SQUIDs and Their Applications

Michael Mück,ez SQUID Mess- und Analysegeraete

1. Introduction
2. The dc SQUID
3. 'Traditional' Applications of SQUIDs (Medical Diagnostics, Nondestructive Testing of Material)
4. Using a dc SQUID as a high-frequency amplifier
5. A SQUID amplifier with microstrip input coupling (MSA)
6. Gain and Noise Temperature of Microstrip SQUID Amplifiers
7. Some Recent Applications of MSAs

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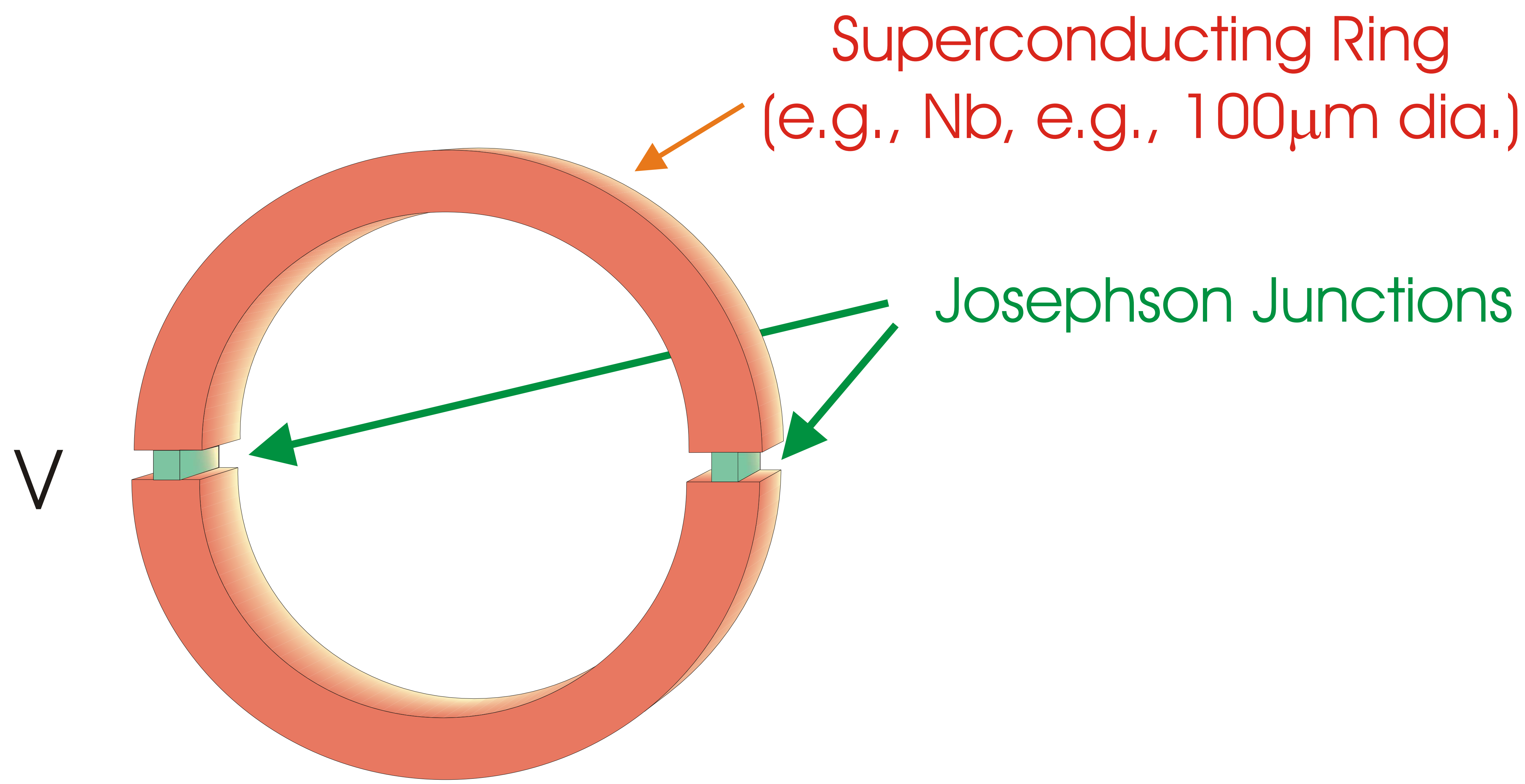
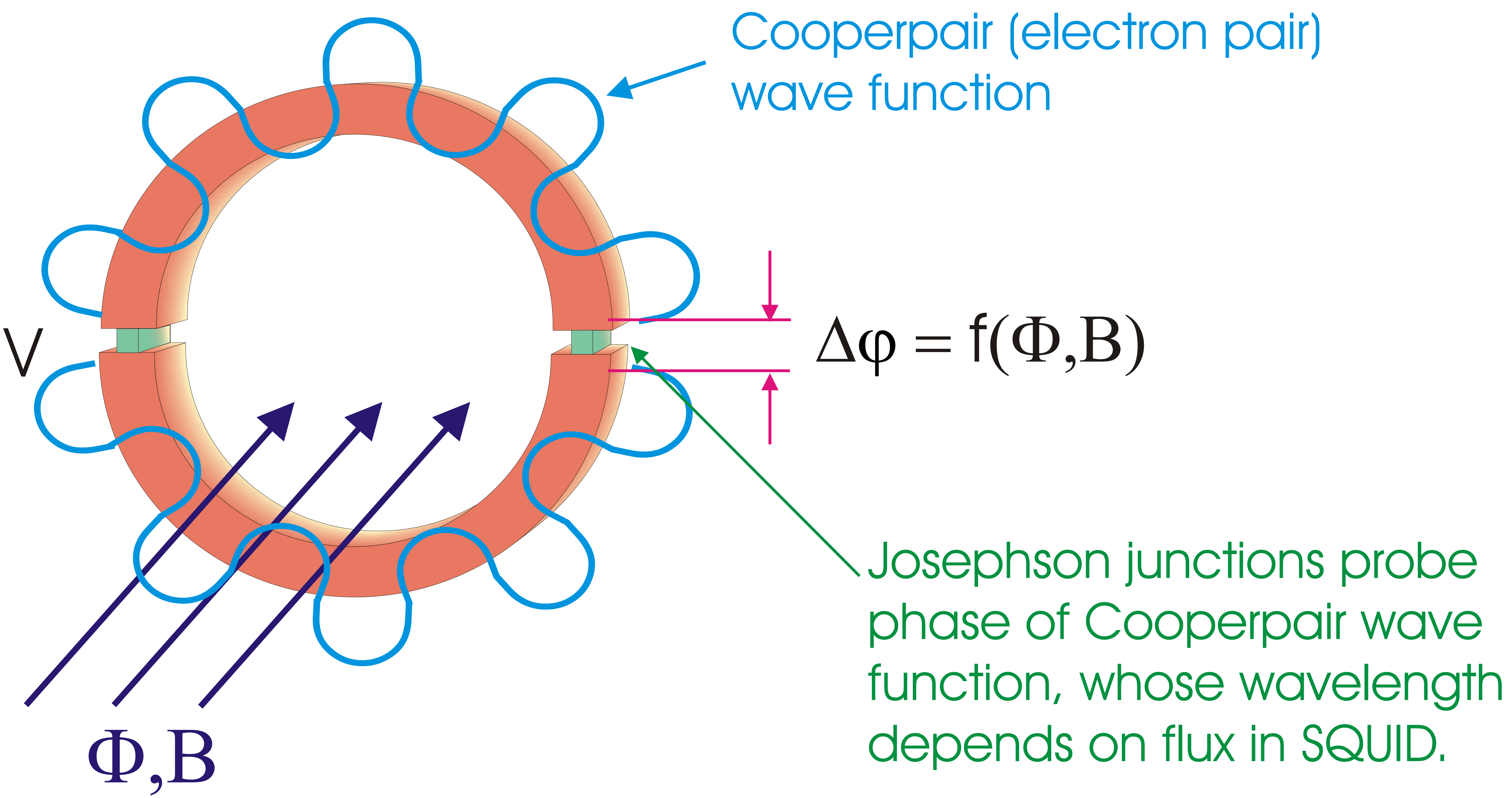
This talk is dedicated to
John Clarke
on the occasion of his
82nd birthday.

