

# Josephson effects in superconductors

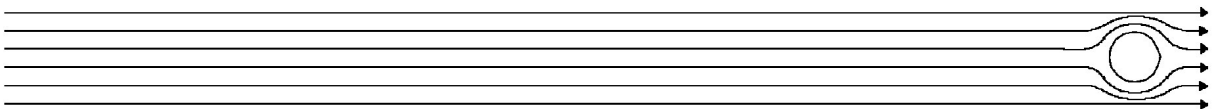
Experiment 16

at the

Technical University Munich

**Walther–Meissner–Institute**

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# Chapter 1

## Safety

**All handling of equipment is only permitted together with or after consulting the tutor!**

### 1.1 Dealing with liquid helium

#### General

At the Walther-Meißner-Institut liquid helium is operated in a closed cycle. Dewars have to be kept connected to the return line, a short transport within the building is possible without danger, tilting is not permitted. The transport in the lift is permitted only without accompanying persons.

#### Danger

At touch of liquid, cold gas or materials that were in contact with them cold burn and frostbite can occur (temperature of the liquid: 4.2 K). There's the danger of asphyxiation if large quantities of liquid/gas escape (lack of oxygen). In the case of uncontrolled escape of helium the room has to be left immediately.

#### Precautions

- personal protective equipment: gloves and goggles
- make sure that the helium can rests on a stable base
- never leave the helium can without connection to the return line
- only controlled and slow lowering (and lifting) of the measurement dipstick. Check the optimum adjustment of the crimp connection (Danger: jerky lowering may lead to evaporation of large quantities, in the worst case to the breakdown of the insulation vacuum)

## 1.2 Electrical equipment

### **Danger**

Touching conducting materials in contact with the mains supply of 230V may be lethal!

All apparatus used for the measurements have a 230 V mains supply together with a grounded chassis. Modifications to the setup are only done by the tutor. The assembly of the signal lines can be changed without danger. Any problems with the equipment have to be reported to the tutor immediately.

*Further information concerning safety can be found in the "red ring binder" in the laboratory.*

# Chapter 2

## Basics

### 2.1 Superconductivity

When the metal mercury (Hg) was cooled down to the temperature of liquid helium for the first time by Kamerling Onnes (1911 at Leiden), it was expected that the metallic conductivity would break down due to the immobility (no kinetic energy) of the conducting electrons. Exactly the opposite result was obtained: the conductivity increased during the cooling process and suddenly jumped to infinity at 4.2K (which corresponds to zero electrical resistivity). Therefore Kamerling Onnes discovered the *phenomena of superconductivity* for Hg. (Fig. 2.1).

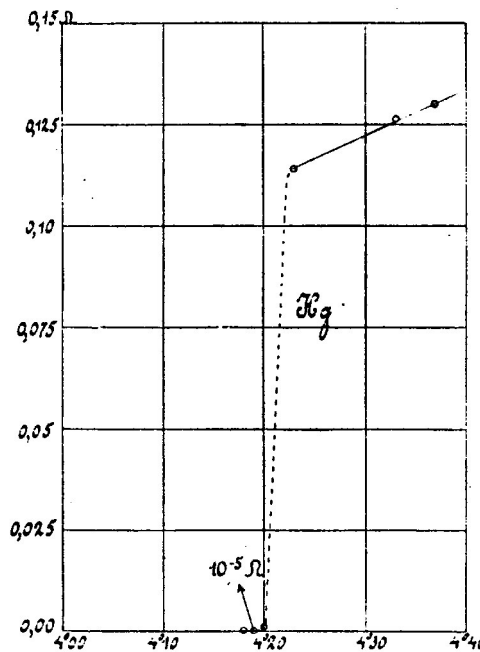


Figure 2.1: Superconductivity in mercury

Two decades later, along with the development of quantum mechanics, it was found that the conducting electrons form a gas of fermions with a high (zero-point) energy on the scale of a few eV (width of the conduction band) even at  $T = 0$ .

The electrical conductivity is mediated only by the highly energetic electrons in the conduction band (which are located at the Fermi-Energy), whose mobility - in a perfect crystal - is infinite and in a real system is reduced due to impurities (already at  $T = 0$ ) as well as due to scattering processes with phonons (higher temperatures).

This model described *normal metallic conductivity*, but broke down for *superconductivity*, especially as the superconductivity apparently did not depend on the purity of the metal.

The superconducting state is obviously a new eigenstate of the electron gas, where the electrons are able to move non-dissipatively like in atoms or molecules. The electrons loose their entropy (no degrees of freedom, highly ordered state), which explains the stability of the superconducting state only at sufficiently low temperatures. The state is thermodynamically stable at the minimum of the free energy  $F = U - TS$ . In order to compete with the normal state (higher entropy), the intrinsic energy (binding energy)  $U$  of the superconducting state has to be smaller. The whole metallic crystal appears to the electron as a (giant) molecule in which the wave packets move *with a stable phase towards each other*. In a current-free state, the phase is constant in space. If the phase *varies with space* ( $\frac{\partial}{\partial x} \Psi(r_i) \neq 0$ ), a supercurrent appears. E.g. in a superconducting ring, the wave train has to be closed, which is quantum mechanically equivalent to the quantisation of the angular momentum:

$$\oint (\vec{p} + e\vec{A}) ds = n \cdot h \quad (2.1)$$

( $\vec{p}$  is the mechanical and  $\vec{p} + e\vec{A}$  the canonical momentum of the electrons (in the presence of a magnetic field with its vector potential  $\vec{A}$ )).

From (2.1) the quantisation of the *magnetic flux* can be deduced. A continuous superconductor like a sphere, which is subject to a moderate magnetic field, always prefers (due to energetic reasons) the flux quantum state  $n = 0$ , where the  $\vec{B}$ -field within the superconductor is zero, as the external field is shielded by a supercurrent in the surface layer (thickness  $\lambda \approx 500 \text{ \AA}$ , *London penetration depth*): *Meissner Effect* (fig. 2.2)

This extraordinary state does not violate eq. (2.1) at the surface layer, as simultaneously a  $\vec{B}$  field exists as well as a current is flowing in such a way that both terms  $\vec{p}$  and  $e\vec{A}$  cancel each other in eq. (2.1).

