

   Provides feeding current 10 µA for the Cernox temperature sensors (table 1). Wires go to the contact pad 5.

4. **Banana connector pad**
   Are also used to connect the data cable wires. These can then be rewired to banana-plug wires.

5. **Contact pad**
   The pad is used to connect the Lakeshore 121 in series to the Cernox.
   Note: Not shown in the picture are two instrument amplifiers used for amplifying the signal of the two Cernox to the DAQ 1.

6. **Ectron Differential DC amplifiers**
   Three used for amplifying the signal from the voltage taps.
   Settings: Gain 1000x; filter bandwidth 10 Hz

7. **Input Ectrons**
   The voltage taps are connected here. To prevent thermocouple effects, insulation is scraped from the copper and bare copper-to-copper connections are used.
   From one of the inputs a loop to the ground input of 2 is established through a resistance of 10 kΩ. This is done to prevent a voltage buildup of 300 V on the output of the Ectrons.

8. **Output Ectrons**
   Voltage taps 1-3 go to connections ai0-2 of the DAQ 2 device.

9. **Pc**
   Used for Labview as well as Matlab.

10. **Voltage divider**
    Because the DAQ device can only handle an signal of 10 V, the voltage from the quench heater is measured over one of two 28kΩ resistors.

11. **Panic button**
    Goes to the inhibit of the quench detector.

12. **EMS in-house Instrument Amplifier**
    To stabilize the current control signal, an amplifier with 1x gain. **The current control output signal can differ from the set current in Labview. The current shown by the power supply is also just an indication. Use a voltage meter connected to the zeroflux to ensure you have the right current output.**

13. **Multimeter**
    Voltage meter to the linear output of the quench detector to check signal (not necessary).

14. **Moekotte Automatisering DC quench detector**
    Two quench detectors were used: one which measures over the whole tape and one to protect the Nb_3Sn leads.
    Settings QD1 (CTS 87/3): gain 250x, filter 1 Hz; connected via current control

Settings QD2 (CTS 87/6): gain 100x, filter 1 Hz; digital output connected to the QD plug of the power supply.

15. **Delta E030-1**
    Power supply for the embedded heater, used in voltage mode for more accurate adjustment.

16. **Delta CST 100**
    Two power supplies for the edge heaters.

17. **BOS/S amplifier**
    With an external input, the signal from DAQ 2/ao.0 is amplified in voltage mode. The output is connected to the quench heater in series with an accurate 0.1 Ω resistance. This is done to determine the current through the quench heater precisely.

Not shown in Figure 6 or Figure 7: Two EMS instrument amplifiers for thermometer signal amplification, at gain 100x, to the DAQ 1 device. In the software this is adapted to 30x.

Quench detector sensitivity

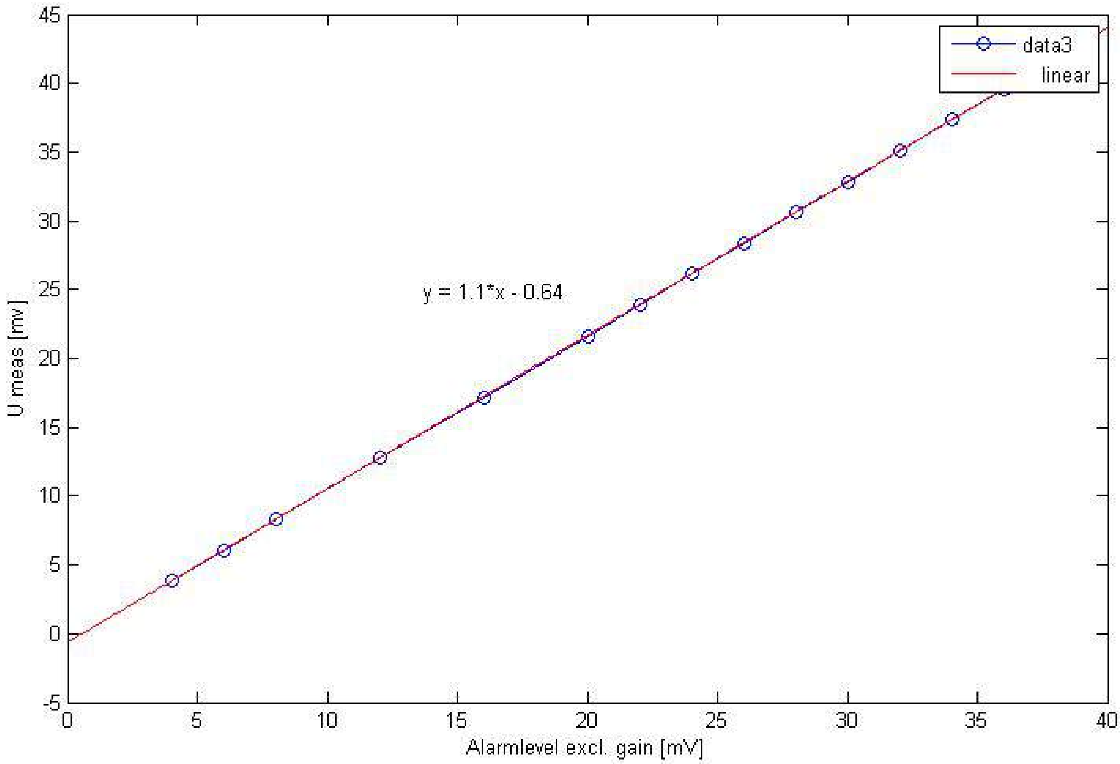


Figure 8: For CTS 87/3. The input voltage versus the trigger voltage set by the alarm level. The line should be x = y.

