



*Department of Physics UZH*

*Manual for the experiment*

# Measurement of the electrical resistance of a cuprate superconductor at low temperature

*PHY220 Advanced Laboratory Course in Solid State Physics*

October 1, 2023



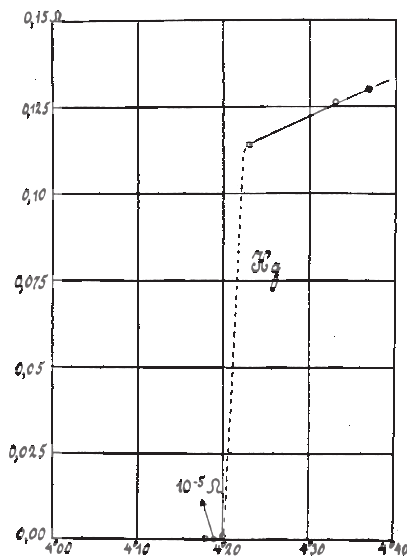
## 1 Goal of the experiment

Within this experiment of the advanced laboratory course in Solid State Physics, you will measure the temperature dependence of a superconducting material, YBCO or  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  across the superconducting phase transition at the critical temperature  $T_c$ . Moreover, at  $T_c$  the effect of an external magnetic field will be studied.

Beside the physics of the high-temperature superconductor, you will learn about experimental techniques, which are often used in solid state physics experiments: measurement of a resistance by the four-point method, the use of an electromagnet, cryogenic technology for obtaining low temperature, electronic control of temperature, as well as using a vacuum system for thermal isolation.

## 2 Superconductivity: a short introduction

### 2.1 Phenomenology



Shortly after the worldwide first helium liquefaction in Leiden by Heike Kamerlingh Onnes in 1908, he could finally reach temperatures well below 4.2 K. In 1911, he measured the resistivity of mercury at very low temperature. The graph he obtained is shown in the graph to the left. These measurements marked the discovery of a new phase in condensed matter called superconductivity. Moreover, in 1911 he realized some particular behavior of liquid  $^4\text{He}$  which could later on be explained by P.L. Kapiza as superfluidity of helium. In 1913 H.K. Onnes was awarded the Nobel prize for his discoveries.

Superconductivity appears as a complete loss of electrical resistance below a critical temperature  $T_c$ .

This state appears in many metals and alloys. Another very important property was the observation by W. Meissner and R. Ochsenfeld in 1933 that a superconductor expels any external magnetic field. The effects appear irrespective of the material being cooled down into the superconducting state with or without the external field, as shown in Fig. 1. This has the important consequences that the expulsion of the magnetic field is an inherent property of the superconducting state and that the latter is a true thermodynamic phase. The phase is called the Meissner phase.

In 1986 J.G. Bednorz and K.A. Müller (IBM Rüşchlikon) discovered superconductivity in ceramic compounds at temperatures much higher than those known so far (Nobel prize in 1987). The compounds investigated contained copper oxide units in chains and planes and were named cuprates. They were named high-temperature (or HTc for high critical temperature) superconductors (HTSC). Very shortly after this discovery the phase was shown for many compounds of this cuprate family and the maximum critical temperatures observed increased very fast. Some milestones are summarized in Fig. 2. (Note that this plot does not contain recently found HTSC of different compound families.)

Beside the Meissner phase the HTSC (and some conventional superconductors) show a second state in which the magnetic field penetrates the superconductor. This happens in vortices, i.e. a small tube

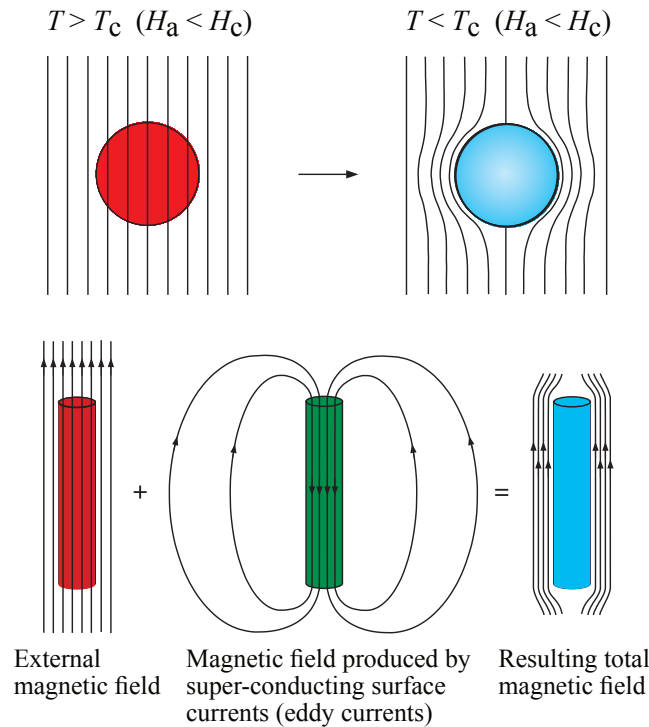


Figure 1: Sketch of the Meissner-Ochsenfeld effect (top row): an external magnetic field generates eddy currents at the surface of a superconductor. The magnetic field of these eddy currents perfectly cancels the magnetic field inside the superconductor and increases the field outside the superconductor (flux conservation, bottom row).

which each carry exactly one quantum  $h/2e$  of magnetic flux (note the charge  $2e$  due to the Cooper pairs) and in which the material is in its normal state (see Fig. 3 for a schematic drawing). These vortices may move freely except when they are pinned by defects, for instance. The  $H(T)$  phase diagram of such type-II superconductors is shown in Fig. 3 beside the phase diagram of conventional superconductors. For each phase there is a maximum field strength at which the magnetic energy gain of the superconductor inside a magnetic field equals the energy liberated by the formation of the superconducting state and the material transits into the normal state.

