Jülicher SQUID GmbH
Sensortechnik

User Manual
for
JSQ Magnetometer SQUID and Electronics

The Jülich SQUID Company (JSQ)

„Manufacturer of

the world´s finest

HTS-rf-SQUIDs“

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Research Center Jülich
(Forschungszentrum Jülich GmbH)

Contents

1. SQUID Fundamentals

A SQUID (Superconducting QUantum Interference Device) is a superconducting interferometer, serving as an extremely sensitive magnetometer. It is formed by a superconducting loop incorporating a weak link, a so-called Josephson junction. The laws of physics demand that the magnetic flux enclosed by a superconducting ring is quantized, $\Phi = n\,\Phi_0$, $n = 0,\pm1,\pm2,\ldots$. Changes of the external magnetic field are compensated for by a variation of the superconducting current around the ring. In the case of a weak link within the ring, this shielding current, however, is limited. The critical current of the Josephson junction, I_c, its Ohmic resistance in the normalconducting state, R_N, and the inductance of the ring, L, are the fundamental parameters governing the behavior of the SQUID.

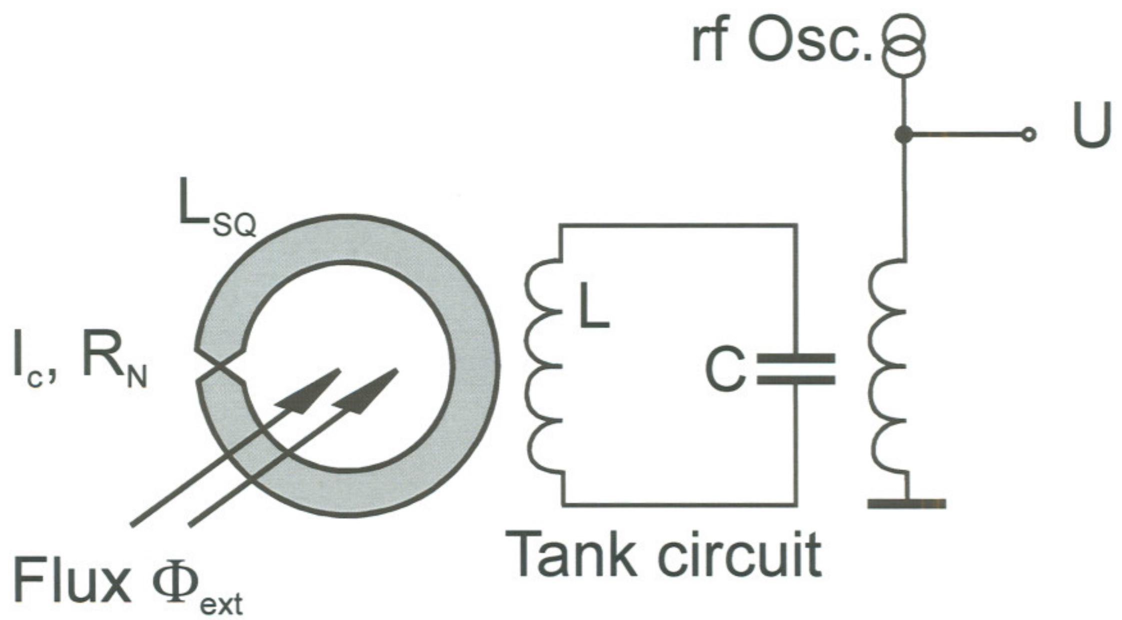


Fig. 1. rf SQUID principle.

The SQUID is read out inductively by means of a tank circuit, a LC resonance circuit operated close to its rf resonance. By means of a VCO (voltage controlled oscillator), the operating frequency of the tank circuit is adjusted. The tank circuit is inductively coupled to the SQUID. The amplitude I_{rf} of the bias current applied to the tank circuit is regulated by a VCA (voltage controlled attenuator). If the bias current of the tank circuit is increased, the voltage drop U_{rf} across the tank circuit is also increased. If the current I_{rf} is sufficiently high

to cause the first flux jump, then U_{rf} does not rise further. A plateau in the U_{rf}-I_{rf}-characteristics is formed, because the energy needed to change the magnetic flux is delivered by the tank circuit.

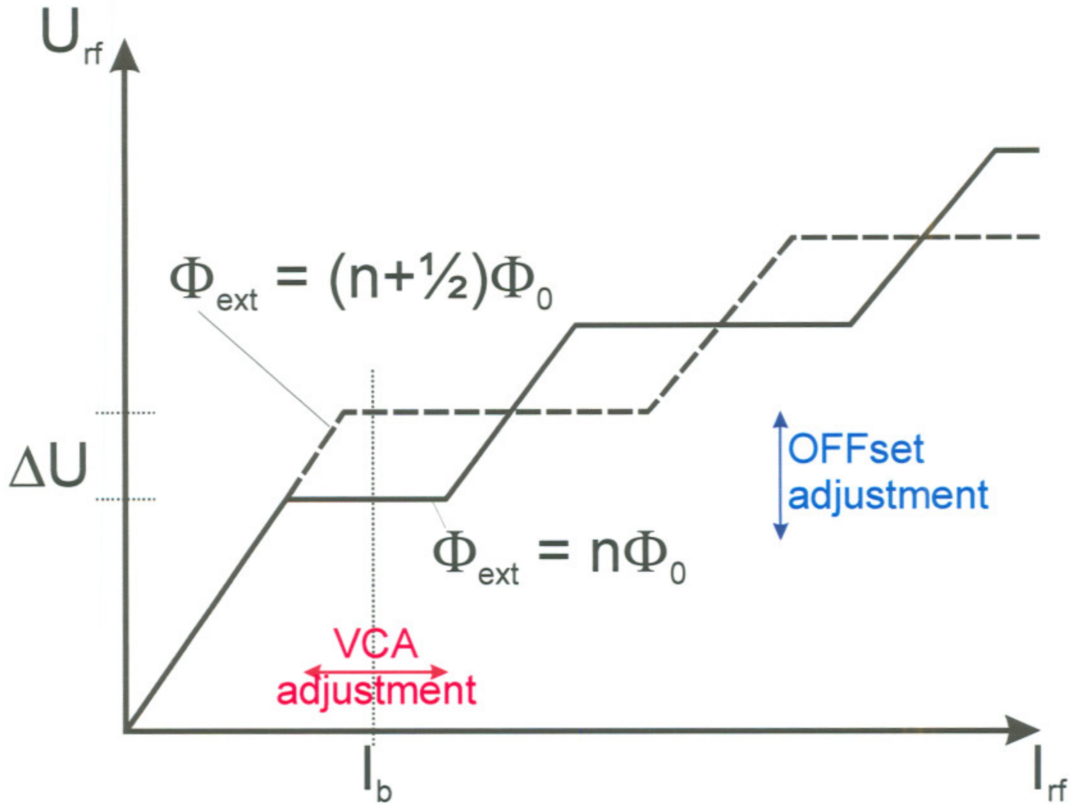


Fig. 2: U – I – characteristics of an rf SQUID.

Depending on the externally applied flux, this point is reached at different values of the current I_{rf} (point A and B in Fig. 2), and the plateau is formed at different values of U_{rf}. In order to be able to further process this voltage electronically, it is necessary to choose the amplitude I_{rf} of the bias current such that the emerging voltage difference ΔU according to the external applied flux becomes maximum. This can be achieved if the amplitude I_{rf} of the bias current is adjusted so that the U_{rf}-I_{rf}-characteristic line takes the shape of a plateau for any external flux (e.g. I_c in Fig. 2). The amplitude I_{rf} of the bias current is adjusted by means of the VCA control (Fig. 16). From the U – I – characteristics of an rf SQUID (Fig. 2), the U – Φ – characteristics, the so-called transfer function (Fig. 3), is derived. The transfer function is a periodic function if the magnetic flux threading the SQUID loop, with the magnetic flux quantum Φ_0 denoting the periodicity constant.