Because the HTS tape is very sensitive, the same has to be for the quench detector. The quench detector is the first and fastest protection during a quench. The quench detector is custom build and can be set in several ways. The alarm level determines the quench threshold value. The sensitivity is important to know and was therefore checked (figure 8, table 3). In principle the alarm level should be the same as the input voltage. This is not the case for both quench detectors. Though the CTS 87/3 is far more sensitive than the CTS 87/6, so V0 is used as input for the CTS 87/3.

Input voltage [mV]	Alarm level trip value
10	0.81
5	0.62
1	0.46
0.1	0.41
0	0.41
0	0.41

Table 3: For CTS 87/6. The input voltage versus trigger voltage. This quench detector is less sensitive than CTS 87/3.

Sample Preparation

The tape is pretty durable due to the hastelloy steel and copper, but very sensitive for kinking and sharp edges. Furthermore, the conductor should be heated as little as possible. Try to keep the temperature below 240 ^{o}C, because excessive heating can cause degradation due to the escape of oxygen from the ReBCO.

Wire pair	**Description**	**Abbreviation**	**Resistance at contact pads [Ω]**	**Resistance at instrumentation [Ω]**
1	Voltage tap 0	V_0	12	20
2	Voltage tap 1	V_1	11	19
3	Voltage tap 2	V_2	13	21
4	Voltage tap 3	V_3	13	21
5	Voltage tap 4	V_1'	12	20
6	Voltage tap 5	V_2'	13	21
7	Voltage tap 6	V_3'	13	21
8	Voltage of temperature sensor 1	V_{T1}	85	93
9	Current for temperature sensor 1	I_{T1}	85	93
10	Voltage of temperature sensor 2	V_{T2}	124	132
11	Current for temperature sensor 2	I_{T2}	124	132
12	Voltage tap 7	V_4	12	20
13	Voltage tap 8	V_5	11	19
14	Current for embedded heater	HE	38	47
15	Current edge heater 1	H_1	28	36
16	Current edge heater 2	H_2	27	35

Via vacuum/DIN-connector

Wire pair	**Wire pin**	**Description**	**Abbreviation**	**Resistance at contact pads [Ω]**	**Resistance at instrumentation [Ω]**
17	1-2	Voltage of quench heater 1	V_{HQ}	10	281
18	3-4	Current for quench heater 1	HQ	10	42

Table 4: Description of the elements and its wiring.

Position [mm]	Element
10 mm from end	V0 (QD)
- 70	V3
- 65	V2
- 60	V1 / V5 (Ic)
- 45-50	H1
- 35-40	T1
- 30	V4 (Ic)
- 20	V3
- 15	V2
- 10	V1
Center of tape	HQ
+ 10 mm	V1’
+ 15	V2’
+ 20	V3’
+ 30	V4 (Ic)
+ 35-40	T2
+ 45-50	H2
+ 60	V1’ / V5 (Ic)
+ 65	V2’
+ 70	V3’
10 mm from other end	V0 (QD)

Table 5: Positioning of the elements

Figure 9: Picture of 2 mm tape with placed elements.

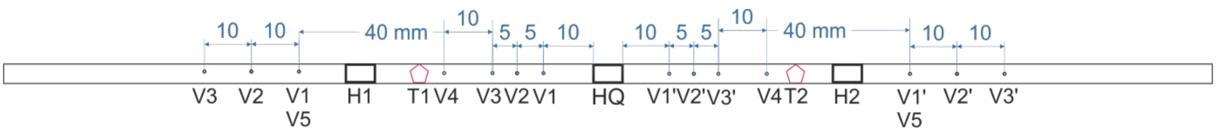


Figure 10: Schematic of the placed elements.

Starting with 75 mm of tape, indication for the heaters, voltage taps and temperature sensors have to be marked on the tape. Make the markings on the hastelloy side, so the ReBCO side is on the inside of the sample holder and against the copper terminals.

At least a full turn of tape is soldered around the copper terminal with a low temperature Bismuth Lead Tin alloy, which has its melting point at 105 ^{o}C. **Caution** should be taken during the soldering of the sample to copper terminals, because the niobium tin leads could be unsoldered.

All the wiring near or in contact with the tape, should be made of 0.1 mm manganin.

Mounting procedure

- Put on gloves, bismuth is a heavy metal and toxic, just like lead. And acetone is not that good for you either. Excess bismuth solder should be removed from the terminals using the soldering iron and maybe some solder wick. Cool the terminal with wet paper when it gets too hot. Clean the terminal with acetone.

- Pre-tin the contact pieces of the ReBCO- tape.
- and. Start with aligning the quench heater mark on the tape in the middle of the heater and at the same height as its contact pads (Ma & PhB). Secure the sample with kapton tape and wrap it clockwise around the heater towards the top terminal. Then secure the end of the sample on the terminal with kapton tape and start soldering the HTS-tape from the edge of the terminal. Use a tweezers to push the end of the sample on the terminal.
  Take care not to overheat the copper, to prevent the niobium tin leads to unsolder
- Clean the terminals with acetone.

During measurements on 2 mm tape, Lorentz forces pulling on the tape were greater than the strength of the solder. To prevent the tape from being pulled off, it has to be reinforced with niobium titanium wire. Wire from an old batch of conductor (mono-filament NbTi) was used. The varnish surrounding it can be removed by soaking it in sulphuric acid for 15 minutes.