## 2.2 Theoretical description

It took decades and many experiments to obtain a theoretical description of this state, from the phenomenological London equations (penetration of magnetic fields inside superconductors) over the theory of Ginzburg and Landau introducing the coherence length as length scale of the macroscopic ground state until the first microscopic theory due to Bardeen, Cooper, and Schrieffer (BCS theory) in 1957 (Nobel prize in 1972). Briefly, always two electrons close to the Fermi energy and with momenta  $+\vec{k}$  and  $-\vec{k}$  and anti-parallel spins combine in so-called Cooper pairs with net momentum 0 and spin 0. Due to their total spin they obey Bose-Einstein statistics and may condense into a macroscopic ground state described by a single macroscopic wavefunction with a global phase. This state is characterized by the appearance of an energy gap in the electronic density of states. This energy gap, which can loosely be pictured as the energy necessary to break up one Cooper pair, can be used as order parameter which is characteristic of the superconducting phase and vanishes above  $T_c$ .

Electrical resistivity is due to scattering of charge carriers at lattice vibrations (phonons) or defects. Due to the macroscopic phase of the condensate, the scattering of single electrons or Cooper pairs is

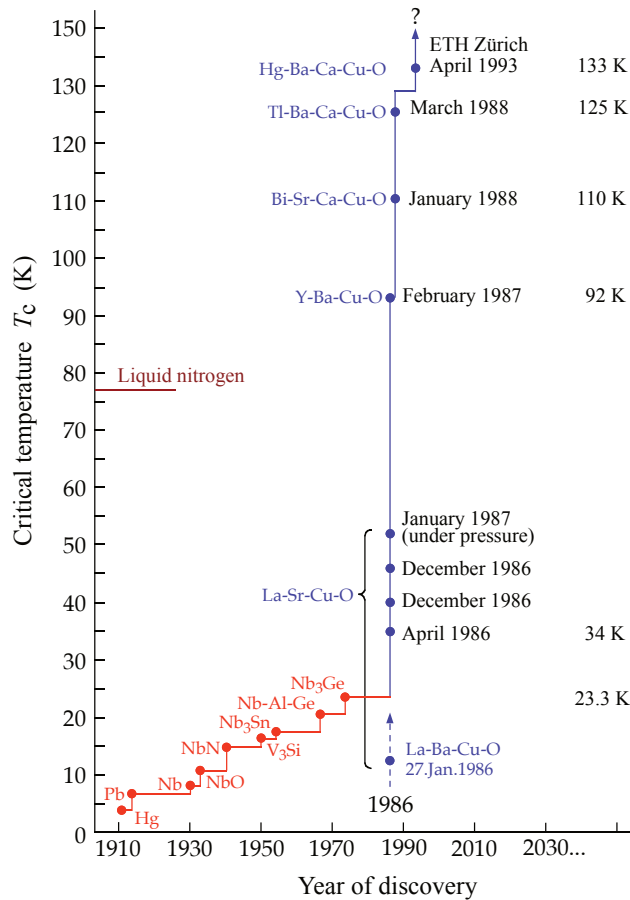


Figure 2: Critical temperatures plotted against the year of discovery between the first observation in 1911 and the development of high-temperature cuprate superconductors in the early 1990s.

forbidden, hence there is no electrical resistance and the state is superconducting.<sup>1</sup> According to BCS the attractive interaction needed for binding two electrons of the same charge is provided by phonons: Briefly one electron creates a lattice deformation which is felt by the second electron. Below some critical temperature the net energy of pairing of electrons outweighs the energy gain due to entropy and Coulomb energy and the material transitions into the superconducting state.

This pairing mechanism explains well the so-called *conventional* superconductors (like elemental metals). Moreover, BCS theory provides a basic description with Cooper pairs and macroscopic wavefunction in the case of HTSC (or unconventional superconductors). Yet BCS fails to explain the pairing mechanism in the case of unconventional superconductivity. All oxide superconductors like YBCO fall into this second category. Since their discovery in 1986 the pairing mechanism remains elusive and is strongly debated.

### 3 This experiment

The topic of superconductivity is usually treated only at the end of the lecture Solid State Physics I, or even in the second part Solid State Physics II. Therefore, within this experiment we want to have a phenomenological look at this highly interesting phase by measuring the critical temperature and

<sup>1</sup>The same reasoning holds for the superfluid state with viscosity zero of <sup>4</sup>He below 2.17 K or fermionic <sup>3</sup>He below 2.6 mK.