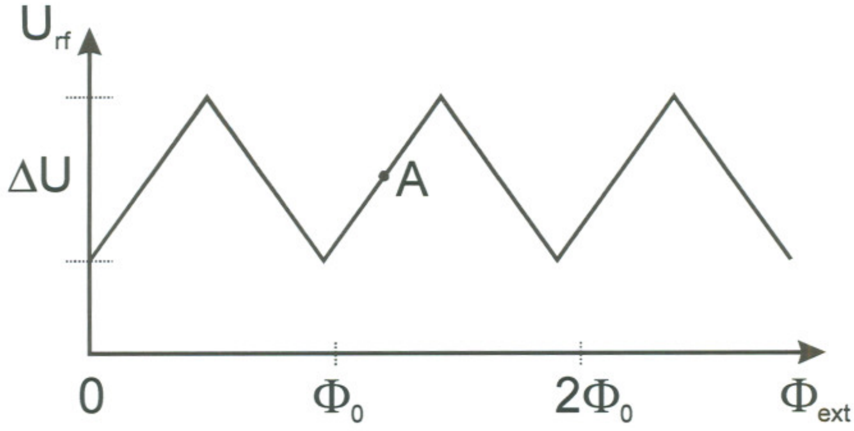


Fig. 3. U – Φ – characteristics (transfer function) of an rf SQUID. The transfer function is periodic in the magnetic flux quantum Φ_0. A denotes the working point (see text).

The JSQ SQUIDs use an inductively coupled tank circuit (Fig. 4). With this design, the tank circuit noise is minimized and the quality factor Q of the tank circuit is maximized. An important advantage of this concept is that no galvanic connection from the electronics to the SQUID, therefore static discharges pose no threat to the SQUID's life. A 50 Ω transmission line connecting the readout electronics with the SQUID is terminated by a coupling coil adjacent to the SQUID and its tank circuit. The coupling coil serves two purposes: applying the pumping radio frequency to the SQUID's tank circuit and generating the feedback flux. In order to linearize the transfer function (Fig. 3), the SQUID is operated in a so-called flux-locked loop: The SQUID is kept at a well-defined external flux state (locked at a working point A, see Fig. 3) by generating a magnetic feedback field compensating all measured external flux variations.

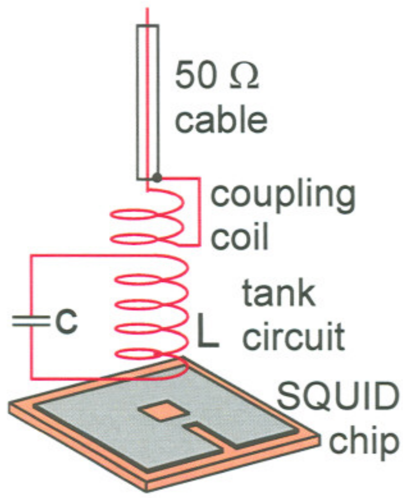


Fig. 4. Tank circuit concept.

2. Components of the JSQ Magnetometer SQUID Sensor System

2.1. JSQ Magnetometer Capsule and SQUID Holder

The JSQ Magnetometer SQUID Sensor consists of a capsule containing the Magnetometer SQUID chip, the tank circuit and the coupling coil. A 50 Ω transmission line cable is used for connection with the readout electronics channels, see Fig. 5.

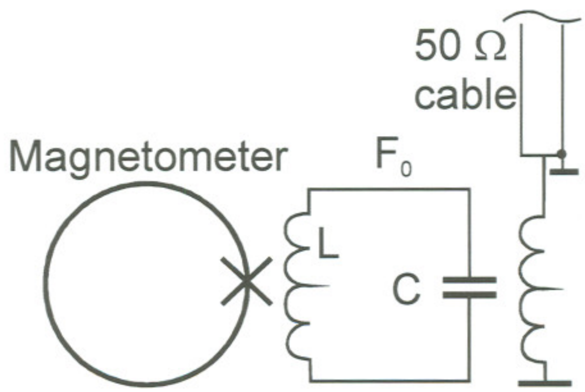


Fig. 5. Principle of the JSQ Magnetometer SQUID Sensor.

Fig. 6 shows the layout of the Magnetometer SQUID. The sensor was developed at Forschungszentrum Jülich. It is manufactured by JSQ. On a $LaAlO_3$ single crystal substrate, a ditch is prepared by ion beam etching. An epitaxial layer of $YBa_2Cu_3O_{7-x}$ is grown by laser ablation. Then, the sensor layout is structured using a photolithographical process in a clean room environment.

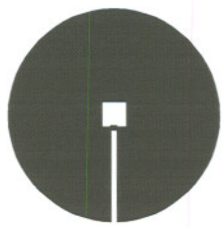


Fig. 6. Layout of the SQUID Magnetometer.

In order to protect the superconducting YBCO thin film from moisture and other harmful substances, the JSQ SQUID is encapsulated in a sealed package. The sensor package consists of a magnetometer, the corresponding tank circuit, the coupling coil and the coaxial connecting cable. Fig. 7 shows the SQUID holder with the SQUID Capsule mounted at the end.

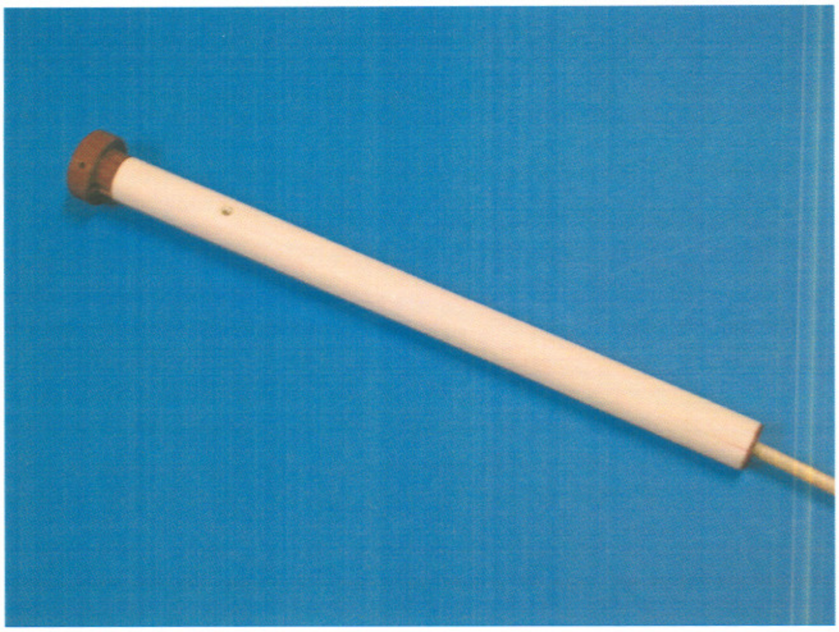


Fig. 7. Photograph of the JSQ SQUID Holder.