- Use 2x25 cm of niobium titanium wire to reinforce the tape around the terminals. Fix a small length of wire on the terminal.
- Apply a little bit of solder flux on the terminal and wind the wire tightly for several turns around the terminal. Then twist the ends of the wire together.
- Solder everything together with low temperature solder (yeah, it looks messy, but it works)

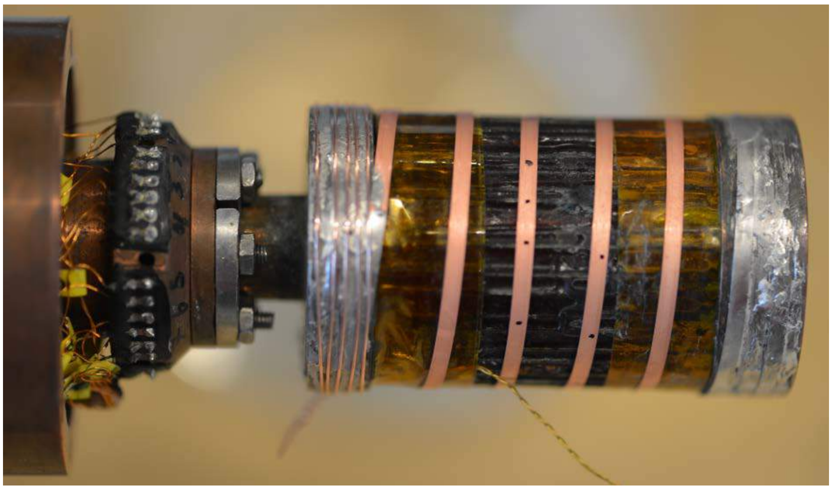


Figure 11: 2 mm tape with element position markings, soldered to the current leads and on the left, reinforced with niobium titanium wire.

After the sample has been firmly attached to the terminals (figure 11), the copper casings for the Cernox temperature sensors and the voltage taps can be soldered on the tape (table 5, figure 9, 10). The casings can be made by bending a small strip of 2 by 5 mm around the tip of Cernox casing shaping tool (screwdriver nicely adapted by Sander).

Now the heaters can placed. The type of heaters used on the 2 mm tape can be viewed in table 2. <u>All the soldering should be done</u> (especially the heater wires) <u>before stycasting the heaters to the tape</u>, because stycast can crack and detach when heated above 200 ^{o}C. Make sure two manganin wire pairs are soldered on the quench heater.

The edge heaters can be glued on the tape, using alumina loaded epoxy, called stycast. This is made by mixing (a small amount) stycast 2850 with 28LV catalyst, 7% of the stycasts weight. Stick the heater to some kapton tape and apply with a sate stick a little bit of stycast onto the bottom of the heater. Place the kapton with heater and let the stycast harden for a least eight hours.

Because of large temperature gradients, the quench heater got lose during measurements on 2 mm tape. So a different approach was needed. The quench heater was fixed with thread and stycast on the edges to prevent lateral movement. Apiezon conductive paste was used on the bottom side of the heater as thermal conductor.

The Cernox have to placed and secured in their casings: first put a thin thread through the casing, then fill it with the thermal conducting (awfully expensive) grease Apiezon and put the same grease on the Cernox. Insert the correct sensor (check it's T1 or T2) in its case and use your best knotting skills to secure it.

Finally, the wiring can be soldered on the contact pads. The quench heater has four specific contacts that are connected to the wires from the vacuum tube. Try to keep the wiring of the quench heater away from the voltage taps. The quench pulses can distort the voltage signal and might even cause a unintentional quench.

Testing

To know whether everything is connected, the contacts should be tested for their resistances. In table 4, the resistance per wire pair is given. These are indications, because the manganin wire length between the elements and contact pads is variable. The connections of the copper wires from the data cable have to be connected on the instrumentation panel. To prevent thermocouple induced voltages, use copper-to-copper connections, so scrape the insulation of copper wires with a scalpel.

After all the elements are checked for their resistances, they have to be checked that they are not in contact with the tape, because of possible grounding problems.

For example: if the Cernox temperature sensor is in contact with the tape, grounding of the whole measuring setup will cause it to malfunction. A solution was disconnecting the ground from the cryostat. But better prevent than cure!

Closing up

When all the connections are made and tested, the vacuum chamber can be installed. To insure a good seal, indium wire is used. Indium is toxic and handling it should be done with gloves. Indium is a soft metal like lead and the only appropriate seal at cryogenic temperatures.

- Measure up a wire of indium by folding it around the edge of the vacuum chamber. Let the ends overlap.
- Coat the indium wire with a little vacuum grease. It makes the removal of the indium easier (otherwise it's like smeared out chewing gum, nasty to remove)
- Place the vacuum chamber (watch out for displacement of the wire) and secure it with the M3 bolts. Tighten the bolts. Use the vacuum-bolt tighten-procedure: tighten the first bolt, then skip the second, until you're around. Then crossover the other side and do the same procedure again with the bolts you first skipped (so now you skip the 'first' bolts). Repeat till the pod is firmly tight.

3. Measurement protocols

Preparation - day before measurements

For all measurements the pod has to be pumped vacuum for at least a night, but way better is pumping it for a weekend. An acceptable rate for out gassing is 2 Pa/h. The residual gas in the pod will precipitate against the wall when cooled down in liquid helium, like a cryopump, insuring a good vacuum.

A small leak was discovered at room temperature before measurements. Tests of the vacuum pressure were conducted with the whole probe cooled to 4.2 K and no significant rise of the pressure inside the vacuum chamber was determined.

Preparation - day of measurements

Screw the aluminum ring to the pod. It prevents movement of the sample holder sideways in the magnetic field. Inspect the plastic tape on the edge of the ring. The plastic tape is required to prevent grounding problems. Place the right insert holder in the magnet cryostat, close the valve to the vacuum pump of the probe and detach the pump.

In the meantime, turn all the devices on and make sure everything is connected. The DAQ devices could give some connectivity problems with Labview. If this happens, you have to restart the computer with the USB cable of the devices disconnected. Plug them back in when Windows has started.

The quench detector have to be connected correctly. QD1 (CTS 87/3) is connected with V0 and QD2 (CTS 87/6) is connected to the QD wires, which soldered to the niobium titanium current leads.

Before cooling down, check the polarity of the voltages by driving a small current (<0.5 A) through the conductor. Done that, you can finally cool down (though there's no relaxing, yet).