More fascinating effects can be observed, when two superconductors are brought into weak contact with each other - via a geometrically thin contact (e.g. a tip contact), an oxide layer or a conducting (but non-superconducting) layer. The principle of such contacts is shown in fig. 2.3

While the phase of the center of mass of the superconducting electrons in each superconductor (SC 1 and SC 2) is still well defined, it is now possible - due to the weak

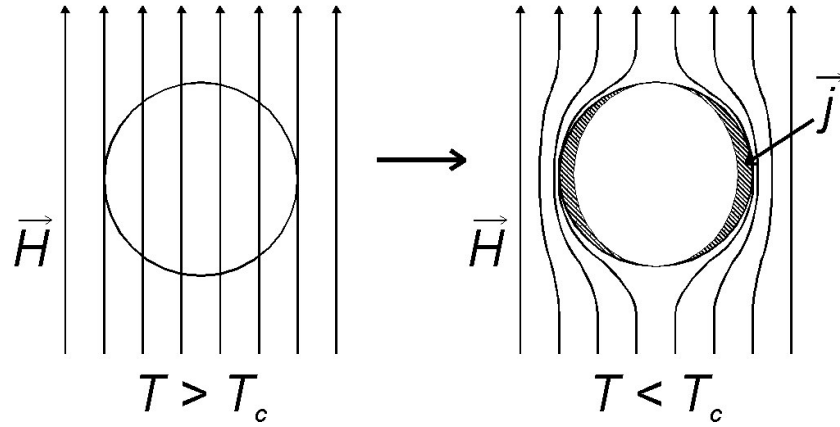


Figure 2.2: Meissner effect

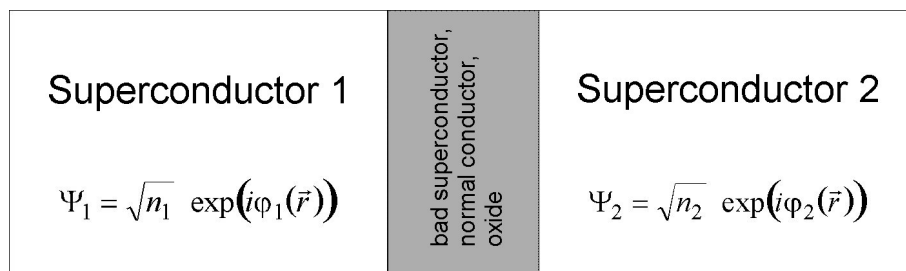


Figure 2.3: Josephson contact

coupling - to have a *phase shift* between SC 1 and SC 2. In the theory of superconductivity by Bardeen, Cooper and Schrieffer (BCS-theory, 1957), the electrons in the superconducting electron gas are correlated in pairs (*Cooper pairs*) whose binding energy (despite the low entropy) stabilizes the superconducting state with regard to the normal (non-superconducting) state. A Cooper pair can be basically regarded as a wave packet with the extension of the coherence length  $\xi$  ( $\xi \approx 10^4 \text{ \AA}$ ). For contact layers between two superconductors considerably thinner ( $\approx 10 - 10^2 \text{ \AA}$ ), it is possible that Cooper pairs are able to tunnel between both superconductors without being destroyed, which is similar to the possibility of weak supercurrents (Josephson current) between SC 1 and SC 2. *Josephson effects* contain the correlation of the Josephson currents between SC 1 and SC 2 as well with or without magnetic field (in the contact layer) as with or without difference in the electrical potential between SC 1 and SC 2.

## 2.2 Josephson effects

Some of the most important applications of superconductivity are connected with Josephson effects, e.g. extremely fast switches. Another application is the measurement of magnetic flux (to the precision of a fraction of a flux quantum) with two Josephson contacts embedded into a ring structure.

The task of this experiment is to examine a niobium point contact. The experimental setup allows to survey different kinds of Josephson contacts and to prove the AC-Josephson effect with radiometry of the emitted microwave radiation in the X-band (X-band: 8.2 - 12.4 GHz).

### 2.2.1 Theory

Superconductivity is a quantum phenomena on macroscopic scale. The BCS theory describes the superconducting state as a condensate of electrons bound in pairs (Cooper pairs), which are correlated with fixed phase. The *total wave function* can be written as

$$\Psi = \sqrt{n_S} \cdot \exp(i\varphi(\vec{r})) \quad (2.2)$$

with the density of Cooper pairs  $n_S$  and the phase of the wavefunction  $\varphi$ .  $\Psi$  can be figured as the movement of the center of mass of the superconducting electrons. The general expression for the quantum mechanical current is

$$\vec{j} = \frac{iq\hbar}{2m^*} \cdot (\Psi \vec{\nabla} \Psi^* - \Psi^* \vec{\nabla} \Psi) - \frac{q^2}{m^*c} \cdot \vec{A} \cdot \Psi \Psi^*. \quad (2.3)$$

With the space independent density of Cooper pairs  $n$ ,  $q = -2e$  and  $m^* = 2m$ , we derive

$$\vec{j} = -\frac{\hbar en}{m} \cdot \vec{\nabla} \varphi - \frac{2e^2 n}{mc} \cdot \vec{A} \quad (2.4)$$



with the elementary charge  $e$  and the electron charge  $m$ . Eq. (2.4) shows the relation between the current density  $\vec{j}$  in the superconductor, the phase of the wavefunction  $\varphi$  and the vector potential  $\vec{A}$ . From eq. (2.4) the *2. London equation* can be derived  $\vec{\nabla} \times \vec{j} = -\frac{1}{\lambda_L^2} \vec{B}$ , which leads to the understanding of the *Meissner effect*.

As the current density has to be gauge invariant, it can be deduced that for the gauge transformation  $\vec{A} \rightarrow \vec{A} + \vec{\nabla}\chi$  the phase of the wave function transforms into

$$\varphi \rightarrow \varphi - \frac{2e}{\hbar c} \chi \quad (2.5)$$

which is equivalent to gauge invariance - as the equation is independent of the choice of the vector potential  $\vec{A}$ , to which a gradient of an arbitrary potential function  $\chi$  can be added without altering the magnetic field  $\vec{H}$ :

$$\begin{aligned} \vec{A}' &= \vec{A} + \nabla\chi \\ \vec{H} = \text{rot}\vec{A}' &= \text{rot}\vec{A} + \underbrace{\text{rot}\nabla\chi}_{\equiv 0} = \text{rot}\vec{A} \end{aligned} \quad (2.6)$$

### 2.2.2 Josephson equations

For two superconductors linked via a *weak link* (a region with obviously reduced contribution of the order parameter  $\Psi$ ) - see fig. 2.3 - the whole system is still described by a uniform condensate wavefunction. Unpaired electrons as well as Cooper pairs are able to cross the region of the weak link - the resulting effects were predicted by B.D. Josephson in 1962.

The current across a barrier between two superconductors depends on the *phase difference*  $\gamma = \varphi_2 - \varphi_1$  between both sides:  $j_{12} = f(\gamma)$ , which is analogue to the correlation between current and phase gradient within a superconductor (eq. 2.4).

As a time reversal transformation changes the direction of the current and the sign of the phase, this implies that the current needs to be an odd,  $2\pi$ -periodic function of the phase difference  $\gamma$ . It can be shown that - under the assumption of a weak coupling (e.g. tunnel contact) - the first fourier component of the expansion of  $f$  in terms of the phase difference is sufficient, which means that  $j_{12}$  is a sine of the phase difference:

$$I = I_c \sin \gamma \quad (2.7)$$

This equation is known as the *1. Josephson equation*. The critical current  $I_c$  at  $T = 0$  for a tunnel contact is proportional to the energy gap:  $I_c \propto \Delta$  (Ambegaokar-Baratoff-relation).