2.2. JSQ HTS-rf-SQUID Electronics V4.0

The JSQ SQUID Electronics V4.0 (see Photograph, Fig. 8) is used to generate the pumping radio frequency for SQUID operation, with the required adjustments of rf frequency and amplitude for working point adjustment. Furthermore, the electronics serves as preamplifier and demodulator of the rf response of the SQUID. After demodulation of the SQUID signal from the rf carrier, the signal is integrated and fed back to the coupling coil in order to operate the SQUID in a so-called "Flux-locked loop" (FLL). Thus, the SQUID is kept at a well-defined flux state (e.g. working point A, see Fig. 3). All external flux variations, detected from the moment of locking onward, are compensated by a magnetic feedback flux of opposite sign. The SQUID serves as a null detector. The feedback voltage, proportional to the feedback current, gives the measured magnetic field relatively to the (arbitrary) working point. This operating principle ensures a linear transfer function. It allows a dynamic range from a few 10^{-5} to about 10^{3} magnetic flux quanta with excellent linearity.

Fig. 9 depicts the functional block diagram of the JSQ SQUID Electronics V4.0.

Fig. 8. Photograph of the JSQ HTS-rf-SQUID Electronics V4.0.

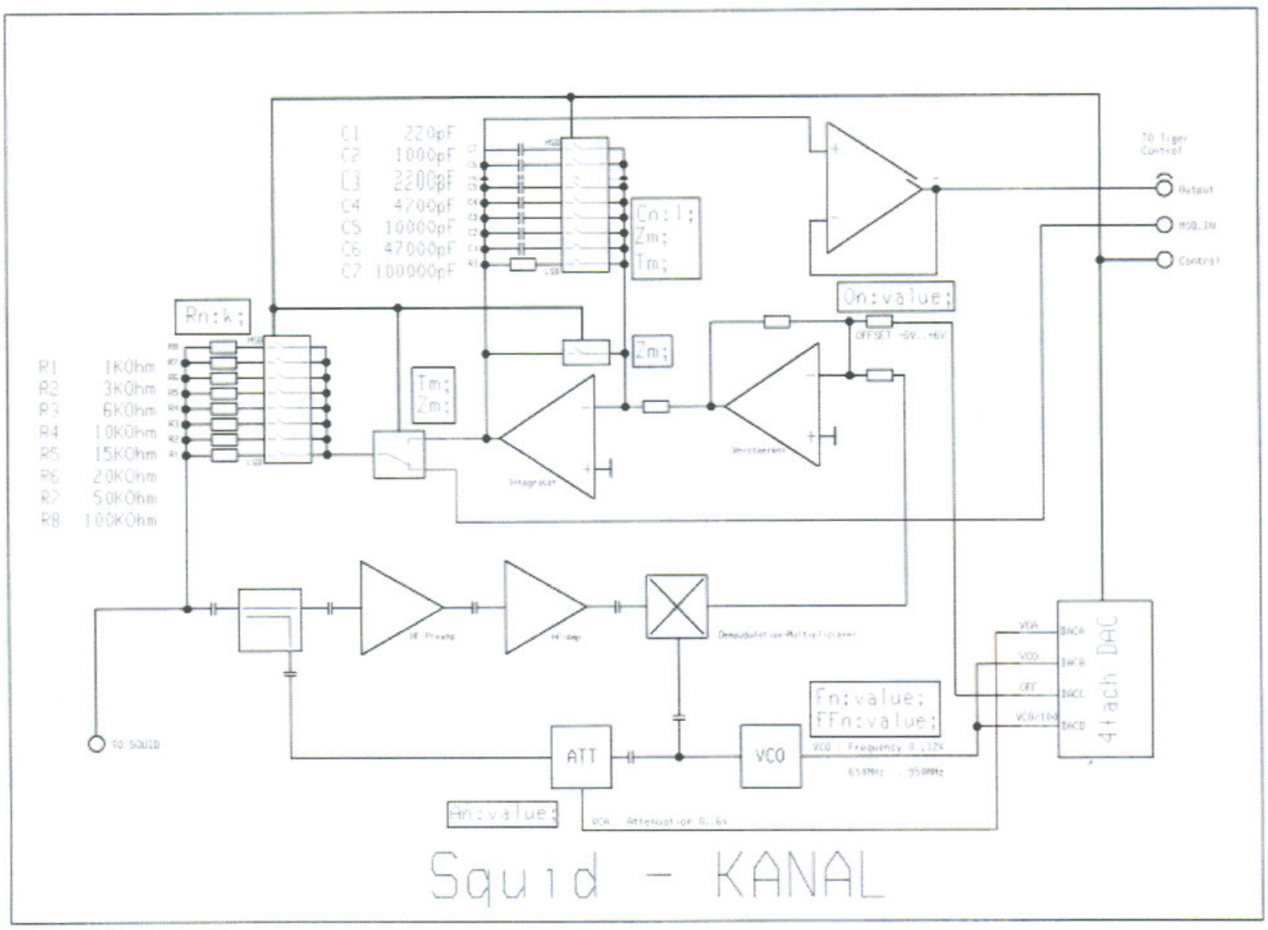


Fig. 9. Schematic of the JSQ V4.0 electronics.

Fig. 10 and Table I denote the parameter adjustment range of the JSQ rf-SQUID electronics V4.0.

Table I. Specifications of the JSQ HTS-rf-SQUID Electronics V4.0.

RF-power output	: -75 dBm to –115 dBm (adjustable)
frequency	: 630 MHz to 970 MHz (adjustable)
signal output ampl.	: ±10 V
test output ampl.	: < 1 V_{pp}
mod. output ampl.	: < 1 V_{pp}

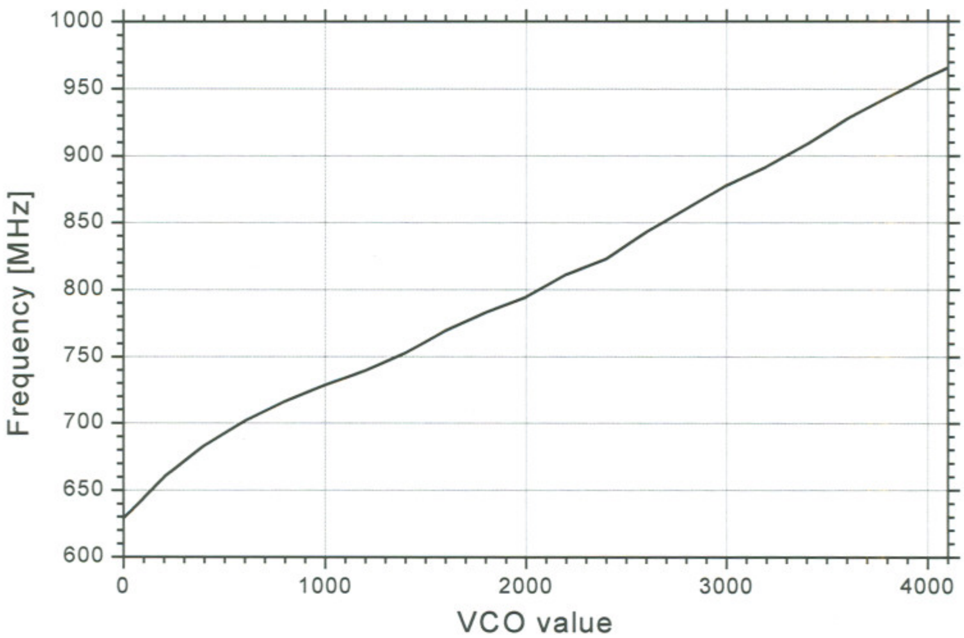


Fig. 10. Typical calibration curve of a JSQ SQUID Electronics V4.0.