Normal zone propagation velocity measurements

During cool down, soldering connections or stycast can break, so every element has to be checked.

- Can you pass a current through? (slow ramp rate to 100 A at 4.2 K)
- Does the temperature respond when turning up the edge heaters and embedded heater?
- Fire the quench heater at a low rate (pulse amplitude: 3 and width: 0.03)
- Do the quench detectors together with the power supply respond when turning down the alarm level (go as low as you have to)?

Everything is okay? Well, you can ramp up the magnet, sit back and relax.

Before you can start your measurement plan, fire the quench heater at the planned temperature, but without a current. The temperature should go up with only two degrees for a safe start. Then ramp to the planned operating current and turn the alarm level of the quench detectors to a point they trip without firing the quench heater. For your first measurement, set your alarm level just above that quench point. Now can safely start your measurements.

Probably at first, the detectors will trigger before you can measure a useful signal. Raise the alarm level until you have a clear signal.

During the measurements

- Prevent voltage over 10^{-2} V on the voltage taps
- Keep the alarm level of the quench detectors in mind when going to higher current. Check table 6 and 7.
- Adjust the offset of the voltages on the amplifiers, when running a current at the right temperature. The voltage should be 10 μV or preferably lower.
- Go up in steps of 0.01 pulse amplitude.
- Use the Matlab routine to check your quench result.

Sample Current	LP-Filter	Gain (fixed)	Trigger
$0 - 50\ A$	$1\ Hz$	250	$9.0\ V$
$50 - 150\ A$	$1\ Hz$	250	$8.0\ V$
$150 - 300\ A$	$1\ Hz$	250	$6.0\ V$
$300 - 400\ A$	$10\ Hz$	250	$2.0\ V$
$400 - 500\ A$	$10\ Hz$	250	$0.8\ V$

Table 6: Quench settings for the NZP measurements on 4-mm tape HTS tape.

Sample Current	LP-Filter	Trigger QD1	Trigger QD2
100-200 A	1 Hz	3.5 V	2.5 V
200-300 A	10 Hz	2 V	1 V
		Gain 250x	Gain 100x

Table 7: Quench settings for the NZP measurements on 2-mm HTS tape.

Labview

The software used for the NZP experiment works in the NI Labview environment (figure 12). The interface is made by J. van Nugteren and is mostly self-explanatory. Take a look at appendix A, for a better description.

To allow Labview to export measurement data to Matlab, an additional package has to be added to the Labview-library. The package is called Matio, it is open source and can be downloaded from the World Wide Web. To be recognized by Matlab using the included m-files, the data files should be named like the next examples:

Ic measurement: B06T25Ic_1.mat

Vnzp measurement: B06T25I170_1.mat ; [field][temperature][current][extension].mat

Critical current measurements

Critical current measurements can be done in the Labview environment of the NZP experiment (Ic for the 4 mm HTS tape were determined using Labview), but the chance of damaging the tape is significant, because you'll still be using the voltage taps in the NZP velocity configuration. So, the permanent 15T setup for Ic/TARSIS measurements is used for measuring the critical current of the HTS tape.

VI is the program used for the Ic-measurements. A VI configuration file for the Ic measurements of the NZP experiment is available. A manual of VI is found as a help-file in VI. Important is to set the right voltage tap length.

In the permanent setup, a Cryocon temperature controller available and can be used to control the edge heaters during the Ic measurements. In this way, an accurate critical current value can be determined without temperature fluctuations influencing the measurement. The temperature can be stable within a few hundred of a Kelvin. The Cryocon does need to be set right. Following are instructions (used during 2 mm HTS tape Ic-measurements):

Cryocon Setup:

The settings for T1/channel A/loop1 have to be done the same as for T2/channel B/loop 2.

- ☐ Connect T1 to channel A
- ☐ Connect loop 1 with H1
  Because the edge heater are only 20 Ω, they have to be connected in series with a 30 Ω resistance.
  - ➢ Power up the Cryocon.
- ☐ Set in 'Ch A' the right sensor: X….. (31553)

If the right sensor table is not available, it has to be loaded in the Cryocon again. (a limited amount of sensor tables can be saved in the Cryocon). Use the utililty.exe found on the PC in file 15T/Cernox/CC.Utility. Connect to the Cryocon and use 'sensor curve download'. Select the appropriate file, a .340- or .crv-file.

- ☐ Check 'loop 1 '
  - o Input: Ch A
  - o Set T to the wanted temperature
  - o Adjust the PID settings
    The settings for the PID can be different every time, it depends on the behavior of the heater with the tape.
  - o Set range: 'low'
  - o Heater load: '50 Ω'
- ☐ Go to 'Options', Relay 1
  - o Set source
  - o Set high T: a few tens above the wanted T
  - o Set high enable: 'yes'

The internal relays can be connected with the inhibit of the quench detector QD2 (CTS 87/6). These relays interrupt the current when a maximum set temperature is exceeded.

The embedded heater is still adjusted manually. Current is also manually controlled. Using a macro (automatic script) is not recommended. Because it is slow with intervening.

Suggestion: it is not necessary to go beyond the 15 μV/m for getting good Ic-curves if enough point. So stay save with the HTS tape.

Analyses

The measurement data can be easily imported in Matlab with a mat-file. Two m-files are available for the analysis of the data: Vnzp.m and Vnzp_2.m. Most important is to set an appropriate voltage threshold value, preferably consistent throughout the whole measurement series.