Since the Josephson current has to be gauge invariant as well, in the presence of a magnetic field the corresponding term of the vector potential in the gauge invariant phase difference has to be considered:

$$\gamma = \varphi_2 - \varphi_1 + \frac{2e}{\hbar c} \int_1^2 \vec{A} \cdot d\vec{s} \quad (2.8)$$

If the current is increased beyond the value of the critical current  $I_c$  of the weak link, the current cannot be carried by the supercurrent alone. The resistivity  $R_n$  of the additional, normal conducting electrons leads to a *potential difference* and therefore to a voltage  $V$  between the two still superconducting regions. To describe this state quantitatively, the effect of a gauge transformation on the properties of a time-independent scalar electromagnetic potential  $\Phi$  has to be taken into account:

$$\Phi \rightarrow \Phi - \frac{1}{c} \frac{\partial \chi}{\partial t} \quad (2.9)$$

This equation together with eq. 2.5 leads to the gauge invariant *2. Josephson equation*

$$\dot{\gamma} - \frac{2e}{\hbar} \cdot V = 0 \quad (2.10)$$

We conclude:

- the *first Josephson equation* correlates the phase difference at the Josephson contact with the current of the Cooper pairs across this contact
- the *second Josephson equation* shows that the phase difference  $\gamma$  changes linearly with time in case of a potential difference between both superconductors

### 2.2.3 Josephson contacts

Josephson effects can be studied on various types of contacts beside the tunnel contact discussed above: e.g. on point-contacts (e) of a tip (this experiment).

### 2.2.4 DC - Josephson effect

For a contact without a potential difference between the two superconductors, we derive from eq. 2.10:  $\gamma = \gamma_0 = \text{const.}$  Therefore a *current constant in time* across the contact is derived from eq. 2.7:  $I = I_c \cdot \sin \gamma$ , which lies within the range given by  $\pm I_c$  (critical current).

This equation is similar to the equation of coupled pendula: no energy is exchanged if the pendula are oscillating in phase or out of phase. The maximum energy exchange takes place for a phase shift of  $\pm\pi/2$ .

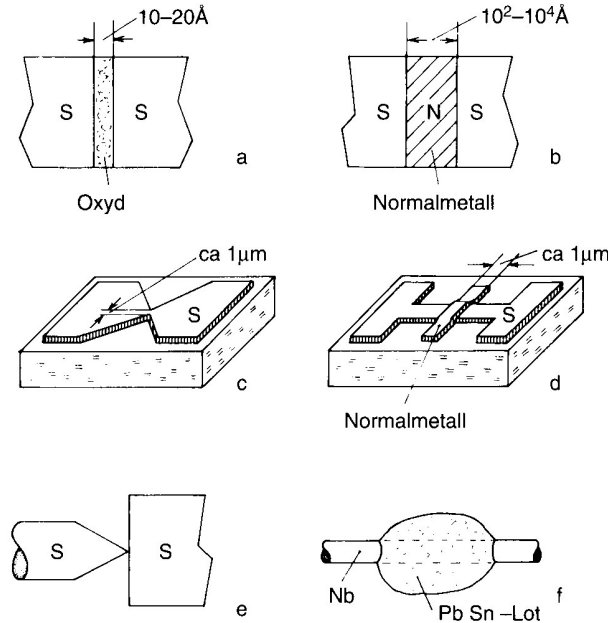


Figure 2.4: Common types of Josephson contacts (see [1]) a) Oxide layer; b) SNS-contact; c) film contact; d) Double layer contact via Proximityeffects; e) point contact; f) multiple point contacts (SLUG)

### 2.2.5 AC - Josephson effect

In case of a temporally constant voltage  $V$  between both superconductors, we derive from eq. (2.10):  $\gamma = \gamma_0 + (2e/\hbar)Vt$  and from eq. (2.7)

$$I = I_c \cdot \sin\left(\gamma_0 + \frac{2e}{\hbar}Vt\right) \quad (2.11)$$

follows that an *AC current* with the frequency

$$f = \frac{2e}{h} \cdot V \quad (2.12)$$

flows across the contact. As  $2e/h = 483.6 \text{ MHz}/\mu\text{V}$ , this frequency lies in most cases in the microwave regime for experimentally achievable voltages. The emitted radiation (frequency  $f$ ) can be measured radiometrically.

An illustration of the AC Josephson effect is the following: the tunneling Cooper pairs are accelerated due to the presence of the voltage  $V$  and gain the energy  $2eV$ . As the Cooper pairs are not allowed to alter their energy while tunneling, a photon of the energy  $hf = 2eV$  (eq. (2.12)) is emitted.

### 2.2.6 Josephson contacts in the magnetic field

Taking into account the finite size of the Josephson contacts, a correlation between  $I$  and the magnetic flux  $\Phi$  through the contact is derived from eq.(2.8). It can be shown that this correlation has the form:

$$I_c(H) = I_c(0) \cdot \left| \frac{\sin\left(\frac{\pi\Phi}{\Phi_0}\right)}{\frac{\pi\Phi}{\Phi_0}} \right| \quad (2.13)$$

with  $\Phi = 2\lambda_L \cdot l \cdot B$  (see e.g. Ref. [1]), the size of the contact perpendicular to the magnetic field  $l$  and the London penetration depth  $\lambda_L$ . This function is plotted in graph 2.5. Note that the form is equivalent to that of bending on a slit.

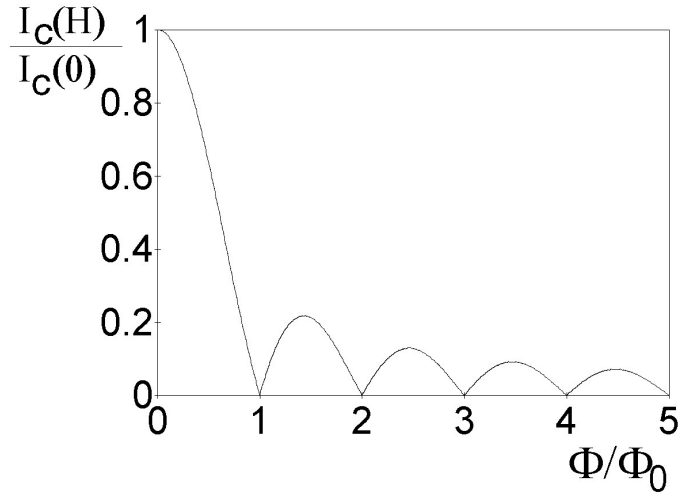


Figure 2.5: Dependence of the critical current  $I_c$  of a Josephson contact on the magnetic flux

## 2.3 I-V Characteristics of Josephson Junctions

The normal-conducting electrons and the capacitance between the electrodes also affect the  $I$ - $V$  characteristics of a Josephson junction. Those two contributions are taken into account by the *RSJ-model* (Resistively Shunted Junction). The equivalent circuit is shown in fig. 2.6.