2.3. JSQ Tiger Controller for JSQ SQUID Electronics V4.0

The JSQ Electronics V4.0 is operated and remote-controlled by means of a micro controller, the JSQ Tiger Controller. The Tiger Controller is integrated with the electronics (see Fig. 11). It is based on the "Tiger" micro controller chip by Wilke Electronics, Aachen.

The working point of the Magnetometer SQUID sensor is stored in non-volatile memory. In addition, the “Tiger” micro controller handles the communication to a user front-end (personal computer) via its RS 232 port (serial port, COM1 or COM2, V.24 protocol).

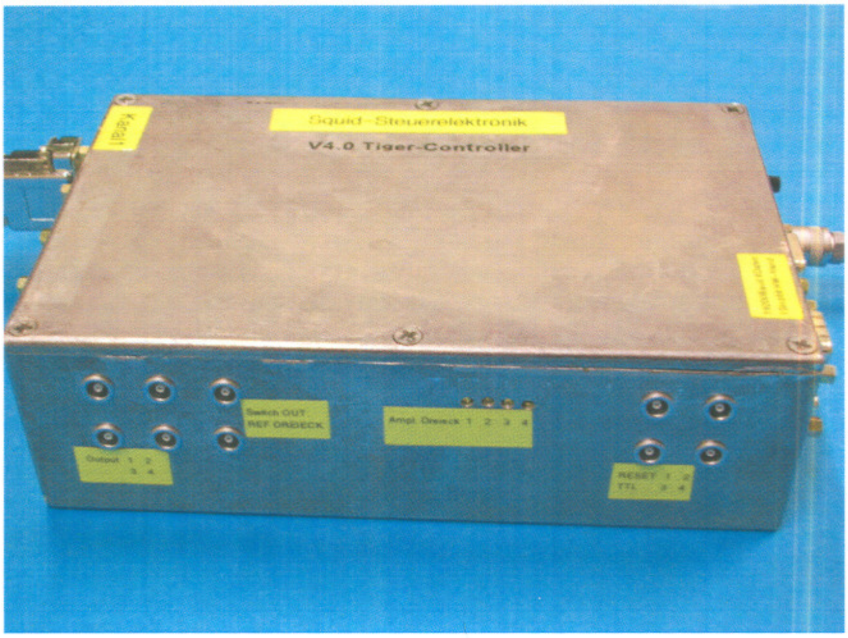


Fig. 11. JSQ Tiger Controller for SQUID Electronics V4.0.

2.4. Power Supply

Fig. 12 displays the power supply for the JSQ Tiger controller, to be plugged into a 230 V, 50 Hz outlet after completing the electronic wiring according to chapter 3.1.

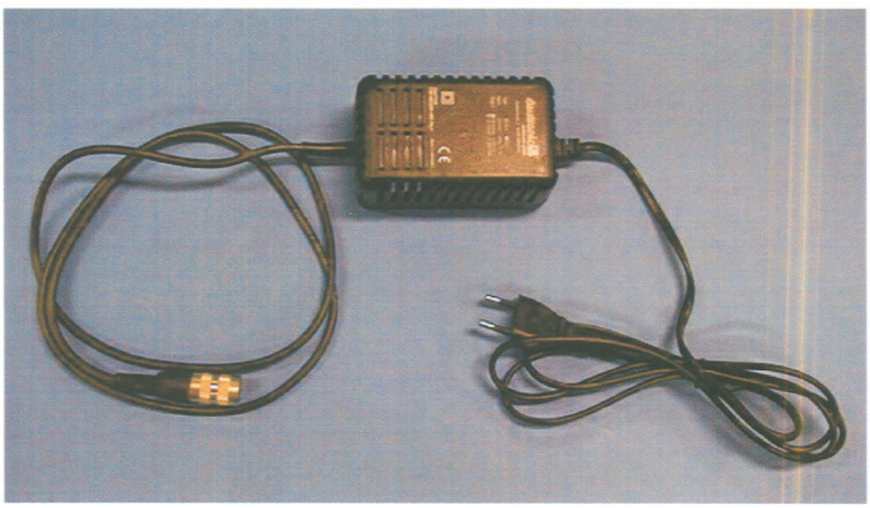


Fig. 12. Power Supply for the JSQ Tiger Controller.

3. SQUID Operation

3.1. Electrical connections

Prepare all electrical connections according to Figs. 13 and 14. The power supply must not be connected to 230 V until all other cables are in place and checked carefully!

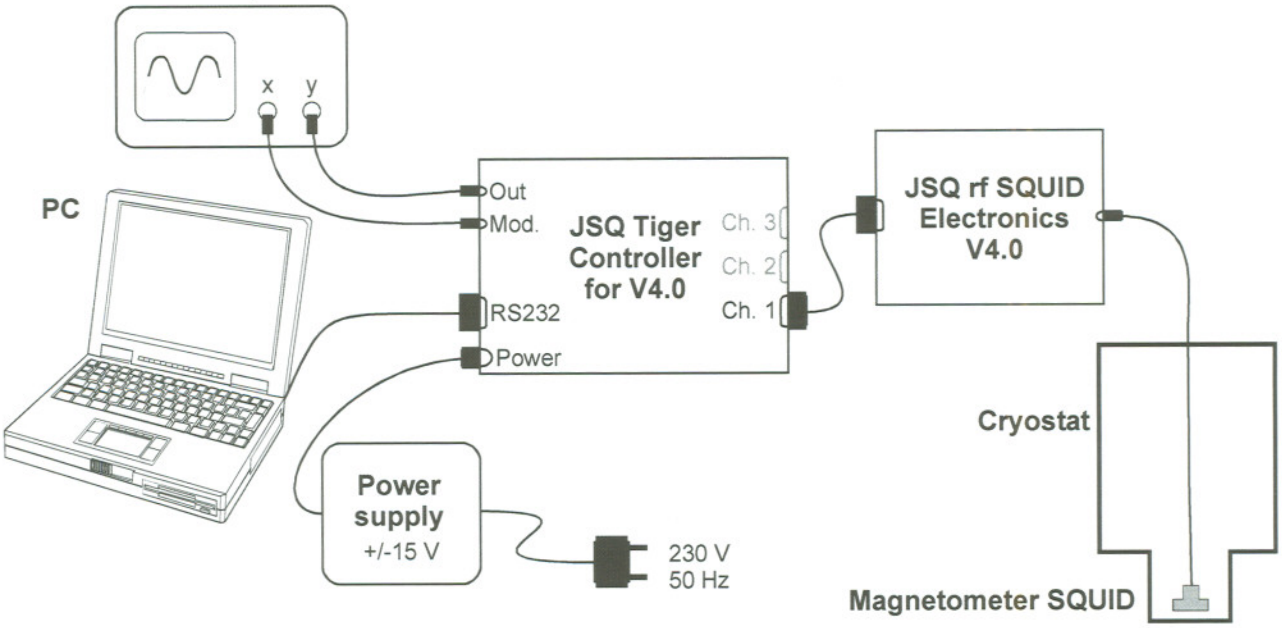


Fig. 13. Sketch of the electrical connections for SQUID operation.