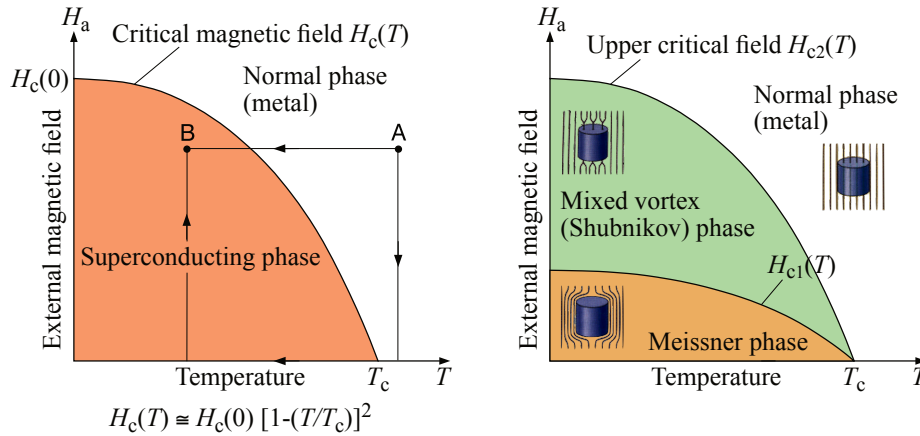
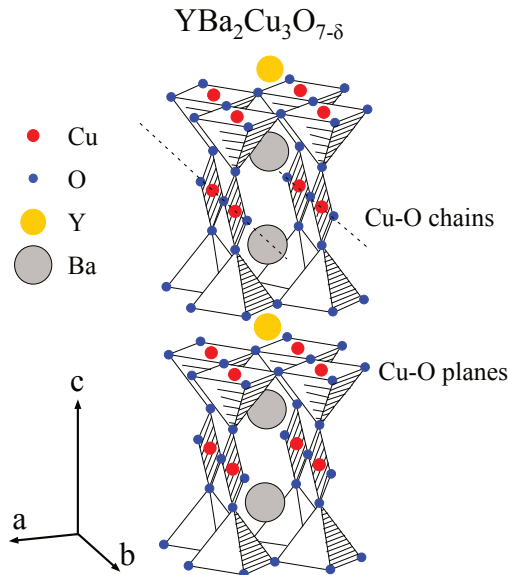


Figure 3: Phase diagram of the magnetic field versus temperature. L.H.S.: type-I superconductor. The delimiting line is called the critical field. The state at point B does not depend on the path between A and B; this is the signature of a thermodynamic state. R.H.S.: type-II superconductor which has a Meissner phase and a mixed phase with vortices called Shubnikov phase. The strength of the upper critical field is often much higher than that of type-I superconductors - these two figures are not to scale.

the normal-state resistivity of a modern HTSC material. YBCO or  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (or Y-123) is a prototypical representative of the cuprate compound family.  $\delta$  stands for slight oxygen deficiency with respect to the parent compound.



The cuprates have the layered, orthorhombic perovskite crystal structure, as shown on the left-hand-side for the HTSC  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ . The Cu-O chains and the Cu-O planes are indicated. This structure is inherent to most of the HTSC compounds with critical temperatures higher than the boiling point of nitrogen at 77 K. All cuprates have Cu-O planes which behave like 2D metallic layers due to a small density of free holes (hole doping). Beside these planes, which are responsible for the superconducting state, there are chains of Cu- and O-atoms which influence the hole concentration in the planes together with the choice and stoichiometry of the spacer atoms between the planes and chains.

The structure of this ceramic compound is layered with metal-like electrical conductivity within the Cu-O (ab)-planes only. The electrical conductivity is strongly anisotropic and almost vanishing along the crystallographic c-direction. We will measure the electrical resistivity of YBCO within the (ab)-plane for a wide range in temperature including the critical temperature. Moreover, if time permits, you may try to observe qualitatively the effect of an external magnetic field on the transition between superconducting and normal state.

You can find information about basic concepts and experimental facts describing superconductivity

in the introductory chapters in the following textbooks, for example:

- Ch. Kittel, *Introduction into Solid State Physics*, chapter 10 *Superconductivity*,
- P. Hofmann, *Solid State Physics - an Introduction*, chapters 10. until 10.1.2 *Superconductivity*,
- (in German) K. Kopitzki (and P. Herzog), *Einführung in die Festkörperphysik*, Kapitel 6 *Supraleitung*.

Keywords include e.g. *superconductivity*, *Meissner-Ochsenfeld-effect*, *Cooper pairs*. The high-temperature superconductors used in the present experiment are so-called type-II superconductors. Beside the physics of superconductivity you will learn about several standard technologies like cryogenics (liquid nitrogen), temperature control and temperature measurement, resistance measurements, as well as get into touch with some vacuum technology.

Some key questions which you may try to answer for preparing this experiment and which may be used as guideline during the initial discussion:

1. How does the resistance of a metal depend on temperature – at low temperature and close to 0 K?
2. What is causing the electric resistance?
3. What is the difference between a perfect (metallic) conductor and a superconductor?
4. Why does the pairing of electrons (fermions) to Cooper pairs change their behavior?
5. What happens if a superconductor is placed in a strong magnetic field?

## 4 Experimental setup

The layout of the experiment is shown in Fig. 4. It consists of different parts which are explained one-by-one further below:

- *The sample holder* with connections for
  - the temperature sensor and the heating stage,
  - the current leads and the contacts for the voltage measurement (see section 4.5).
- *The cryostat* is the part which is cooled by liquid nitrogen (in this experiment), which is pumped through the tubes by a vacuum pump connected to the outlet. The sample is mounted on the end piece of the cryostat. The working principle is explained in section 4.2.
- *The vacuum system* serves as thermal isolation of the cryostat against ambient temperature and to pump out water and oxygen inside the system. Electrical contacts are fed through the walls of the vacuum vessel using stiff wires inside an electrically insulating ceramics which seals the vacuum system against atmosphere. These sealed contacts are called (vacuum) feedthroughs.
- *The electromagnet* produces a strong and homogeneous magnetic field at the sample position allowing the resistance to be measured with and without the influence of an external field.