Appendix A: Labview for the NZP experiment

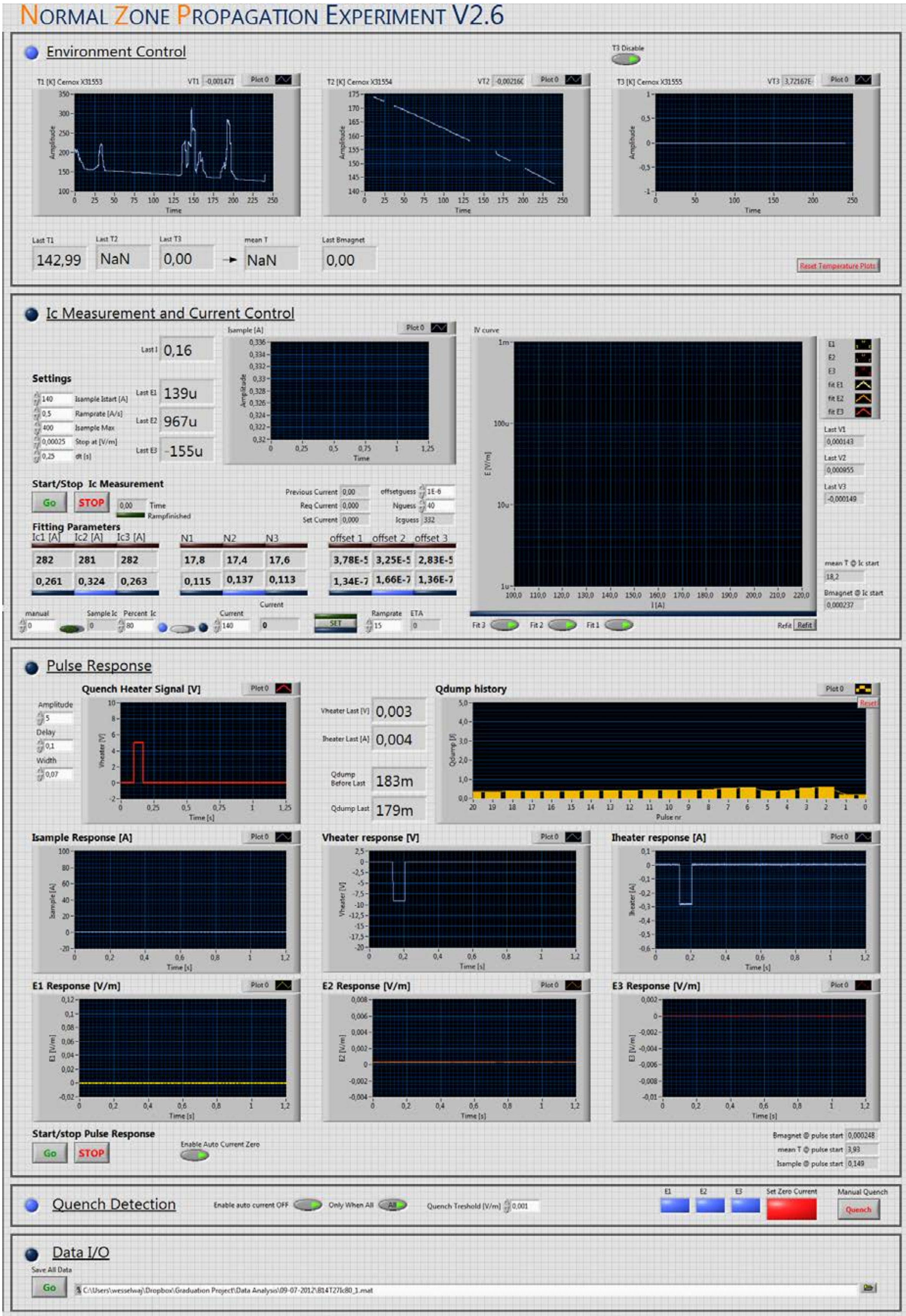
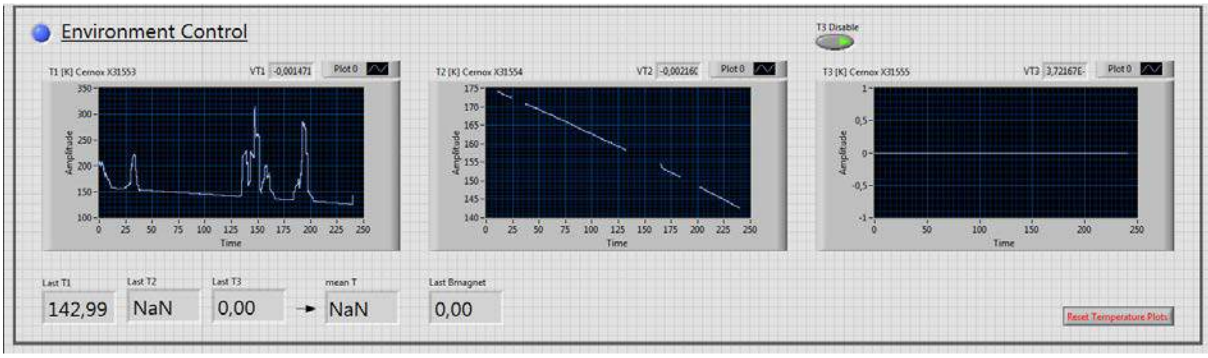
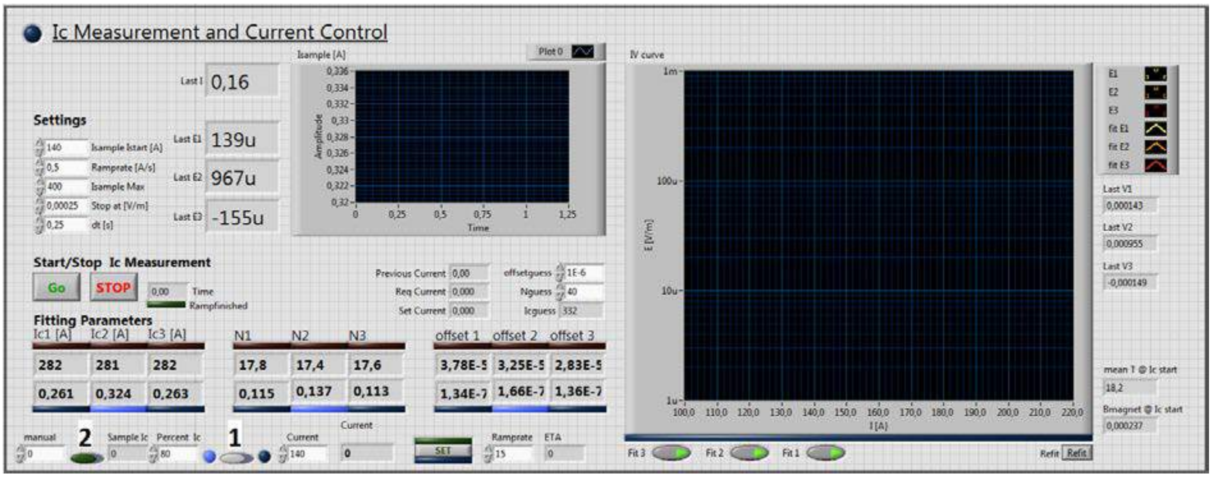