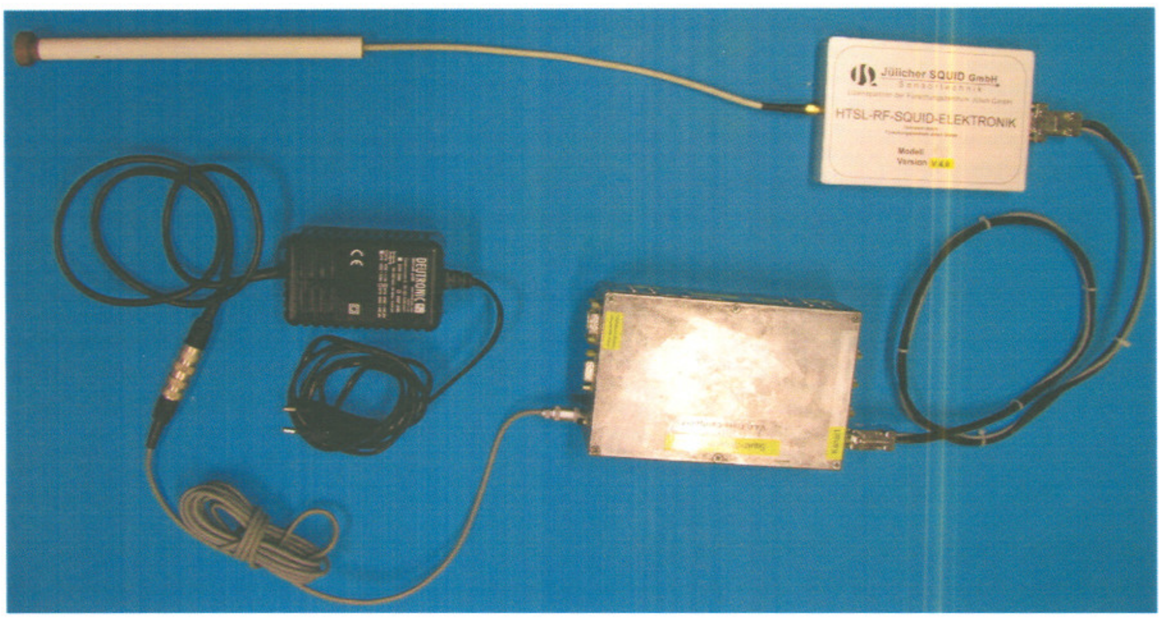


Fig. 14. Photograph of the electrical connections for SQUID operation.

The electrical connections should be made as follows:

1. For SQUID operation, the coaxial cable of the JSQ Magnetometer SQUID Sensor has to be connected to the SMA socket of the JSQ SQUID Electronics V4.0. Connect the JSQ rf SQUID Electronics V4.0 with the JSQ Tiger Controller using the serial cable with DSUB9 connectors.
2. Connect the DSUB9 (female) connector of the Data cable with the JSQ Tiger Controller. Connect the other side (male DSUB9 connector) with the serial COM port of your PC. Connect the 3-pin power connector of the JSQ power supply with the corresponding power jack of the JSQ Tiger Controller.
3. Connect the “Signal out” connector (coaxial LEMO jack) of the JSQ Tiger controller with the vertical y channel of a standard oscilloscope. Connect the “Modulation out” connector (coaxial LEMO jack) of the JSQ Tiger controller with the horizontal x channel of a standard oscilloscope (see Fig. 15). The oscilloscope should be switched to the x-y-mode for SQUID working point adjustment.
4. Make sure that all connections are made according to Fig. 13. Plug the power cable into a 230 V 50 Hz outlet.
5. Allow for at least 5 min., better 10 – 15 min. of warm-up time for the electronics (and cool-down time for the SQUID, see Chapter 3.2) before adjusting the SQUID’s working point (see Chapter 3.5). Otherwise, the working point of the SQUID will drift during the warm-up phase and readjustments of VCO and OFFset will be necessary.

Fig. 15. LEMO connectors for visualization of the SQUID test signal with an oscilloscope.

It is possible to operate up to three SQUID channels simultaneously by the Tiger controller if more JSQ rf SQUID Electronics V4.0 front ends are connected to the controller.

3.2. Cooling

The SQUID holder has to be operated immersed in liquid nitrogen. Allow for at least 5 min., better 10 – 15 min. of cooling time for the SQUID before adjusting the SQUID's working point (see Chapter 3.5).

Ensure that the cryostat and the connecting cable to the electronics are completely enclosed by a metallized rf shield which is connected to the electronics ground (chassis). If this precaution is not being observed, SQUID operation may be strongly disturbed or even prevented by rf interferences from the environment.

3.3. Installing the JSQ SQUID Sensor Software on your PC

In case of first operation or in case the PC is changed, the JSQ SQUID Sensor Software has to be installed on the PC. Insert the JSQ SQUID Sensor CD and copy the folder "JSQ-SQUID-Program" to your hard disk. It is advisable to create a shortcut on the desktop and/or in the list of programs. The software configures the serial RS232 COM port to a data transfer rate of 19200 Baud, 8 data bits, parity N, 1 stop bit, flow control Hardware. In case the Tiger controller is not connected to the serial port "COM 1", please open the file "DuoSensor.ini" with any editor and enter the port number you are using in line three, e.g. "PortNum=2" for serial port "COM 2".

3.4. Starting the JSQ SQUID Sensor Software on your PC

Execute the file "DuoSensor.exe" on your PC. Upon starting, the data of the working point of the Magnetometer SQUID is read from the non-volatile memory of the Tiger Controller via the RS232 connection. This reading is equivalent to a loading operation when pressing the "Load" key. In case of successful transfer, the values appear on the Software panel (Fig. 16) within a few seconds, and the slide controls for VCA, VCO and Offset and the settings for the Flux-locked loop parameters are set accordingly.

If this is not the case, one should check all cable connections and ensure that the power supply is connected to the JSQ SQUID Electronics.

Check the “active” check box of those electronic channels with a SQUID connected. Make sure that those channels that do not have a SQUID connected are not checked. Otherwise the “Auto Reset” function will not work properly because the electronics controller will try to lock an open loop, leading to continuous resets.