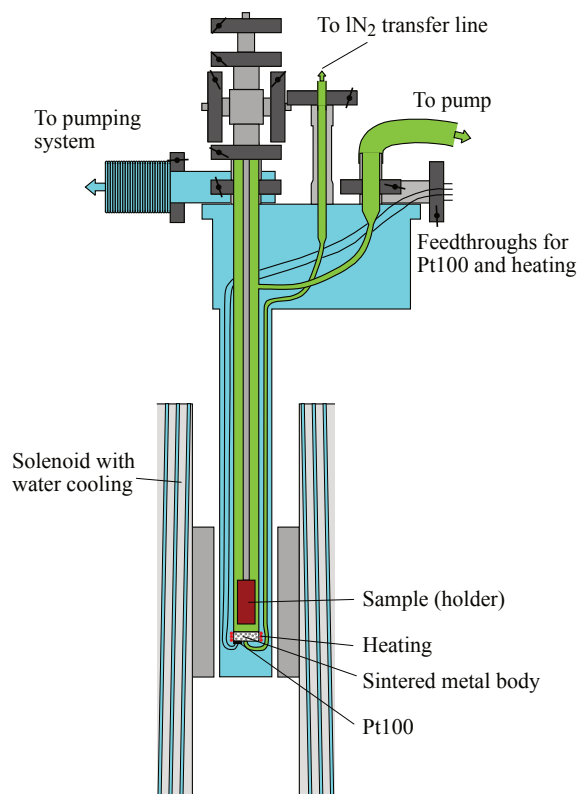


Figure 4: Schematic drawing of the cryostat used here and of the electrical connections. Note that the sample holder is inserted inside the inner tube of the cryostat and immersed into the flow of cold nitrogen vapor at 77 K. The parts colored in blue are the vacuum system evacuated by external pumps. The liquid/gaseous nitrogen circuit is colored in green.



## 4.1 Vacuum system

The cryostat is placed inside a vacuum chamber. The vacuum produced by a turbomolecular pump (TMP) is required for two reasons: Firstly it avoids oxidation and contamination of the sample and, in particular, the cold parts of the cryostat. Secondly, it thermally isolates the cryostat and the sample from the outer parts and the laboratory. The main principle is the same than for a thermos or a dewar, i.e. the suppression of thermal convection by air (or other gases) which is the main contribution to heat transport or thereby, heat loss. Moreover, since the cryostat reaches temperatures well below the triple point of water, it is important to pump water vapor out of the vacuum system *before* cooling the cryostat. For that the final pressure should be well below the vapor pressure of water at the triple point of the water phase diagram. This pressure is about 6 mbar at 273 K. Keeping the pressure below the line of coexistence of solid and gaseous water is essential to avoid icing of the cryostat. Beside water, oxygen should be pumped out as much as possible because oxygen condenses at a temperature of 90 K which is higher than the boiling point of nitrogen at 77 K. Condensed (liquid) oxygen is much more corrosive than gaseous oxygen and easily may oxidize metallic parts of the cryostat.



Figure 5: The vacuum system used in this experiment. The dewar of a former cryopump is used as storage vessel for liquid nitrogen. The cooling agent is pumped through the transfer line into and out of the cryostat by means of a small membrane pump (not on the picture). The nitrogen flow is controlled by a valve installed close to the computer screen.

The vacuum reached here by means of the TMP and a second backing pump providing rough fore-vacuum (about 1 mbar) is of the order of  $10^{-5}$  mbar (note the unit milli-bar typically used in vacuum technology<sup>2</sup>). The working principles of the TMP and the different ways to measure the pressure can be found in two tutorials (in German) on the webpage of this lab course. The vacuum system will be started at the beginning of the experiment after having mounted the cryostat together with the assistant. This ensures a reasonable pressure once you start the cooling of the cryostat. Pumping down from atmospheric pressure to the lowest pressure reached with this setup takes about one hour.

## 4.2 Cryostat

The sample is cooled using liquid nitrogen. The liquid is transferred before the experiment into a storage dewar (see Fig. 5). At atmospheric pressure the temperature of the liquid is about 77 K. The dewar is connected to the cryostat by a transfer line. From the outlet of the cryostat, shown in Fig. 4, a

<sup>2</sup>Torr, after the Italian physicist E. Torricelli, is another unit often seen in this context, in particular in older publications. It corresponds to 1 mm Hg and is equivalent to about 0.75 mbar.

Teflon tube leads to a membrane pumps which sucks the nitrogen through the cryostat. A small valve with a flow indicator (see Fig. 6) is mounted in series between cryostat and pump and allows for fine adjustment of the nitrogen flow.

Inside the cryostat the liquid is pumped into a sintered body, i.e. a ceramic or metal body made from a coarse powder by a thermal process called sintering. The sintering produces a solid and porous pellet. Due to its porosity the body has a large surface. Liquid in contact with the surface evaporates, the enthalpy of evaporation is taken from the (warm) surface of the sinter. In thermal equilibrium the sinter reaches the same temperature as the liquid/vapor mixture. The temperature is below the boiling point of nitrogen at atmospheric pressure 77 K because the gas is pumped at the outlet and the ambient pressure at the sinter therefore lower than the atmospheric pressure. The rate of evaporation and, thereby, the equilibrium temperature depends on the pumping speed or pressure at the outlet, which, in turn, is controlled by the user by means of a small valve shown in Fig. 6. The sample holder is mounted directly behind the sinter and cooled by thermal contact to sinter and the inner tube of the cryostat as well as through the flow of cold nitrogen gas around the sample.