The total current across the junction is given by

$$I_{\text{tot}} = I_c \cdot \sin \gamma + \frac{V}{R_n} + C\dot{V}. \quad (2.14)$$

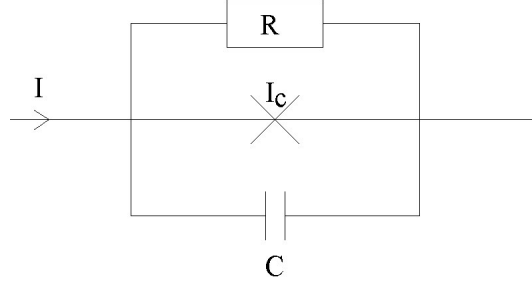


Figure 2.6: equivalent circuit of a Josephson junction according to the RSJ-model

In order to record such an  $I$ - $V$  characteristic, a current  $I_{\text{tot}}$  is applied to the Josephson junction and the voltage drop across the junction is measured. Due to the nonlinear behavior, the frequency spectrum of the current does not contain only the basic frequency according to equation (2.12) but also higher harmonics.

Inserting the second Josephson equation (2.10) in equation (2.14) yields a non-linear differential equation for  $\gamma$  that corresponds to that of a physical pendulum [4]. Solving this differential equation numerically, one has to distinguish two limits with respect to the so called *McCumber parameter*  $\beta_c$

$$\beta_c := \frac{2\pi C R_n^2 I_c}{\Phi_0} \quad (2.15)$$

(  $\beta_c$  is a measure of the Q factor of the resonant circuit,  $\Phi_0 = h/2e$  is the flux quantum. )

- $\beta_c > 1$  (underdamped)

For  $I < I_c$  there are two stable solutions. Therefore, the  $I$ - $V$  curve becomes hysteretic (fig. 2.7a). Starting at zero current and increasing the bias current does not produce any voltage drop across the junction until the critical value  $I_c$  is reached. At  $I_c$  the voltage is switched from zero to a finite value within  $1ps$ . This rapid switching behavior is used in Josephson devices. If  $I$  is now reduced below  $I_c$ ,  $V$  does not drop back to zero until a retrapping current  $I_R$  is reached. This hysteresis can be used to estimate the McCumber parameter  $\beta$ :

$$\frac{I_R}{I_c} = \frac{4}{\pi\sqrt{\beta_c}} \quad (2.16)$$

- $\beta_c < 1$

The  $I$ - $V$  curve shows no hysteresis (fig. 2.7b). In the limit of vanishing capacity  $\beta_c = 0$  and the differential equation can be solved analytically. The time averaged voltage drop  $\langle V(t) \rangle$  is for  $|I_{\text{tot}}| > |I_c|$

$$\langle V(t) \rangle = \pm R_n \sqrt{I_{\text{tot}}^2 - I_c^2} \quad (2.17)$$

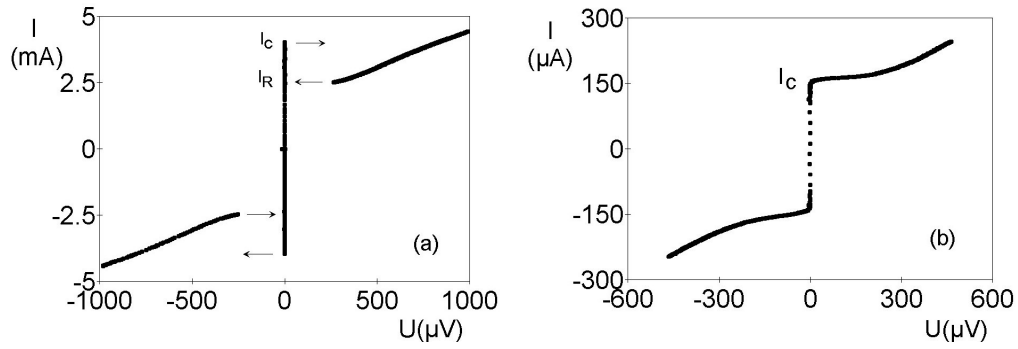


Figure 2.7: Typical current-voltage-curve (a) of a tunnel junction (b) and of a weak link

## 2.4 Radiation emission

The radiation power at a frequency  $f$  depends on several parameters of the Josephson junction. Due to the nonlinearity of the Josephson junction a part of the radiated power is used for the emission of higher harmonics. Furthermore the radiated power is determined by the impedance matching of the Josephson junction to the characteristic impedance of the space. Fig. 2.8 shows an emission curve measured as a function of voltage on a point contact.

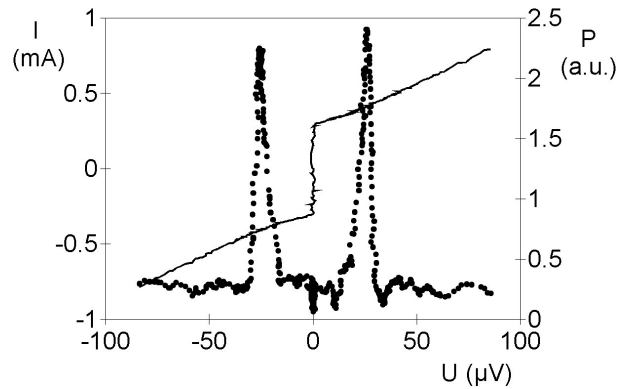


Figure 2.8: Characteristic of a Nb-Contact (straight line) and radiometer signal  $P$  at  $f = 12.75$  GHz (dots)

## 2.5 Point Contacts

A superconducting point contact consists of two superconductors, coupled by a very small area. Experimentally, this is realized by pressing a superconducting tip onto a flat superconducting surface. Naturally, this experimental setup is not well defined, for the properties of this contact depend among other things on the physical pressure and the oxidation at the surfaces of the superconductors. Nevertheless there are two limiting cases that can be distinguished. Under very small pressure the junction can be dominated by the oxide layers and therefore show tunneling behavior. On the other hand under high pressure, a small metallic contact between the two superconductors can result in a weak link behavior. With the experimental setup described above, both  $I$ - $V$  characteristics in fig. 2.7 were measured. Varying the pressure between the superconducting tip and the superconducting surface between these limits yields other  $I$ - $V$  characteristics that most probably result from a parallel connection of metallic paths and tunneling contacts

Due to the often varying properties of the point contacts in this experimental setup you will need a bit of patience and flair in order to adjust the parameters suitable for radiation.

## 2.6 summary of fundamental terms

You should know the meaning of the following terms:

- critical temperature  $T_c$
- Cooper pair
- Meissner effect, ideal diamagnetism
- London penetration depths
- Flux quantum
- Josephson contact, tunnel current
- Josephson equations
- DC- and AC-Josephson effect
- Current-Voltage characteristics of Josephson contacts

# Chapter 3

## Experimental Setup

### 3.1 Sample

You will examine a Nb-point contact according to Fig. 2.4(e).

### 3.2 Sample Holder

You will perform the experiment with a sample holder that can be cooled down in a helium can (Fig. 3.1). It contains a round hollow wave guide with an inner diameter of 19.2mm. Therefore, in the frequency range between 9.8GHz and 11.5GHz only the fundamental wavelength ( $H_{11}$  mode) will be transmitted. In order to couple the radiation emitted by the sample to the wave guide, a Horn antenna is attached to the lower end of the waveguide. The sample is mounted in the center of the Horn antenna. The sample holder contains a mechanical system with an adjusting screw a differential thread and a rocker that enables you to approach the Nb-tip slowly to the opposite flattened Nb-wire by turning the adjusting screw. *Turning the adjusting screw clockwise will close the contact; turning counter-clockwise will open it.* Making use of thermal expansion it is also possible to approach the Nb-wire to the tip by heating a Pb-rod that is attached to the Nb-wire via another rocker.