The DC Superconducting Quantum Interference Device(dc SQUID), a sensitive detector for magnetic fields

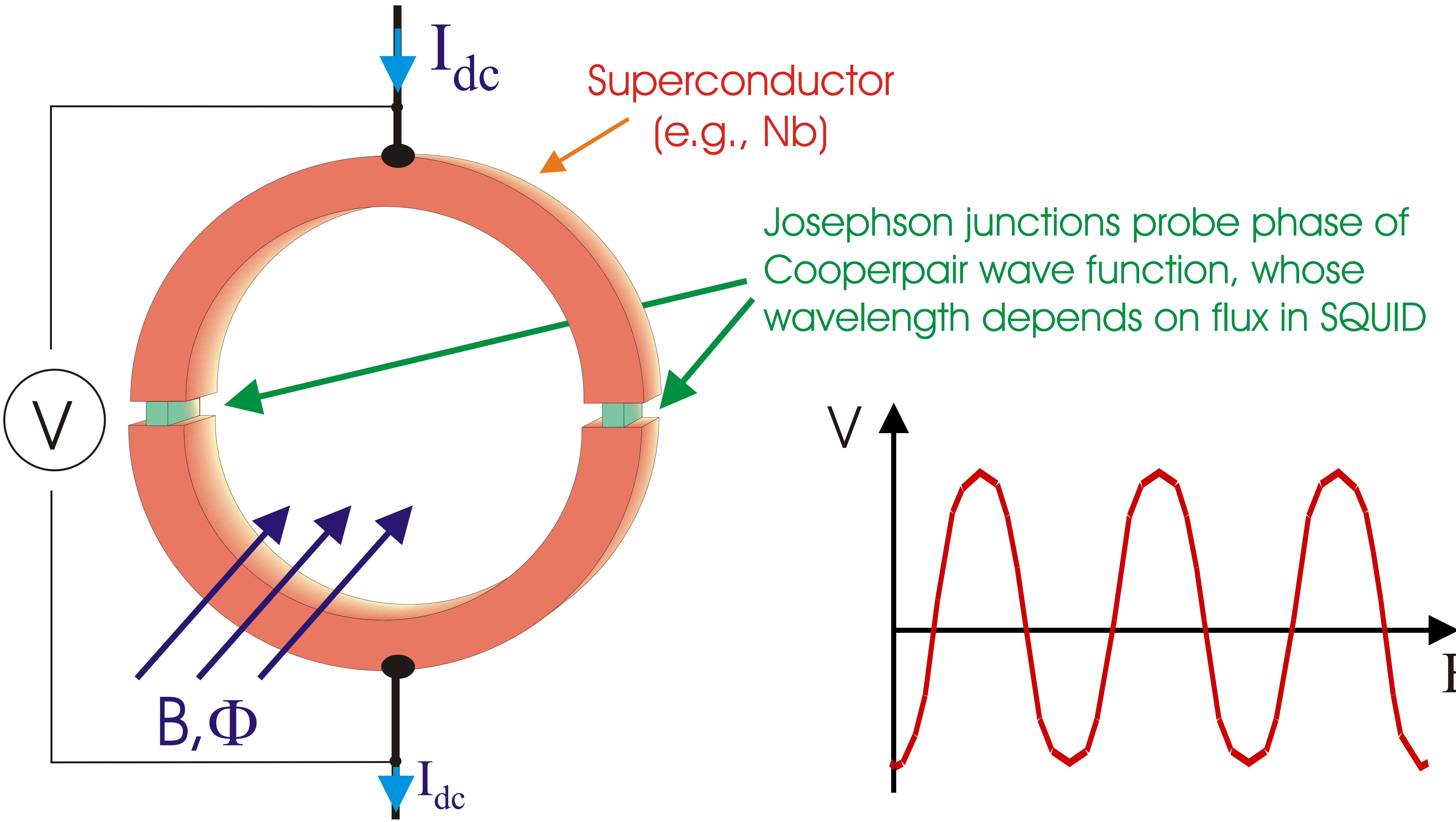


The dc SQUID

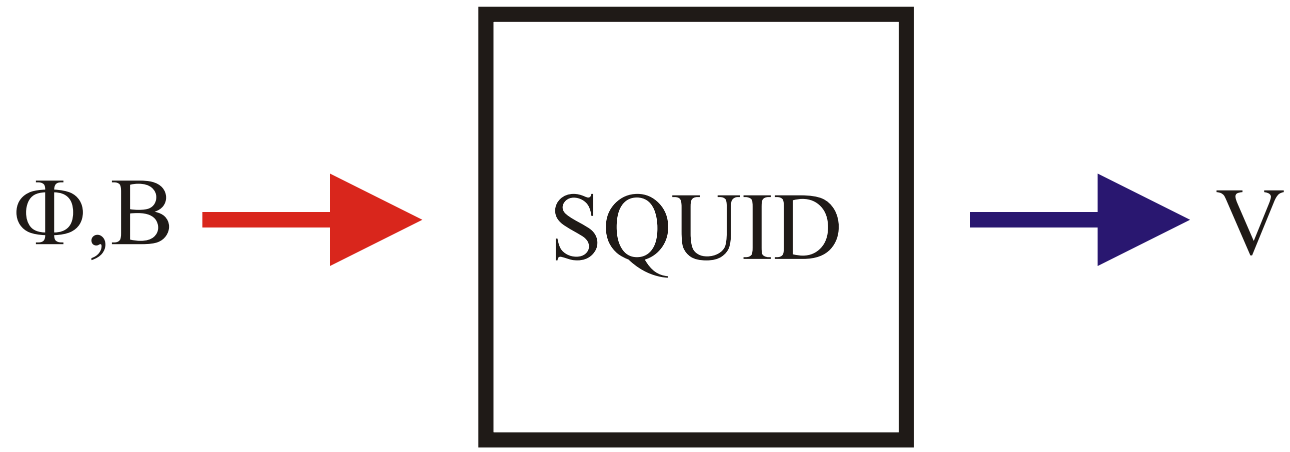


Cooperpair (electron pair)
wave function
V
$\Delta\varphi = f(\Phi, B)$
Josephson junctions probe
phase of Cooperpair wave
function, whose wavelength
depends on flux in SQUID.
Φ,B