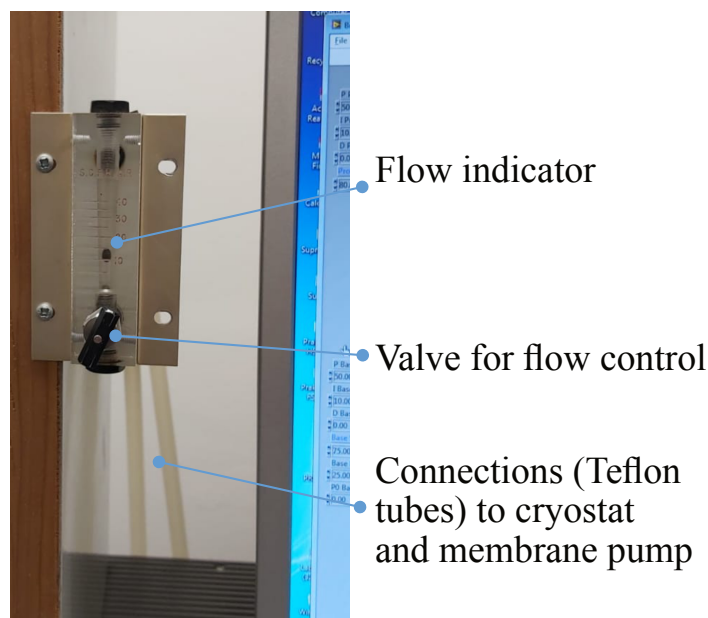


Figure 6: Photograph of the flow control valve and the flowmeter.

### 4.3 Sample holder

The sample is mounted on a sample holder inside the cryostat. The sample is a ceramic compound  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ , briefly YBCO, which has the so-called perovskite crystalline structure as explained in the introduction of this manual. The sample is bonded by special solder to four wires for the four-point measurement of the resistance (see section 4.5). The sample holder is essentially a long tube as schematically drawn in Fig. 7). Inside the tube the wires for resistance measurement, temperature sensors, and the heater are taken to the feedthroughs.

In order to minimize heat exchange by convection and radiation with the environment, several reflectors are mounted along the tube between the head of the sample holder and the vacuum flange. The temperature sensor (Pt100 resistor) is placed directly underneath the sample and in excellent thermal contact by thermally conductive paste with the heater foil.

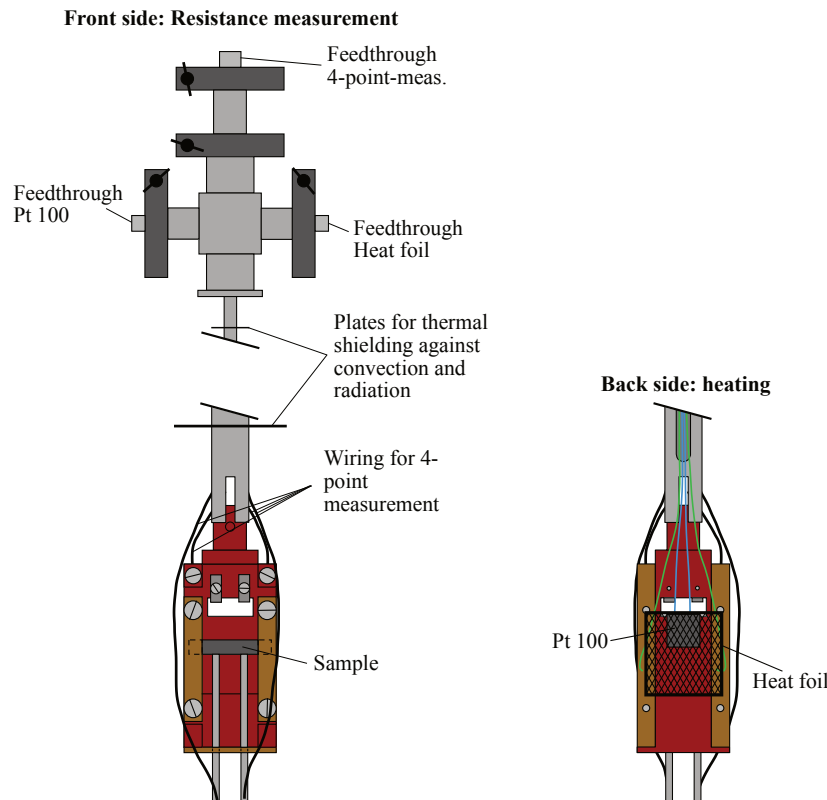


Figure 7: The sample holder. Left-hand-side: front view and electrical connections at the outside of the cryostat. Right-hand-side: view from the back with the sample and the foil used for resistive heating.