### 3.3 Electronic Measuring Equipment

The electronic measuring equipment is placed in a NIM-frame (Nuclear Instruments Module) as it is shown in Fig. 3.2).

#### Measurement of Current and Voltage

The voltage sweeper provides voltages between +10 V and -10 V. Apart from applying a discrete and constant voltage, there is the possibility to ramp the voltage from zero to a setpoint voltage  $V_1$  or to ramp between two adjustable voltages  $V_1$  [-10 V ... +10 V]



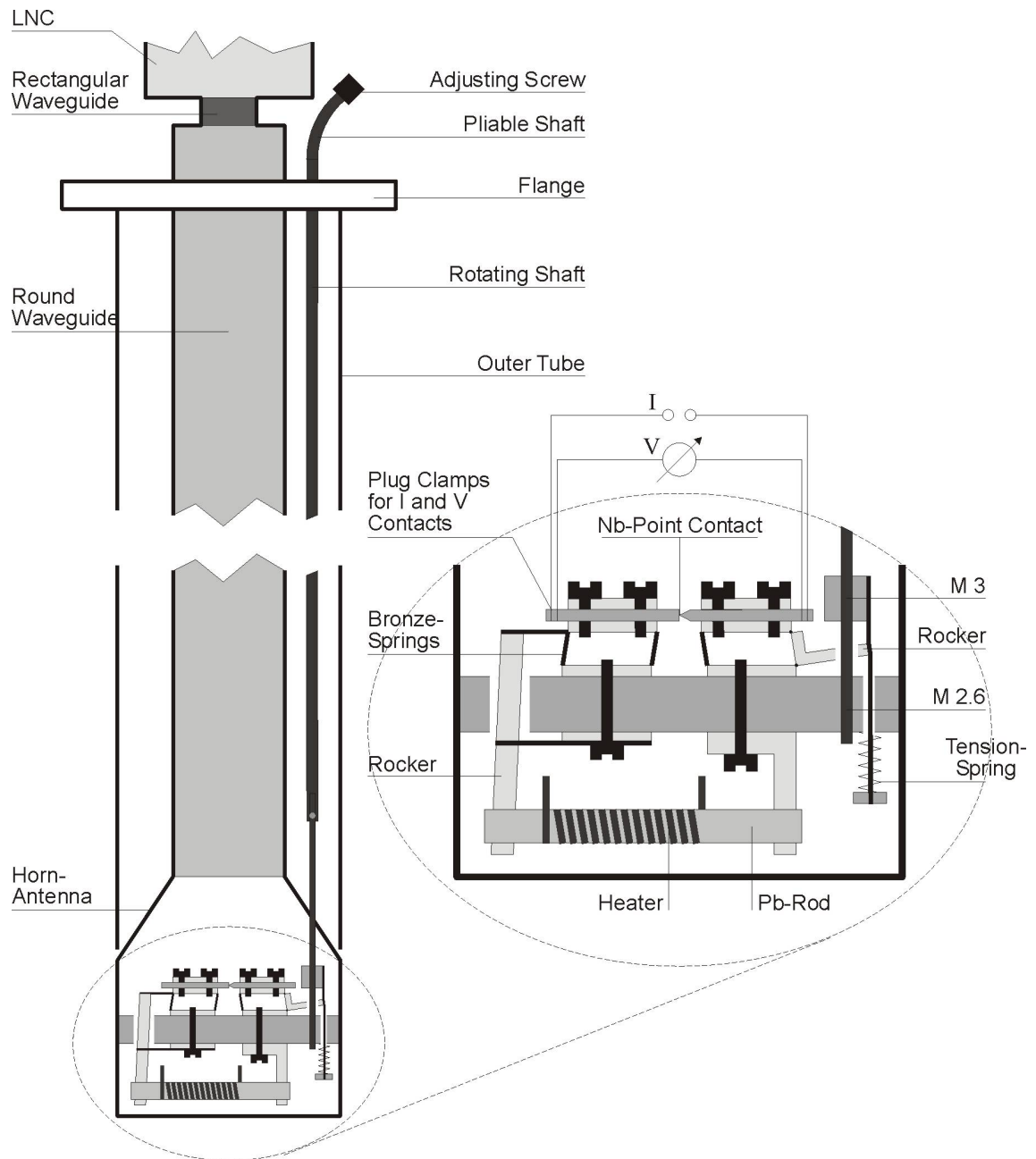


Figure 3.1: sample holder

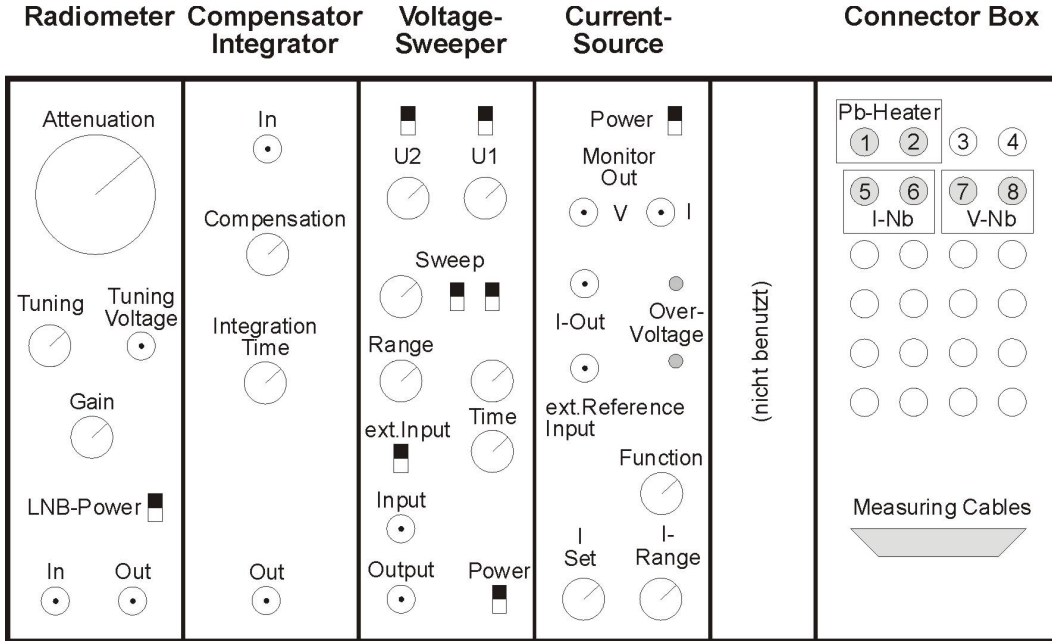


Figure 3.2: drawers of the NIM-frame

and  $V_2$  [-10 V ... +10 V]. The imprinted scale has the unit time/voltage. The slowest ramp velocity is 9.99 min/Volt. The voltage sweeper controls the current source. Choosing  $\pm 10$  V for  $V_1$  and  $V_2$  will ramp the current between  $\pm I_0$ .  $I_0$  can be varied between 1  $\mu$ A and 100 mA. This current is available at *Output I* that has to be connected to the Nb-contact (clamps 5 and 6). In addition to that, the current source supplies a monitor signal at *I monitor* to the DVM 1 (digital voltmeter). The monitor signal is proportional to the current and in each current range, the maximum current corresponds to a monitor signal of 1 V. This is also the case of zero current when the Nb-point contact is open! If the contact is open, the overvoltage LEDs are lit. The voltage drop  $V_S$  at the sample (clamps 7 and 8, typically less than 1 mV) is amplified by a low-noise dc voltage amplifier. The maximum output voltage of this amplifier is  $\pm 1$  Volt. The amplified voltage is measured by the DVM 2. So, the resistance of the Nb-contact is measured with