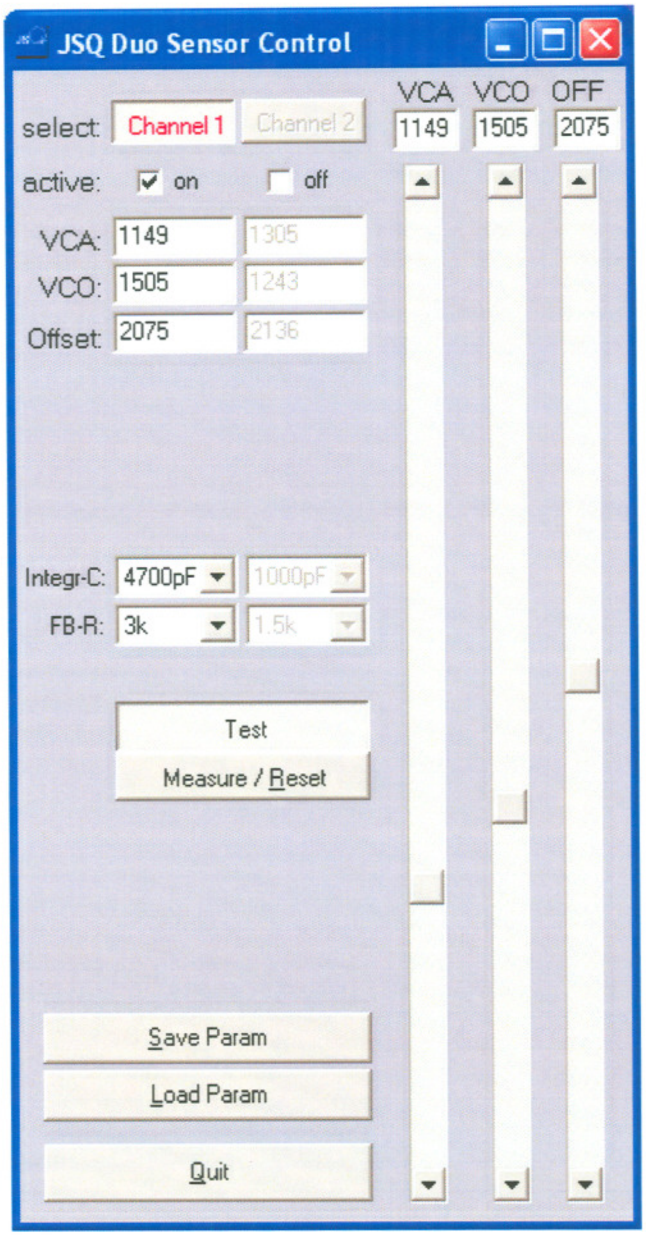


Fig. 16. Panel of the JSQ SQUID Sensor Software

3.5. Adjustment of the SQUID operating point

The controls of the JSQ SQUID Electronics V4.0 with Tiger Controller have been factory-adjusted to the operating point of the SQUID Magnetometer. Upon starting of the software

(or upon pressing the "Load" button), the working point parameters are read from the non-volatile memory of the Tiger Controller. Slight re-adjustments may become necessary in order to achieve optimum performance, or to compensate for changes of the ambient temperature of the electronics.

The VCO (voltage controlled oscillator) slide control is used to adjust the frequency of the tank circuit inductively coupled to the SQUID. The VCA (voltage controlled attenuator) slide control regulates the amplitude I_{rf} of the bias current applied to the tank circuit.

- switch electronics to „Test".
- switch the oscilloscope to x-y mode and the vertical y-channel to AC coupling.
- Adjust VCA slide control to a value of about 1000.
- Adjust VCO slide control to achieve maximum peak-to-peak signal. If several maxima are seen, then choose the one with the largest amplitude.
- Adjust VCA slide control to maximum peak-to-peak signal. (Fig. 17)

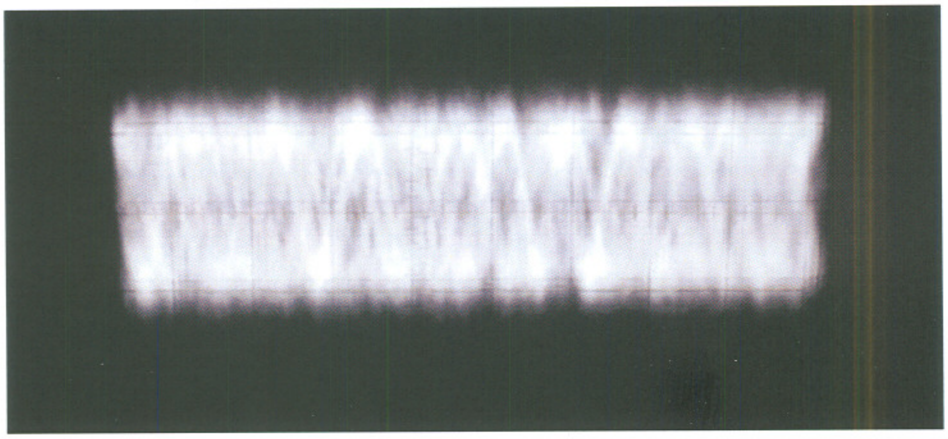


Fig. 17. Typical Oscillogram of the Magnetometer Test Signal during operation in unshielded environment. Due to the ambient 50 Hz power line noise, one does not obtain a standing picture. The triangular shaped transfer function is continuously shifted horizontally, modulated by the ambient 50 Hz disturbances.

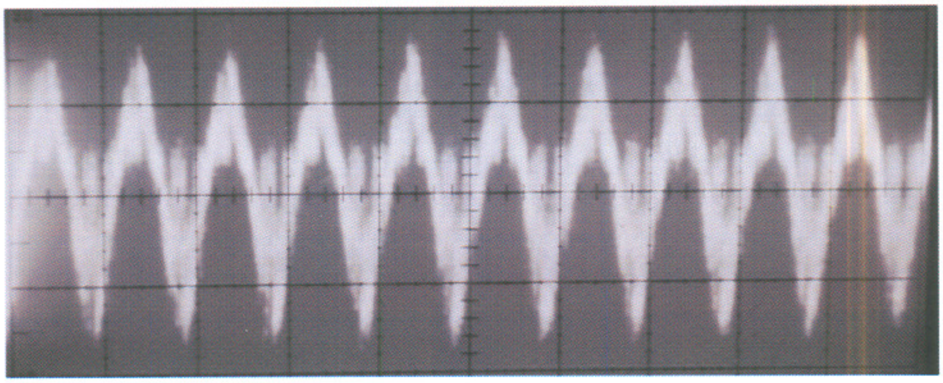


Fig. 18. Typical Oscillogram of the Test Signal inside magnetic shielding. If the ambient 50 Hz power line magnetic fields are small enough, a standing picture is obtained.

Manual adjustment of the Offset:

- Oscilloscope: Check zero position of the y channel. Switch y channel to DC coupling.
- Using the OFF slide control, the level of the SQUID signal is adjusted **exactly** symmetric to the zero level. For a subsequent stable SQUID operation, a precise offset adjustment is important.

If the offset is adjusted too low or too high, the SQUID signal may drift to the limits of this range of voltage supply. By using the OFFset controller, a fine tuning of the offset is feasible in order to adjust the SQUID signal exactly in the central region between the limits. If the signal reaches the limits, the “Reset” button should be pushed. and the OFFset slide control must be fine tuned. (In most cases, this can be avoided by adjusting the offset of the modulation signal very precisely to the central position, before switching from test signal to operation signal.)

3.6. Locking the SQUID Magnetometer for Measurement

- Switch the oscilloscope to the time diagram mode, displaying the y channel as a function of time. Set channel y to DC coupling. Set the y range to allow for voltages up to ±10 V.
- switch electronics to „Measure/Reset“.

In case one does not obtain a stable locked signal, especially in case the signal runs off and remains either at +10 V or at –10 V, one should press “Measure/Reset” again. The precise adjustment of the OFFset is of great importance for obtaining a stable locked state. It might be necessary to readjust the OFFset manually according to the procedure described in chapter 3.5.3.

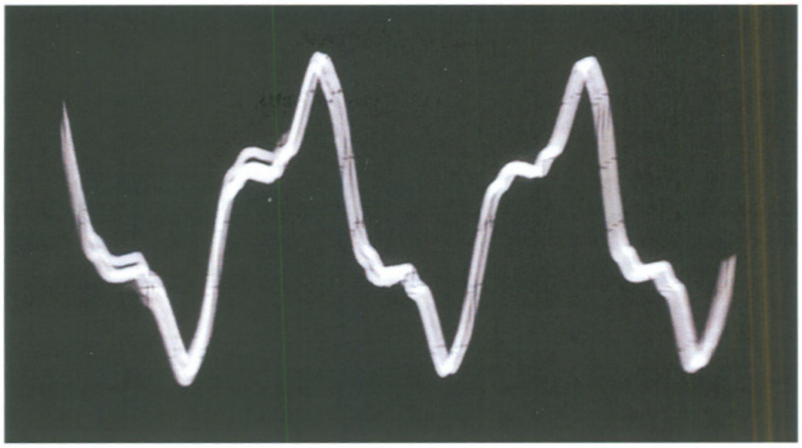


Fig. 19. Typical Oscillogram of the Magnetometer signal in the Measurement mode (flux-locked loop) during operation in unshielded environment. Usually, the ambient 50 Hz power line noise strongly dominates the observed signal in unshielded environment. Switching the oscilloscope to Line Trigger, one obtains a (quasi)-standing picture.