Figure 12: Front screen of the Labview NZP environment.



Environment control

Pretty straightforward, this section shows the temperatures versus the time and the background field. For the HTS NZP measurements, T3 was not used.



Ic Measurement and Current Control

Most important is the current control, which has several options. With button 1, there can be switched between fully manual control (right) and percentage control (left). With button 1 to the left, button 2 determines the set current to percentage of: a previously measured Ic in Labview (right) or manually set current. The set button is used to start turning up or down of the current with the ramp rate specified next to the set button.

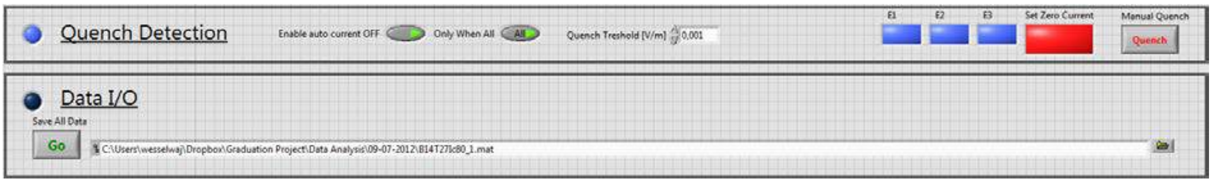
The Ic Measurement function continually measures the voltages after the current has reached the Istart. Then the current goes with the (Settings) ramp rate to Isample max or stops at the voltage stop level. Also the quench threshold has to be adjusted during a Ic measurement in Labview.

The Ic Measurement function was not used for determining the Ic of the 2 mm tape, because there is no temperature control and it does not use voltage taps across the full tape. It can give an good indication of the critical current.

Pulse Response

This is used for to set the pulse of the quench heater and its initiation. In Qdump history the energy of the all pulses is shown. <u>Using the reset button removes all the information shown in the pulse response section, also the other graphs!</u>

With the ‘Enable Auto Current Zero’, the current can be turned to zero automatically after the sample length (General settings in the upper left screen) is reached after a pulse.



Quench Detection

Can be turned on and off using the first button: ‘Enable auto current OFF’. When switched on, the current will be interrupted when one or all (button) reach the quench threshold value. The lights (small) at the end shows which taps reached the threshold value and if there is a quench detected (big light).

Data I/O

Needs to be used with an extra installed Labview library called MatIO. Data from the **last** measurement (data shown in Labview) can be saved.

Appendix B: Checklist NZP measurements

Wire pair	Abbreviation	Resistance at contact pads [Ω]	Resistance at instrumentation [Ω]	Check - Before closure	Check - short with copper	Check - After closure
1	V_0	12	20		X	
2	V_1	11	19		X	
3	V_2	13	21		X	
4	V_3	13	21		X	
5	V_1'	12	20		X	
6	V_2'	13	21		X	
7	V_3'	13	21		X	
8	V_{T1}	85	93			
9	I_{T1}	85	93			
10	V_{T2}	124	132			
11	I_{T2}	124	132			
12	V_{4lc}	12	20		X	
13	V_{5lc}	11	19		X	
14	HE	35	44			
15	H_1	28	36			
16	H_2	27	35			

Via vacuum/DIN-connector

Wire pair	Wire pin	Abbreviation	Resistance at contact pads [Ω]	Resistance at instrumentation [Ω]	Check - Before closure	Check - short with copper	Check - After closure
17	1-2	V_{HQ}	15	281			
18	3-4	HQ	15	42			