a classical 4-point method. *Attention:* The dc voltage amplifier is not very new and may not be overamplified to much. Therefore, at the beginning of each measurement, the sensitivity has at first to be adjusted to 1 V. Afterwards it may be gradually turned down to the mV or  $\mu$ V range.

Sweeping the control voltage  $V_C$  between two fixed limits and recording DVM 1 and DVM 2 thus yields the  $I$ - $V$  characteristic of the Nb-point contact.

There is a low-pass filter installed in each input lead to the sample in order to short-circuit unwanted high-frequency signals as for example from the broadcasting station in Ismaning (801 kHz).

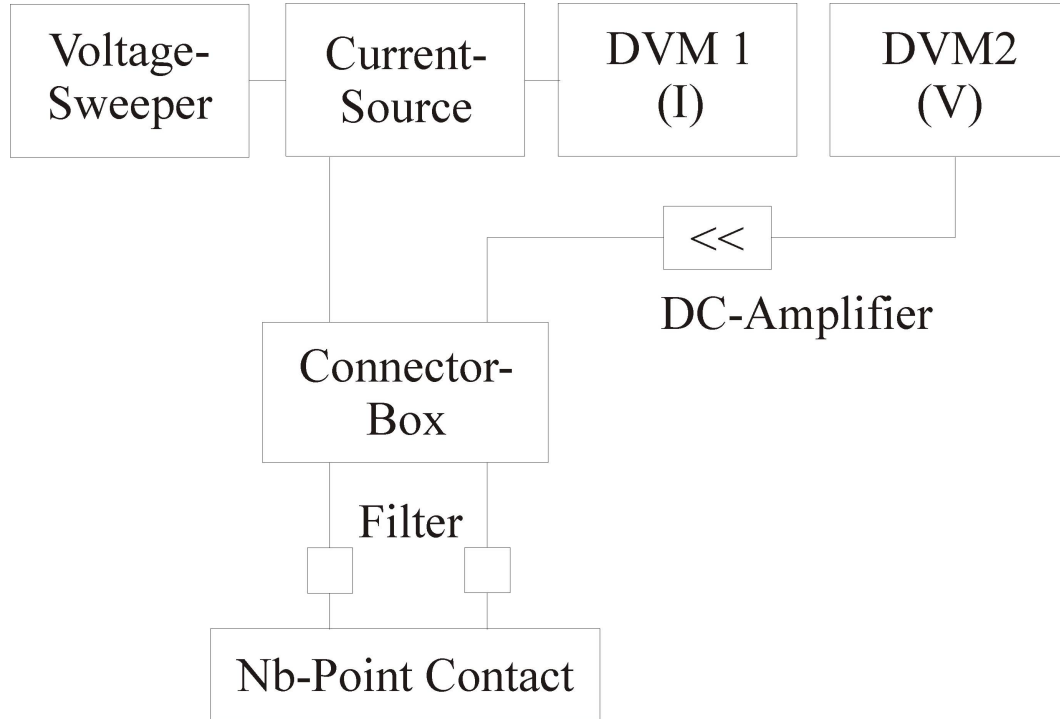


Figure 3.3: Block Diagram of the Current and Voltage Measurement

### Radiometer

The radiation with frequency  $f_J$  emitted by the Josephson contact is detected by the Horn antenna and (with small losses) transmitted via the waveguide to the LNC (Low Noise Block Converter). There, the microwaves pass at first through a high-frequency amplifier. The internal mixer produces from  $f_J$  and the frequency of the internal local oscillator  $f_{LO} = 10.00$  GHz the intermediate frequency  $f_I = f_J - f_{LO}$ .

With the tuner, a 30 MHz wide frequency window is chosen from the spectrum of the first intermediate frequency (950 – 1700 MHz). This window is mapped on  $70 \pm 15$  MHz. The 70 MHz amplifier is anechoically terminated by a  $50 \Omega$  resistor. The HF voltage drop across the  $50 \Omega$  resistor is rectified by a diode. After another low-pass filter which removes residual HF signals, one can measure a voltage with the DVM 3 that is proportional to the square root of the radiated power.