3.7. Adjusting the Feedback Loop Parameters

The controls for the Feedback Loop Parameters are also found on the software control panel. The value of the integrator's capacitor and of the feedback resistor may be adjusted separately for each SQUID sensor. In short, the integrator's capacitor determines the velocity of the feedback loop. A larger capacitance leads to a slower feedback velocity and thus to a smaller slew rate and bandwidth of the feedback loop. The feedback resistor determines how the feedback voltage (±10 V) translates into the feedback current and thus determines the dynamic range of the feedback loop. A smaller feedback resistor gives a smaller voltage-to-flux coefficient and thus a larger number of flux quanta that can be measured, in other words a larger dynamic range of the sensor. The Gain factor determines the internal amplification of the loop. Fig. 20 shows typical transfer functions for different values of the feedback resistor of the loop.

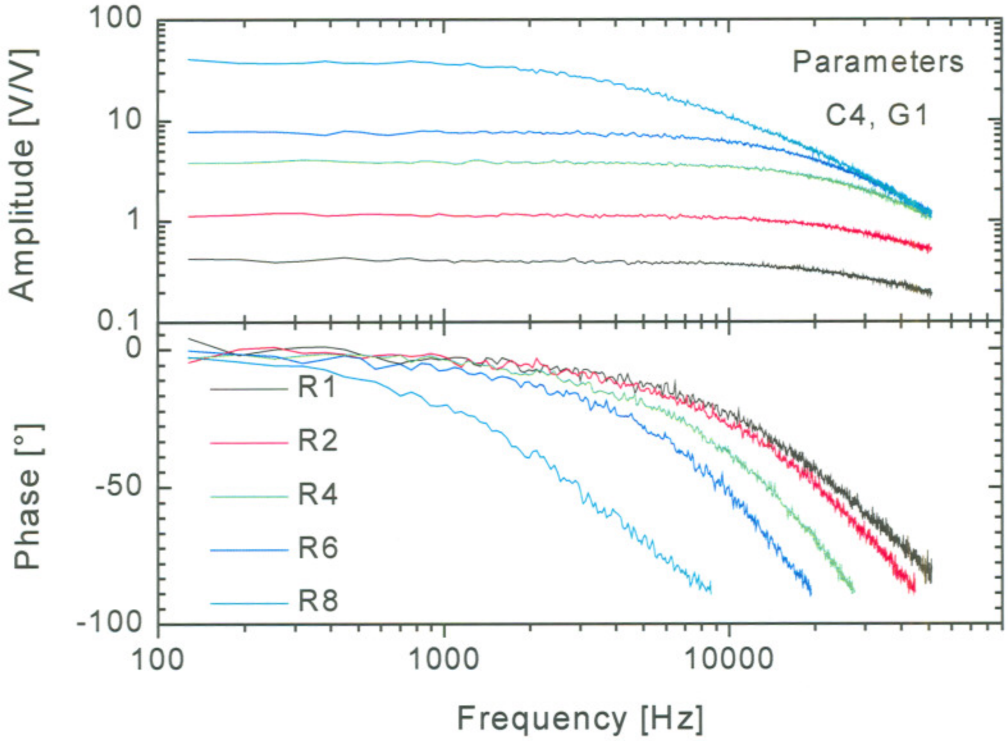


Fig. 20. Typical transfer function of a SQUID for different feedback resistor settings.

Intuitively, one would then choose a minimum capacitance and a minimum resistance in order to achieve maximum slew-rate, bandwidth and dynamic range. However, the larger the integrator's capacitance and the larger the feedback resistance, the more stable the flux-locked loop is. Therefore, the capacitance and the resistance should be chosen only so low as the application requires. One should try to achieve a compromise between performance and stability. The JSQ default factory settings for the capacitance and resistance are 4700 pF and 10 kΩ.

3.8. Saving the Parameters

Pressing the "Save" button results in saving the currently active working point and feedback loop parameters of the Magnetometer SQUID to the non-volatile memory of the Tiger Controller. The saved values will be automatically activated upon the next power-up.

3.9. Quitting and Warming up

The execution of the JSQ SQUID sensor Software is ended by simply pressing the "Quit" button or by closing the window. There is no Message Box reminding to save changes in

the settings of the SQUID parameters. Unsaved working point and feedback loop parameters are lost. However, the factory settings in conjunction with the "Fast Adjust" upon power-up and warm-up usually suffice to find the working point again.

The JSQ SQUID capsule is not sealed. Therefore, special care has to be taken when taking the SQUID out of the liquid nitrogen. The SQUID should be carefully warmed in the warm air of a blowdryer. Check with your hand that the air at the SQUID location is not too hot, otherwise the SQUID may be damaged. Condensing water on the outside of the SQUID capsule should be wiped off when the SQUID is warming up.

4. Troubleshooting during SQUID Operation

4.1. Radio Frequency Interference

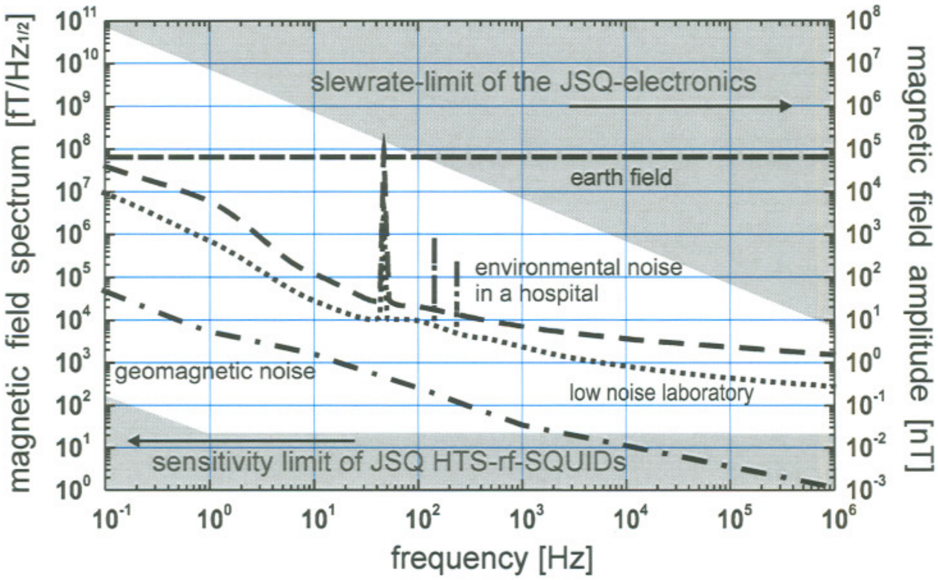
A well-known problem in case of SQUID operation in unshielded environment is the degradation of performance due to environmental Radio Frequency Interference. RF Interference results in a reduction or even suppression of the transfer function of the SQUID which can be observed in the "test" mode. JSQ suggests to operate the SQUID package in a well-grounded metal container, e.g. a cylinder of thin aluminium or lead foil, if the environmental high frequency noise is unacceptably high.

4.2. Flux trapping

Another well-known problem in case of SQUID operation in unshielded environment is flux trapping due to large external field amplitude changes. Flux trapping results in spontaneous signal jumps due to flux vortex hopping within the superconducting thin film, the so-called "shot noise". An increased 1/f noise can be observed, in extreme cases, SQUID operation can be jeopardized. Warming up the SQUID and releasing the trapped flux solves this problem.