Appendix B Ic-graphs

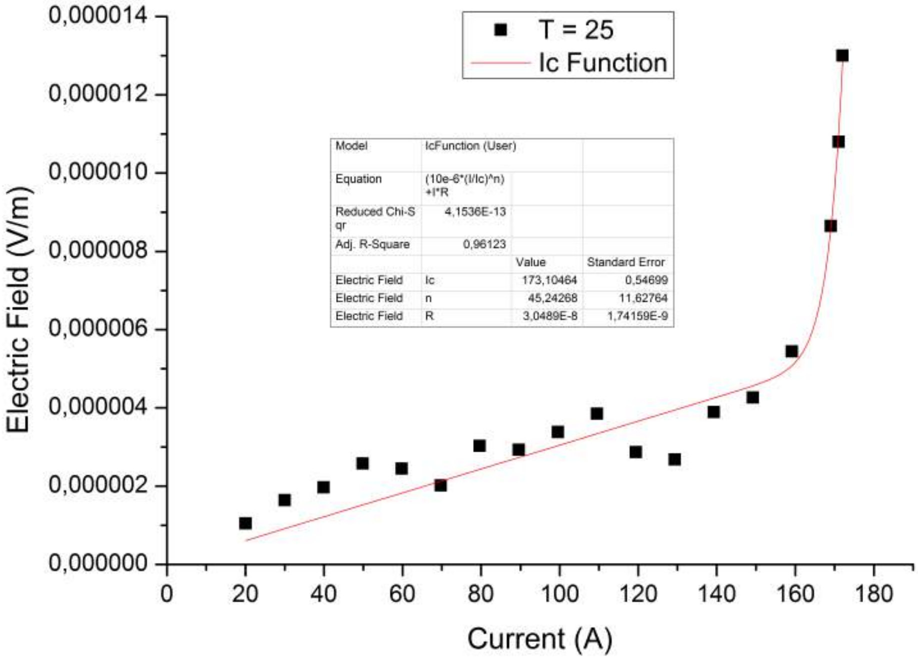


Figure B.1: Critical current measurement of the 2-mm tape at B = 14 T and T = 25 K. Found $I_c = 173A$ with N = 45.

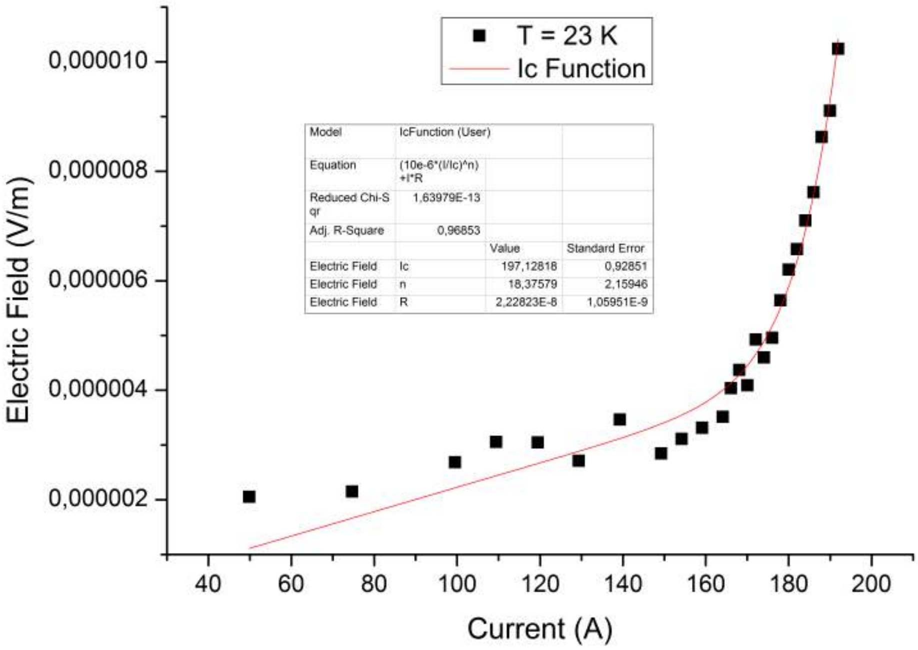


Figure B.2: Critical current measurement of the 2-mm tape at B = 14 T and T = 23 K. Found $I_c = 197A$ with N = 18.

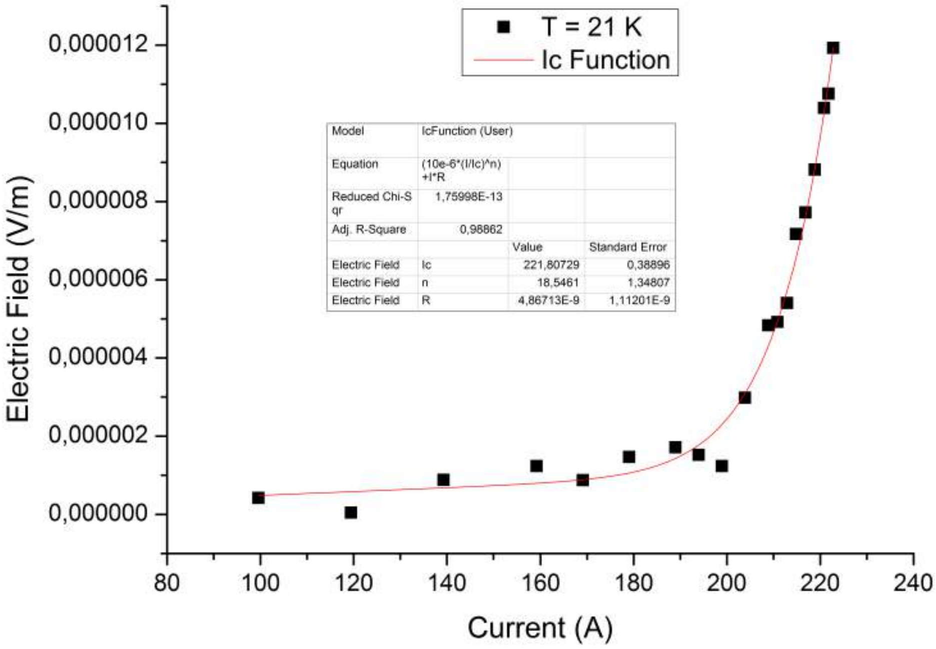


Figure B.3: Critical current measurement of the 2-mm tape at B = 14 T and T = 21 K. Found $I_c = 222A$ with N = 19.