#### 4.4 Temperature control

The temperature can be controlled in several ways:

1. By closing a valve in the pump line of the cryostat: the valve changes the conductivity of the pump line and thereby the pressure at the sinter. The lower the pressure the higher the rate of evaporation and the lower the boiling point of the liquid. Both effects decrease the temperature of the cryostat.
2. By electrical resistive heating of the sinter, controlled electronically using a Pt100 resistor as temperature sensor. The equilibrium between cooling and heating determines the base temperature of the cryostat.
3. By direct heating of the sample using a resistive foil at the back of the sample (see Fig. 7). This so-called Joule heating is the heat produced by an electric current flowing through a resistor. The foil and the Pt100 in direct contact with the sample can be used to make fine adjustments to the sample temperature.

Details of the temperature measurement and the controller will be given in the following sections. During this experiment you will proceed as follows for obtaining the desired sample temperature: The full cryostat will be cooled down to the lowest base temperature possible with the setup. Due to the large masses and heat capacities, and the corresponding thermal inertia of all parts which are cooled, this takes some time. Using the two heating circuits and due to the much lower heat capacity of

the sample holder, the fine adjustments of the sample temperature are fast and allow to run controlled temperature ramps. This can be tested by running some ramps through the critical temperature with and without field in both directions.

The final and best measurements can be done by letting the cryostat warming up while monitoring sample temperature and sample resistance continuously.

#### 4.4.1 Temperature measurement

Beside the electrical contacts the sample (holder) is in thermal contact with a high-precision **Pt100** resistor. Its resistance at 0°C is precisely 100 Ω which is the origin of the name of this resistor. Such resistors are calibrated over a wide temperature range and used as standard for measuring the temperature (other devices like NTC or PTC or diodes use the resistance of semiconductors, for instance, or the thermovoltage between two metals in contact). The calibration curve is usually provided together with the resistor and can be implemented in a computer program which measures the resistance and displays and saves directly the values converted into a temperature.

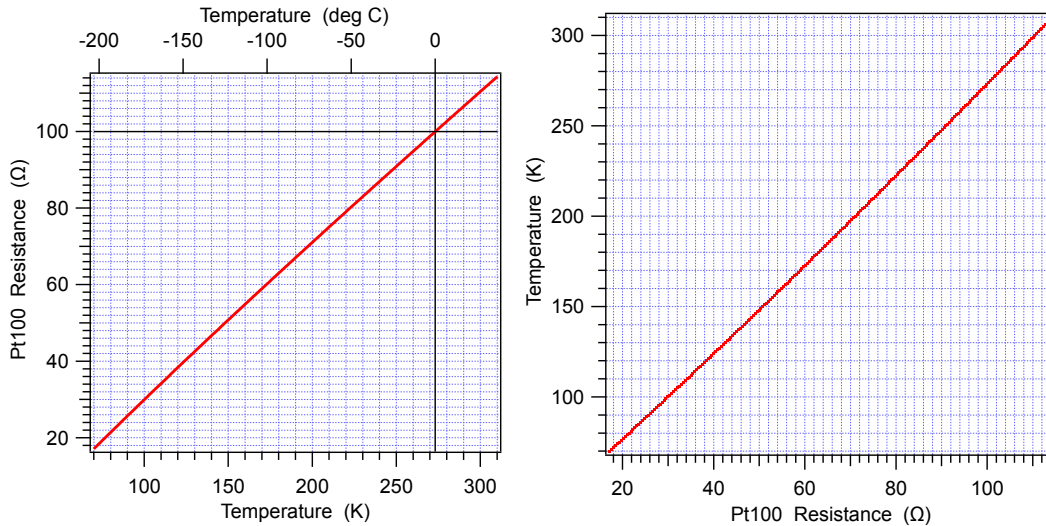


Figure 8: Calibration curves for Pt100 standard resistors. On the right-hand-side we display the standard values as markers together with a fit of a polynomial of order 3. The fit values are given in the text.

The resistance values can be converted into temperature. This is conveniently done using data tables which are standardized for different types of resistors (you will find such tables at the experiment) or else the following formula, which is plotted in Fig. 8 as a polynomial fit for a fast estimate of the temperature:<sup>3</sup>

$$T = 30.11(3) \text{ K} + 2.291(1) \text{ K} \frac{R}{1 \Omega} + 1.39(1) \times 10^{-3} \text{ K} \frac{R^2}{1 \Omega^2} \quad (1)$$

The uncertainty of the temperature value is of the order of 0.25 K if the resistance measurement is done with an accuracy of 0.1 Ω. Here, the uncertainty should be measured experimentally including the statistical fluctuations.

Two of these resistors are mounted inside our experiment: One of them is placed at the sinter itself measuring the base temperature of the cryostat as shown in Fig. 7. The second is mounted in direct

<sup>3</sup>The reference values and plots are based on the standard IEC 60751:2022 published by the International Electrotechnical Commission and similar; the values were obtained from the website <https://us.flukecal.com/pt100-calculator> of Fluke Corp.

thermal contact with the sample and allows the sample temperature to be measured. The latter is part of the feedback circuit for the temperature regulation of the sample (see section 4.4.2). The resistance of both Pt100 resistors is measured using 4-point technique (c.f. section 4.5) and displayed as temperature in Kelvin by the *Conductus* LTC-20 temperature controller.

#### 4.4.2 Active control of the sample temperature

The control and stabilization of the oven temperature is done using a so-called **PID controller**: The acronym PID stands for **P**roportional–**I**ntegral–**D**erivative and means the feedback mechanism widely used for generating a control signal out of a measured quantity. Here, the controller regulates the heating by controlling the current through the heating filament. The temperature of the head of the cryostat is measured using the resistance of a Pt precision resistor in direct thermal contact with the sinter or the sample. This *process variable* is compared to a *setpoint* temperature given by the user and/or the computer program. The correction applied to the heating current is then calculated using the difference of process variable and setpoint as described in the next section.