Applications for HTS rf-SQUIDs by JSQ

With our HTS-rf-SQUIDs, it is not only possible to measure slowly varying magnetic fields, but also rapidly changing fields with extremely high sensitivity. This performance yields additional information for known applications and opens the road towards new applications.



The white area shows the principle operation regime of sensors and electronics by JSQ.

The regimes of operation of our sensors and electronics are plotted in the figure above. The figure shows that for our new sensors, even a moving operation, directly exposed to the magnetic field of the earth becomes possible. This is a true breakthrough. The new HTS-rf-SQUIDs by JSQ are especially qualified for the following tasks:

Non-Destructive Evaluation (NDE) of materials (i.e. detection of flaws and cracks in airplane parts or checking steel reinforcement buried inside concrete structures). These applications use frequencies between 1 Hz and 1 MHz. Mobile operation in the earth magnetic field is essential and therefore gradiometry is the best choice for stable operation. Sensitivity is not the critical issue, but stability and slew rate are.

Geological surveying needs a very high bandwidth from 0.001 Hz up to 10^5 Hz and a high sensitivity, while directly exposed to the full earth magnetic field. The problem of moving within the earth field is less important, because normally the sensors are not moving during operation. Instead they are securely positioned and fixed in a small hole, dug into the ground.

Biomagnetic diagnostics, especially of the heart functions and the brain need the highest sensitivity, but use a small frequency range (0.01 Hz up to 300 Hz). With a sensitivity limit below 30 $fT/\sqrt{Hz}$, our new HTS-rf-SQUIDs are exceptionally well suited for cardiac measurements. Even Fetal Magnetocardiography has been shown feasible with our SQUIDs.

Products

SQUIDs by JSQ are very easy to handle, radiofrequency (rf) driven sensors for extremely low magnetic fields (present limit: 20 $fT/\sqrt{Hz}$) and magnetic field gradients (< 1 $pT/cm\sqrt{Hz}$). These sensors are very fast. Therefore, a realtime measurement of rapidly changing magnetic fields (up to 1 MHz) becomes possible. The sensor material is superconducting YBaCuO, grown in thin films by a patented process. During operation, the sensors have to be cooled by liquid nitrogen (or cryocoolers). Due to the relatively high operation temperature (-198°C) compared to Low Temperature Superconductors (LTS), this material is called a High Temperature Superconductor (HTS). The sensors are fabricated by a modern lithographical process. Their unique design is protected by patents.

JSQ offers these sensors complete with room temperature drive and read out electronics. The JSQ electronic control units run at 600 to 1000 MHz. Adjustment of the SQUID's working points is conducted by a microcontroller integrated with the electronics. The HTS rf-SQUIDs by JSQ are reliable, with fully guaranteed sensitivity and have demonstrated very stable performance.

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Sensortechnik

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Please visit our website at: ***http://www.jsquid.com***

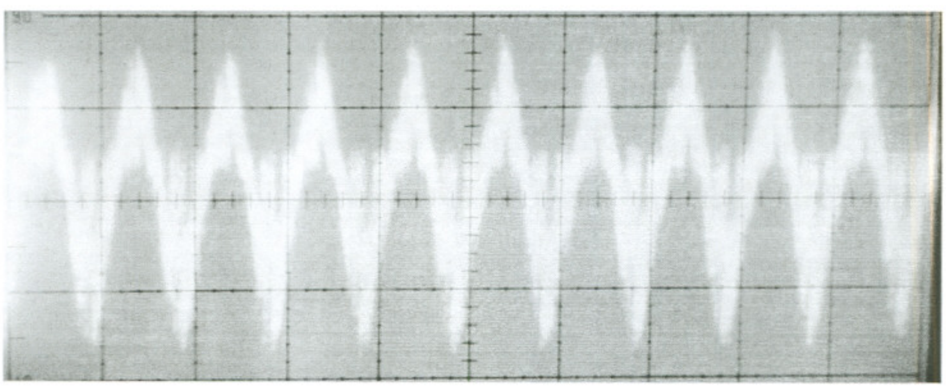
Jülicher SQUID GmbH
Sensortechnik

Magnetometer Data Sheet

Date:	**19.09.07**	
SQUID:	**Standard**	
Washer:	**∅ 3.5**	mm
Loop:	**100 × 100**	μm^2
Tank circuit	**Lumped element**	
Resonance frequency:	**731**	MHz
Coupling (rf absorption):	**-26**	dB
Quality factor:	**340**	
SQUID signal amplitude:	**0.6**	V_{pp}
Transfer coefficient at R_1 = 10 kΩ	**0.195**	V/Φ_0
Calibration:	**9.3**	nT/Φ_0

Feedback-Resistor	R1	R2	R3	R4	R5	R6	R7	R8
R [kΩ]	1	3	6	10	15	20	50	100
Transfer coefficient [mV/Φ_0]	21	60	120	195	290	380	950	1900

Integr-C	C1	C2	C3	C4	C5	C6	C7
C [nF]	0.33	1	2.2	4.7	10	22	100



Open loop SQUID signal in shielding

Steuerbefehle für SQUID-Elektronik über die RS232-Schnittstelle

Befehl	Beschreibung		
A*1* :*value* ;	Setze Attenuation	value = 0..4095	Kanal n = 1
F*1* :*value* ;	Setze Frequenz		
O*n* :*value* ;	Setze Offset		
R*1* :*k;*	Setze Feedback Widerstand	k = 1..8	
C*1* :*l;*	Setze Integrator C	l = 1..7	
ZA*1* :*i;*	Setze Kanal-Freigabe	i = 0 = off	i = 1 = on
ZAR*1:i;*	Setze Autoreset		
Mon;	Setze Modulation ON (alle Kanäle)		
Moff;	Setze Modulation OFF (alle Kanäle)		
S;	Save Data		
L;	Load Data		
WARMUP;	Restart Program		
BD:k;	Setze Baudrate		
Eon;	Setze ECHO ON		
Eoff;	Setze ECHO OFF		
Z*m* ;	Setze Messmodus , Reset	Kanal m = 1 0 = ALL	
T*m;*	Setze Testmodus		
K*m;*	Setze Switch Output	0 = OFF	
F*m;*	Suche Resonanz		
A*m* ;	Adjust Resonanz (Attenuation, Frequency, Offset)		
FA*m* ;	Fast Adjust Resonanz		
GA;	Get Attenuation (Kanal 1..4)		
GF;	Get Frequenz (Kanal 1..4)		
GFF;	Get Frequenz/100 (Kanal 1..4)		
GO;	Get Offset (Kanal 1..4)		
GR;	Get Widerstand (Kanal 1..4)		
GC;	Get Integrator C (Kanal 1..4)		
GAR;	Get Freigabe (Kanal 1..4)		
GZA;	Get Autoreset (Kanal 1..4)		
>	Normaler Prompt - Erscheint nach Ausführung eines Befehls		
?>	Fehler-Prompt - Erscheint nach fehlerhaften Eingabe		

Zuordnung der Baudrateneinstellungen

Standard beim Einschalten : 19200 Baud, 8 Datenbits, 1 Stopbit, HW-Handshake

BD:1;	300 Baud
BD:2;	1200 Baud
BD:3;	2400 Baud
BD:4;	4800 Baud
BD:5;	9600 Baud
BD:6;	19200 Baud
BD:7;	38400 Baud
BD:8;	76800 Baud