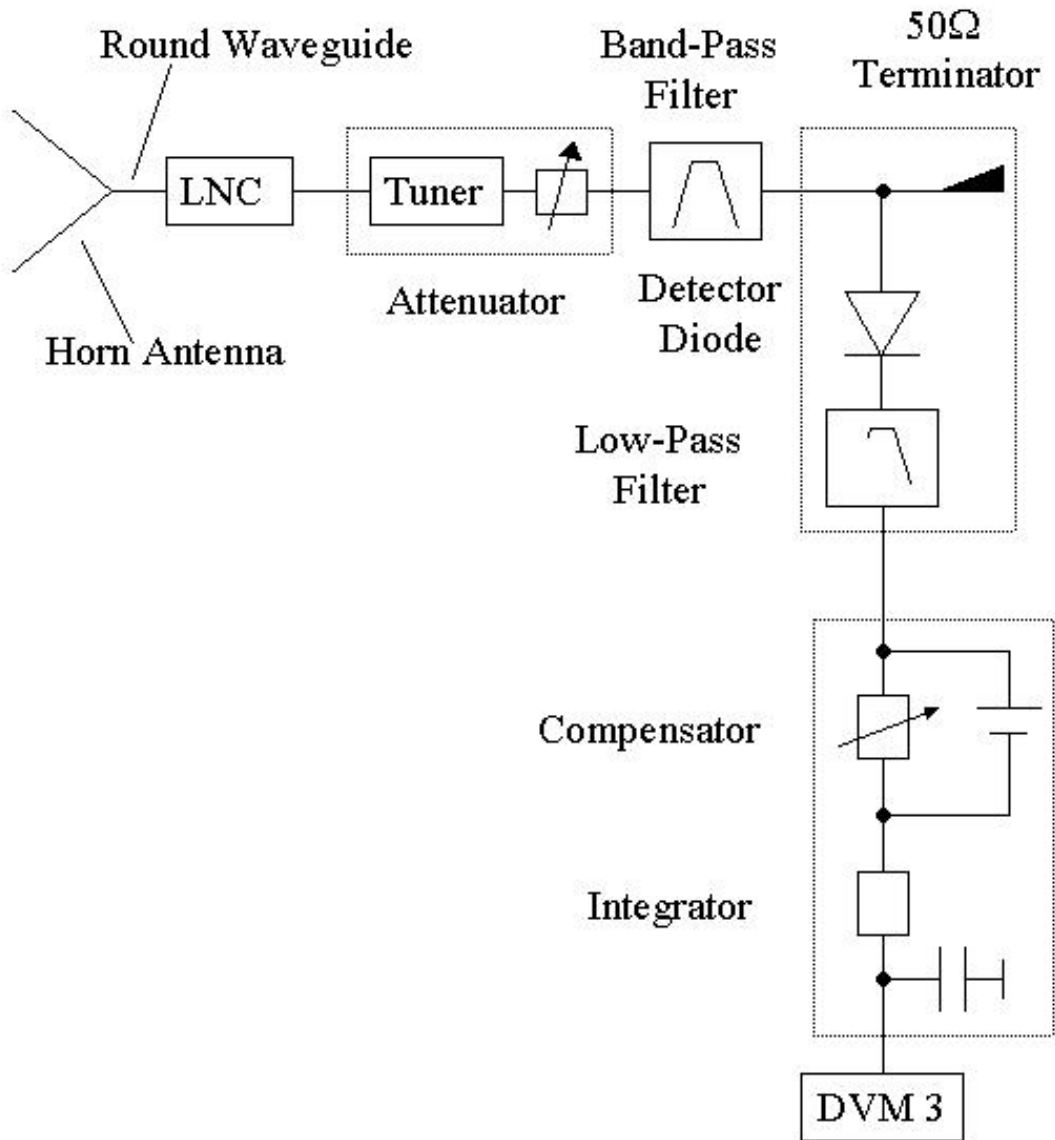


Figure 3.4: Assembly of the Radiometer

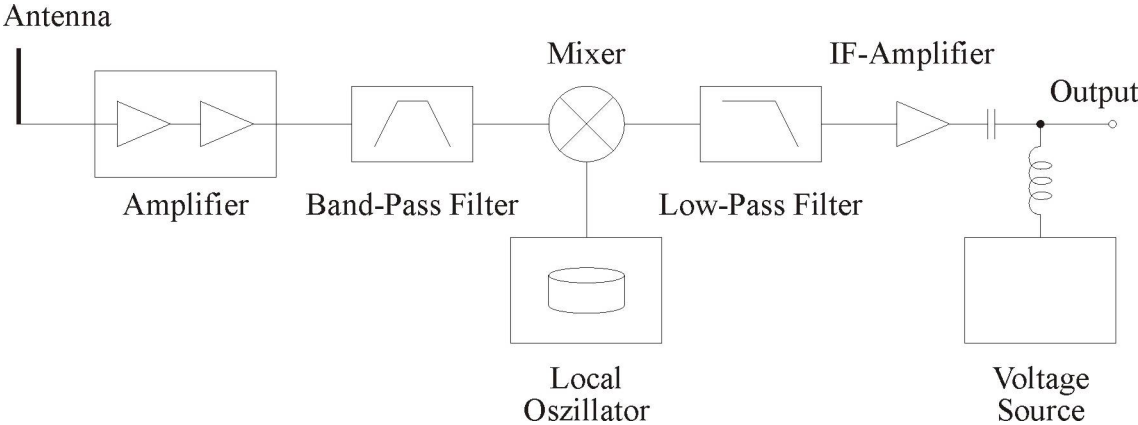


Figure 3.5: Assembly of the Low Noise Block Converter LNC

# Chapter 4

## Measurement

The signals from the digital voltmeter can be captured by the program 'xyzkplot' (will be explained at the pc). With that you will get binary files, which can be converted with the helper program 'xyzcnvt' to ASCII-files. These ASCII-files can then be analysed with standard programs.

### 4.1 Cooling down the sample rod

*While bringing the sample rod into the helium can, the tutor must be with you !*

Turn the tuning knob of the point-contact at the top of the sample rod *anti-clockwise* to the end limit, *without* applying a big force. This separates the Nb-tip from the Nb-counterplate. After that turn the tuning knob a half turn clockwise.

Remove the big valve from the He can and connect the sample rod there. Take care that the sample rod is pushed up completely. Now remove the He exhaust hose of the He can from the He recycle line and connect it to the gas meter. Write down the actual value of the gas meter.

Now push down the sample rod *slowly* into the He can until the gas meter starts to move. Move it further down slowly, while keeping the gas meter move *slowly*, approx. 1 rotation / 10 s . If it moves too fast pull the sample rod a little bit up again. The sample rod is cold, if there is not much He gas leaving anymore. Overall you should need not more than 1.5 m<sup>3</sup> He gas for cooling down.

### 4.2 Tuning of the radiometer amplification

The tuning voltage of the radiometer should be set constant to 5 V (position 2.50 at the potentiometer). This results from graph 4.1 in a frequency of 11.146 GHz, which is allready optimised. In general the frequency follows from:

$$f_D = f_{LO} + 880\text{MHz} + 51.86 \frac{\text{MHz}}{\text{V}} \cdot V_{\text{Tuning}} \quad (4.1)$$

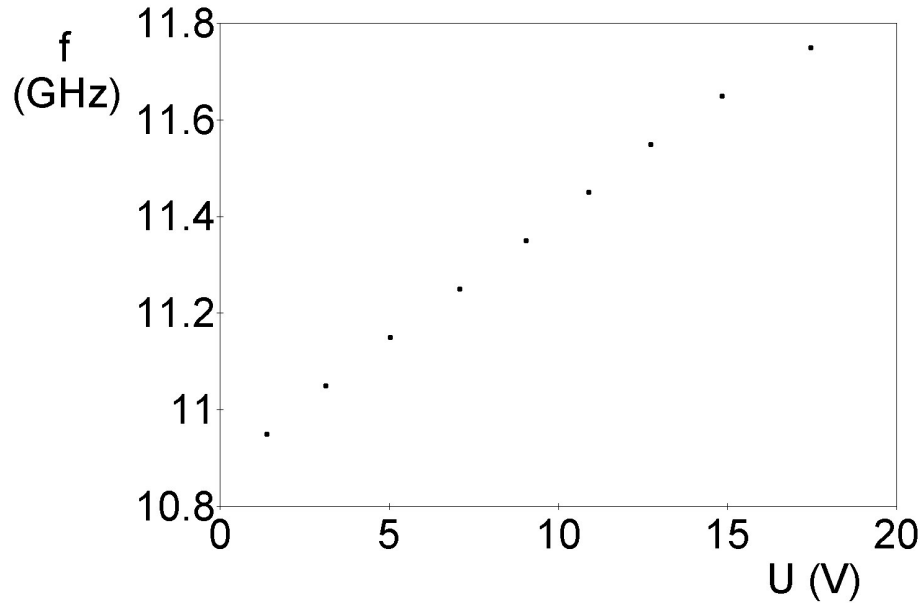


Figure 4.1: Detection frequency  $f_D$  as a function of the tuning voltage  $V$ . (LNB-Power 13 V;  $f_{LO} = 10.00\text{GHz}$ )

### 4.3 Measuring the I-V curve and the emission

After having cooled the sample rod for a while in the liquid He, tune the voltage delivered from the radiometer with the compensator to an optimal value. For that connect the output of the radiometer to the input of the compensator and the output of the compensator to the digital voltmeter 3. By that you can measure relative to the background noise and work in a sensitive range. The signal of the radiometer rises only by some mV in case of a signal detection.