**Important:** the sample temperature measured together with the resistance of the sample is always the reading of the resistance of the Pt100 resistor in direct contact with the sample! In this way, temperature differences between the cryostat and the sample do not falsify the results of the experiment.

#### 4.4.3 The PID controller

In this section the working principle of a PID controller is briefly described taking as an example the stabilization of the sample temperature in our experiment. It is based on a closed feedback loop which is schematically drawn in Fig. 9. The temperature of the sample shall be stabilized at some desired

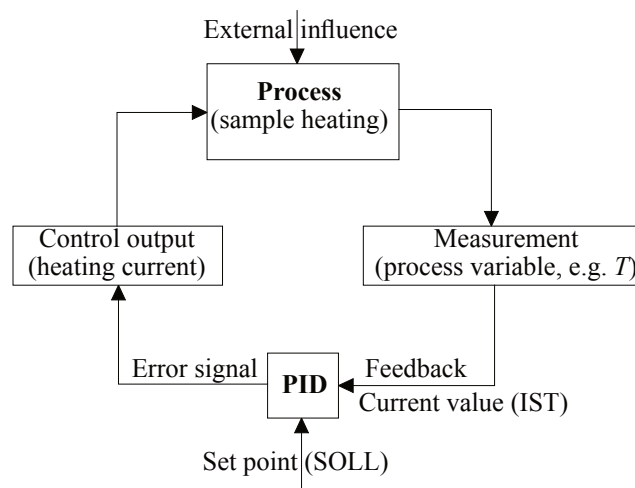


Figure 9: Generic scheme of a control circuit.

value as defined by the user or some computer program running a temperature ramp, for instance. The true temperature is influenced by external parameters like flow of liquid nitrogen in the cryostat and may be different from this *setpoint*. The measured temperature is called the *process variable*. Its value is compared to the desired value (setpoint). Out of the difference signal the controller generates an *error signal* which is applied as correction to the control variable (heating current): if the temperature difference is negative, i.e. the sample temperature lower than the setpoint, the error signal shall increase the heating current and vice versa.

PID refers to the way in which the error signal is calculated from the difference signal in the feedback loop:

1. **Proportional:** The error signal is proportional to the feedback signal, i.e. the correction of the heating current is proportional to the temperature difference signal at the input. The P–correction is almost instantaneous essentially limited by the response speed of the system, i.e. here the time between the increase of the heating current and the increase of the measured temperature. Moreover another problem is the fact that the temperature will only exponentially approach but never reach the desired value because the correction is always getting smaller at the same pace than the temperature difference.
2. **Integral:** This part averages the measured value over some time constant  $t_{\text{int}}$ . The error signal is then proportional to the difference between the averaged (integrated) measurement and the setpoint. Owing to the time constant this correction is slower than the bare P–signal and, as a positive side effect, averages over fast variations of the feedback signal as produced by electronic noise, for instance. Using the P– and the I–correction, one can show that the output indeed reaches the desired value.
3. **Derivative:** This part takes the instantaneous derivative of the temperature in to account for producing the error signal. Thereby it extrapolates the present process variable by multiplying the slope of the temperature with some time constant  $t_{\text{der}}$ . This part can substantially speed up the correction but makes the system unstable against perturbations of the process signal and tends to overdrive the system. This may be particularly harmful if the inertia or the time constant of the process (or response speed, c.f. P) is very slow.

#### 4.4.4 Realization of the control circuit

For the temperature controller used here the PID is set in the following way:<sup>4</sup>

The P–part is limited to a certain *proportional band*, that means a temperature range in which the P–correction is applied. This is required by the limited power output provided by the controller. The maximum temperature range  $\Delta T_{\text{max}}$ , in which the controller tries to apply the direct proportionality between feedback signal and error signal is given by (we still use the German terms IST for the measured signal and SOLL for the setpoint):

$$\Delta T = T_{\text{IST}} - T_{\text{SOLL}} \quad \Rightarrow \quad \Delta T_{\text{max}} = \alpha \frac{P_H^{\text{max}}}{G}$$

where  $\alpha$  is some constant.  $P_H^{\text{max}}$  denotes the maximum heating power at the output of the controller and  $G$  the gain factor which can take values between 1 and 999. In Fig. 10 we show this proportional band schematically. Please note:

1. The larger the gain  $G$  is chosen, the smaller will be the proportional band.
2. The proportional band is *one-sided*, i.e. the controller will only heat if  $T_{\text{IST}} < T_{\text{SOLL}}$ .

The integral I–part will integrate the process signal over a time constant

$$\bar{T}_{\text{IST}} = \frac{1}{t_{\text{int}}} \int_0^{t_{\text{int}}} d\tau T_{\text{IST}}(\tau) \quad \text{with} \quad t_{\text{int}} = \frac{999 \text{ s}}{R},$$

where the integration time interval  $t_{\text{int}}$  is determined by the *reset-rate*  $R$  with values between 1 and 999 (e.g.  $R = 100 \Rightarrow t_{\text{int}} \simeq 10 \text{ s}$ ).

Finally the time constant  $t_{\text{der}}$  for the derivative D–part is given by  $t_{\text{der}} = (1/4)\beta t_{\text{int}}$ .  $\beta$  is a number in percent with values ranging from 0 to 200. In our experiment, we usually switch off the differential D–part due to the slow response time of the oven.