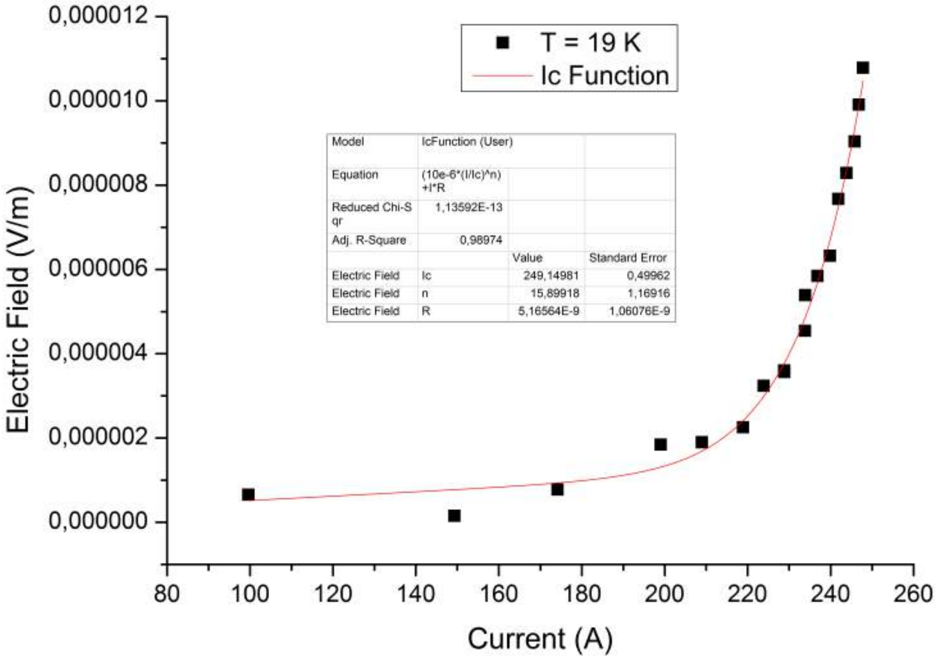


Figure B.4: Critical current measurement of the 2-mm tape at B = 14 T and T = 19K. Found $I_c = 249A$ with N = 16.

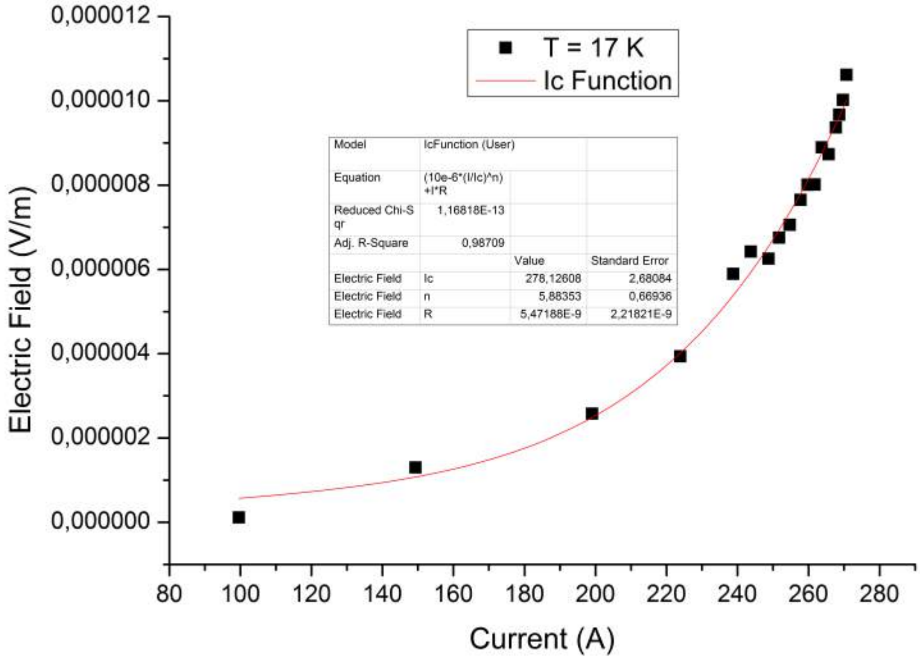


Figure B.5: Critical current measurement of the 2-mm tape at B = 14 T and T = 17 K. Found $I_c = 278A$ with N = 6.

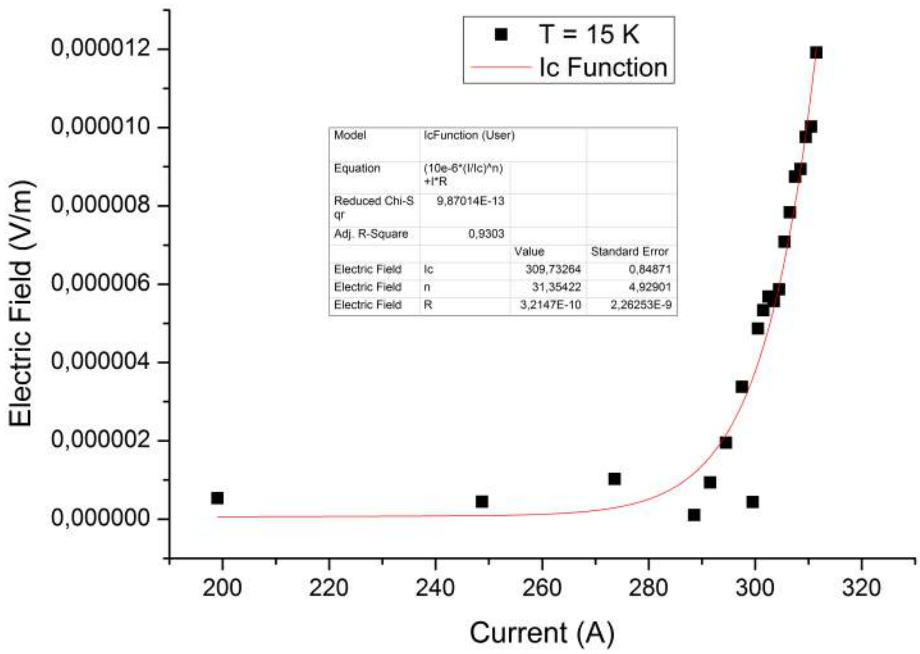


Figure B.6: Critical current measurement of the 2-mm tape at B = 14 T and T = 25 K. Found $I_c = 310A$ with N = 31.