If necessary repeat this tuning before each measurement run.

1. For the measurement of the I-V curve use the setup shown in graph 3.3. For that connect the *I output* of the current source with the connections ' $I_{Nb}$ ' shown in graph 3.2. At the connectors ' $V_{Nb}$ ' the voltage at the Nb-contact can be measured with the help of a DC-amplifier.
2. Set the time ramp of the voltage sweeper to 1 min/Volt. For  $U_1$  and  $U_2$  set +10 V and -10 V. Connect the *output* of the sweeper with the *ext. Ref.* of the current source.

- For the first tuning of the Josephson-junction use a current of  $100\mu\text{A}$ . For that switch the source to internal reference and set the current in the  $100\mu\text{A}$  range manually to maximum.

The Nb-contact is still open, what you can see at the shining of the Voltage-limit-LED  $U_+$  or  $U_-$  of the source and at the relatively high voltage at the NB-contact (DVM 2).

- Now turn the tuning knob at the sample rod *carefully* clockwise. While doing so observe the voltage-limit-LED and the voltage at the DVM 2. After 2-5 turns of the knob you should get into contact. The voltage at the DVM 2 should now fall to a small value less than 1 mV. The Voltage-limit-LED should now be off.

*Do now NOT turn the knob further !*

- Tune the current source to 0 and the range to 1 mA. Increase now the current slowly to 1 mA. If the voltage at the DVM 2 remains small (in the  $\mu\text{V}$  range) the point-contact is still purely superconducting. Increase the current source range and repeat this test.
- Often the  $I$ - $V$  characterisitic is purely ohmic (no sign of superconductivity). Then the oxide layer at the Nb-tip is to thick and the tuning knob at the sample rod has to be tuned clockwise to make the oxide layer thinner.
- At a critical current of mostly some mA suddenly the voltage at the Nb-contact increases. Write down the values and increase the current a little bit. (This will be important for the setting of the measurement range of the DVMs while recording  $I$ - $V$  curves with the computer)
- If the critical current is higher than 100 mA, turn the tuning knob anticlockwise back to open the contact, and then try again to get a weak contact with a lower critical current.
- The tuning knob of the sample rod should never be turned more than two rotations over the critical point clockwise, because then the Nb-tip will be destroyed. This will have as a consequence the warming of the sample rod, repairing of the tip and starting again - severals hours more for you...*
- Switch on the computer and the monitor. Choose the 'xyzkplot'-menu (see separate instructions). Set the current-source and the DVMs to the values you obtained before. Set the program to:

Coordinate	Voltmeter	Range	
x	Nb-Voltage	DVM 2	-1 V ... +1 V
y	Nb-Current	DVM 1	-1 V ... +1 V
z	Radiometer	DVM 3	-0.1 V ... +0.1 V



Change the current-source mode from 'intern' to 'extern'. Set the sweep time with the range and fine-tuning knob to a typical value of 2 minutes.

11. Concentrate now on the  $I$ - $V$  curves. While sweeping, there is the possibility to make a 'finetuning' of the point-contact with a thermal expansion of a Pb-rod. This will change the contact distance a little bit (see graph 3.1). Typical heating voltages of this Pb-rod are in the range 5-9 V.
12. If the tunnel characteristic has huge hysteretic jumps (as shown in graph 2.7a), record this curve with the computer and save it to disk. (With this curve it makes no sense to search for Josephson-radiation, because the concerning voltage will be skipped fast.)

After this try to change the contact by carefully turning the tuning knob of the sample rod or using the Pb-rod heater to get a 'weak-link' as shown in 2.7b.

If you get a 'weak-link' right from the start, so first do the next point (Josephson-radiation) and try after that to get a hysteretic tunnel characteristic by opening the contact a little bit.

13. With a 'weak-link' you can search for the Josephson-radiation. For that reduce the voltage-range of the DC-amplifier to  $\pm 100 \mu\text{V}$  and choose in the menu **SET INTEGRATION PERIOD** the setting **S4** to reduce the noise level. Pay attention that you sweep slowly enough to see the often sharp signal of the emission.
14. Save your measurements always to disk and write down in your protocol the used source ranges and other used values for each file!
15. If not done as yet, record now a hysteretic tunnel characteristic as described above and save it.

## 4.4 Warming up the sample rod

Turn the tuning knob of the sample rod *anticlockwise* to the limit, to open the point-contact. Now turn the knob back clockwise a half turn. Switch off the heating current of the Pb-rod, if you have used it. Disconnect the gas meter from the He recycle line. Disconnect the He can from the gas meter and directly connect it to the He recycle line.

Now pull the sample rod slowly up to the top and let it warm up to room temperature. After that you can unmount the sample rod from the He can and remount the big valve to the He can.

*The tutor should be with you for that !*

# Chapter 5

## Exercises

### 5.1 Questions

Answer the following questions in a written report *before* doing the experiment. After doing the experiment add the measurement results and conclusions to this report.

1. What are the benefits of a 4-point resistance measurement ?
2. At which voltage do you expect radiation emission of the Josephson-contact with a frequency of 10 GHz ? At which voltage do you expect the 2. harmonic to have a frequency of 10 GHz ?
3. Derive the 2. Josephson equation (2.10) starting from  $i\hbar\frac{\partial}{\partial t}\psi_{1,2} = E_{1,2}\psi_{1,2}$  with respect to the wavefunction of a Cooper-pair, described by equation (2.2) ( $n = 1$ ).
4. Derive from equation 2.10 and 2.14 a differential equation for  $\gamma$ . Which analogy consists between the parameters  $C$ ,  $R_n$ ,  $\gamma$ ,  $I$  and the fundamental parameters of a physical pendulum ?
5. Show the transformation invariance of equation 2.10.

### 5.2 Evaluation

1. Discuss your measured curves and calculate from the slope of the curves at high voltages the normal conducting resistance  $R_n$ .
2. Estimate from the hysteretic curves with the help of equation 2.16 the McCumber parameter  $\beta_c$ . From the reversal of the definition of  $\beta_c$  you can then calculate the capacity of the Josephson-junction.
3. Determine for the 'weak-link' curves the critical current  $I_c$  and the differential resistance  $dV/dI$  in the emission maximum. Which influence has the differential resistance on the line width of the emission ?

4. Calculate from the Josephson frequency-voltage relation (2.12) and the position of the emission maximum the value of the flux quantum  $\Phi_0$ . How big is the deviation from the literature value ?

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