<sup>4</sup>For details, please, refer to the controller manual.

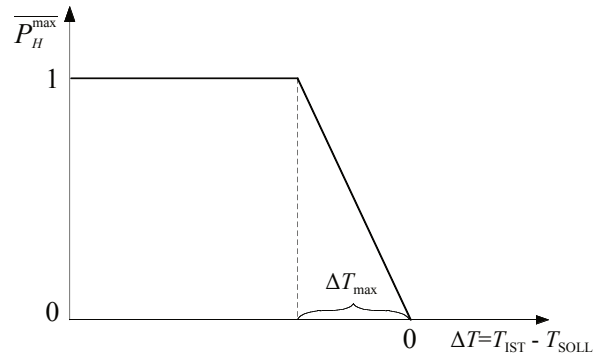


Figure 10: Sketch of the proportionality band of the controller.

#### 4.5 Measurement of the resistance

Four electrical contacts were spot-welded to the sample. These four contacts serve as current leads and voltage probes for the resistance measurement described here. Note that the terms *resistance* (German: Widerstand) and *resistivity* (German: spezifischer Widerstand) have a different meaning: resistance means the (electrical) resistance of a particular sample, which determines the voltage measured across the sample as function of current flowing through the sample. From the measurement of the resistance, one can determine the resistivity as property of the sample material by eliminating all dependencies on the measurement geometry, what is in general a fairly complex task! Since the resistance is directly proportional to the resistivity we will focus on the measurement of the resistance and assume that the material property *resistivity* will behave the same as function of temperature and field.

The resistance of the sample will be determined by the **four-point-method**: four contacts means that the current leads and the contacts for the voltage measurement are separated. At the points-of-contact between current leads and sample so-called *contact resistances* appear which depend critically on the quality of the bonding and on the materials in direct contact. In particular, at metal-semiconductor contacts a small barrier (Schottky barrier) may be formed which acts like a diode and whose voltage drop may depend exponentially on the current passing through the contact. Even if the contacts exhibit metallic behavior (so-called ohmic contacts) the finite resistance may take fairly large values and cause a significant voltage drop across the contact. Connecting the voltmeter to the same two contacts would then mean that the sum of the voltages at the contacts plus the voltage across the sample is measured. This is a systematic error.

In turn, if the voltage measurement is done using two separate wires and a voltmeter with very high internal resistance, the correspondingly small drain current used for the voltage measurement only causes a very small voltage drop at those contacts. In this way the systematic uncertainties due to the contact potentials and the wire resistances between sample and voltmeter can therefore be kept to a minimum.

#### 4.6 External magnetic field

If there is time left you may check the influence of an external magnetic field onto the superconducting gap. The cryostat sample holder is placed between the soft iron pole pieces of an electromagnet. The solenoid producing the magnetic field is water cooled. At maximum current, which can be set by using the potentiometer attached at the experiment, the magnetic induction between the poles reaches

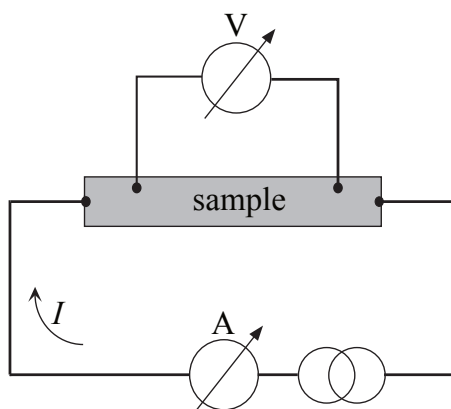


Figure 11: Schematic diagram of the 4-point-measurement. Note the separate contacts of current carrying wires and voltage measurement.

a field strength of about 0.8 T. The value can be found on a calibration sheet.<sup>5</sup>

The effect will be fairly small. In order to observe the change the temperature range around the phase transition at  $T_c$  must be measured during a slow temperature ramp with many points on the transition, once with and once without the magnetic field turned on.

**Notes for operating the magnet:** Do not forget to turn on the cooling water (blue 90° valve) – cooling has to be running all the time during operation of the magnet! Check for water leaks and do not leave the magnet running over night.

<sup>5</sup>The magnetic field strength can be measured using a small calibrated Hall probe (see experiment H of the Basic Laboratory Course II for Physics Majors). The magnetic field is given in Gauss on this display. This is a former unit based on the former c.g.s. (centimeter–gram–second) unit system. The conversion factor to the SI unit Tesla is given by  $1 \text{ Ga} = 10^{-4} \text{ T}$ .



## 5 Questions to answer in your report

1. Does the resistivity of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  show metallic behavior in the normal state? Describe the dependence of the resistance on temperature quantitatively.
2. How does the electrical resistivity depend on magnetic field in the metallic state (qualitatively and for weak field strength)?
3. From your data, determine the critical temperature  $T_c$  for the phase transition between metallic and superconducting state. Which criterion do you use for determining the transition temperature?
4. Why is the resistance always measured twice, once for each polarity of the current? And why is the average value not zero?
5. Why and how should the critical temperature change in presence of an external magnetic field? You may use the phase diagram in Fig. 3 for arguing. Note that we are dealing with a type-II superconductor, and that the field strength is well below the upper critical field. What would you expect in the case that the measurement current is very close to the critical current density?