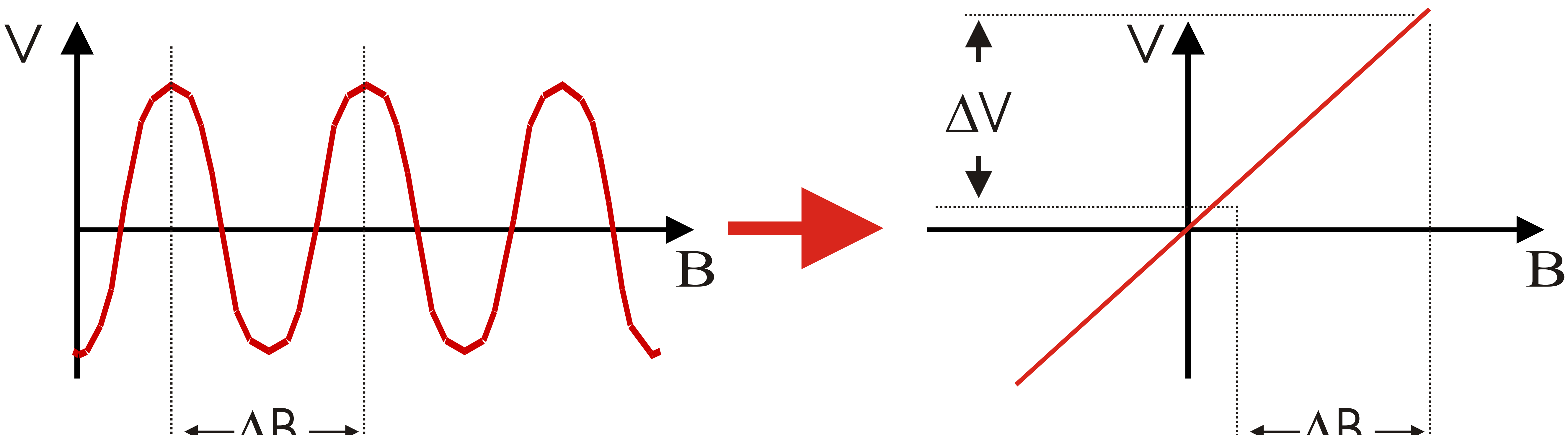
The dc SQUID



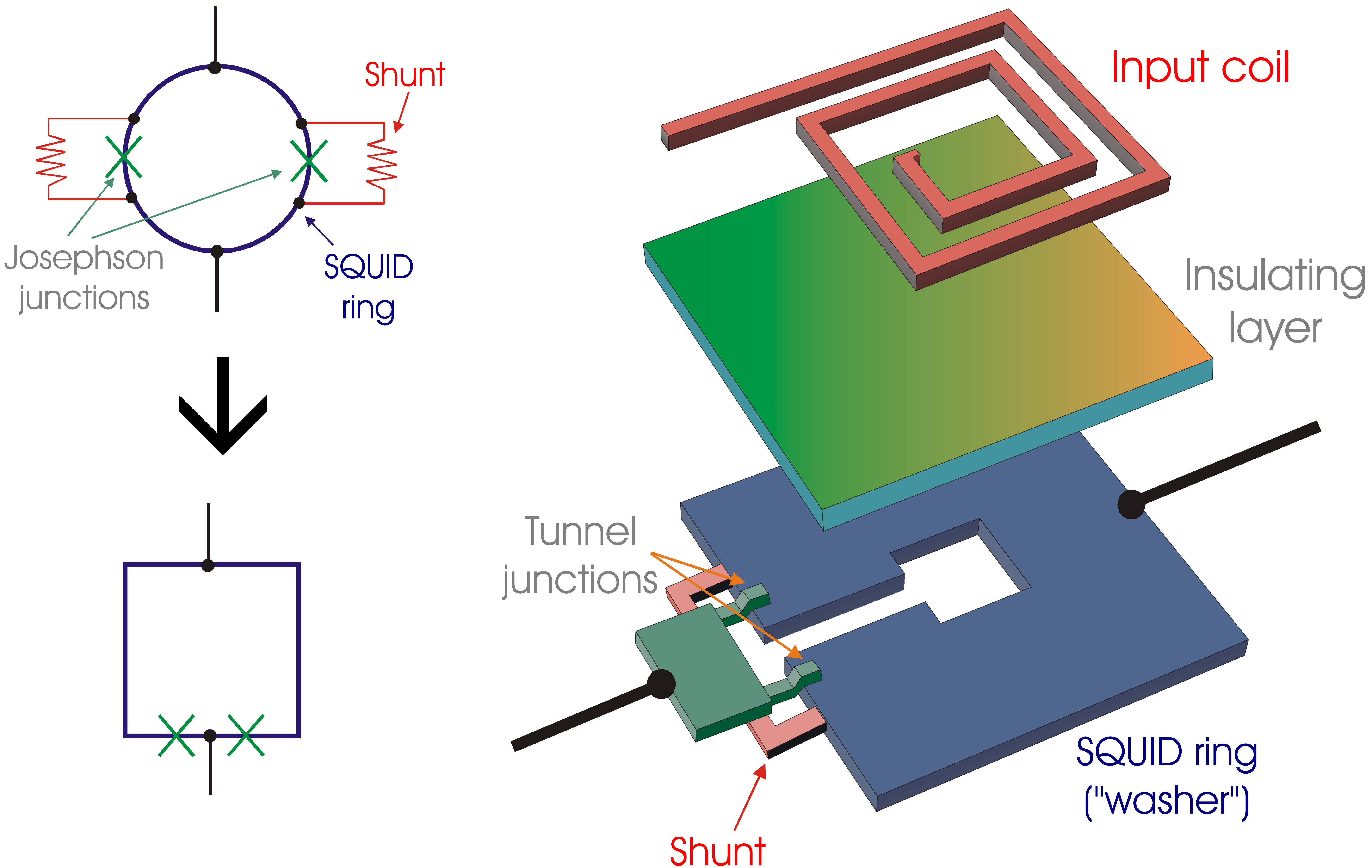
Typical values: $I_c \sim 10\ \mu A$, $\Delta I_c \sim 5\ \mu A$, $\Delta V \sim 50\ \mu V_{pp}$,
$A \sim 100 \times 100\ \mu m^2$, $L \sim 150$ pH



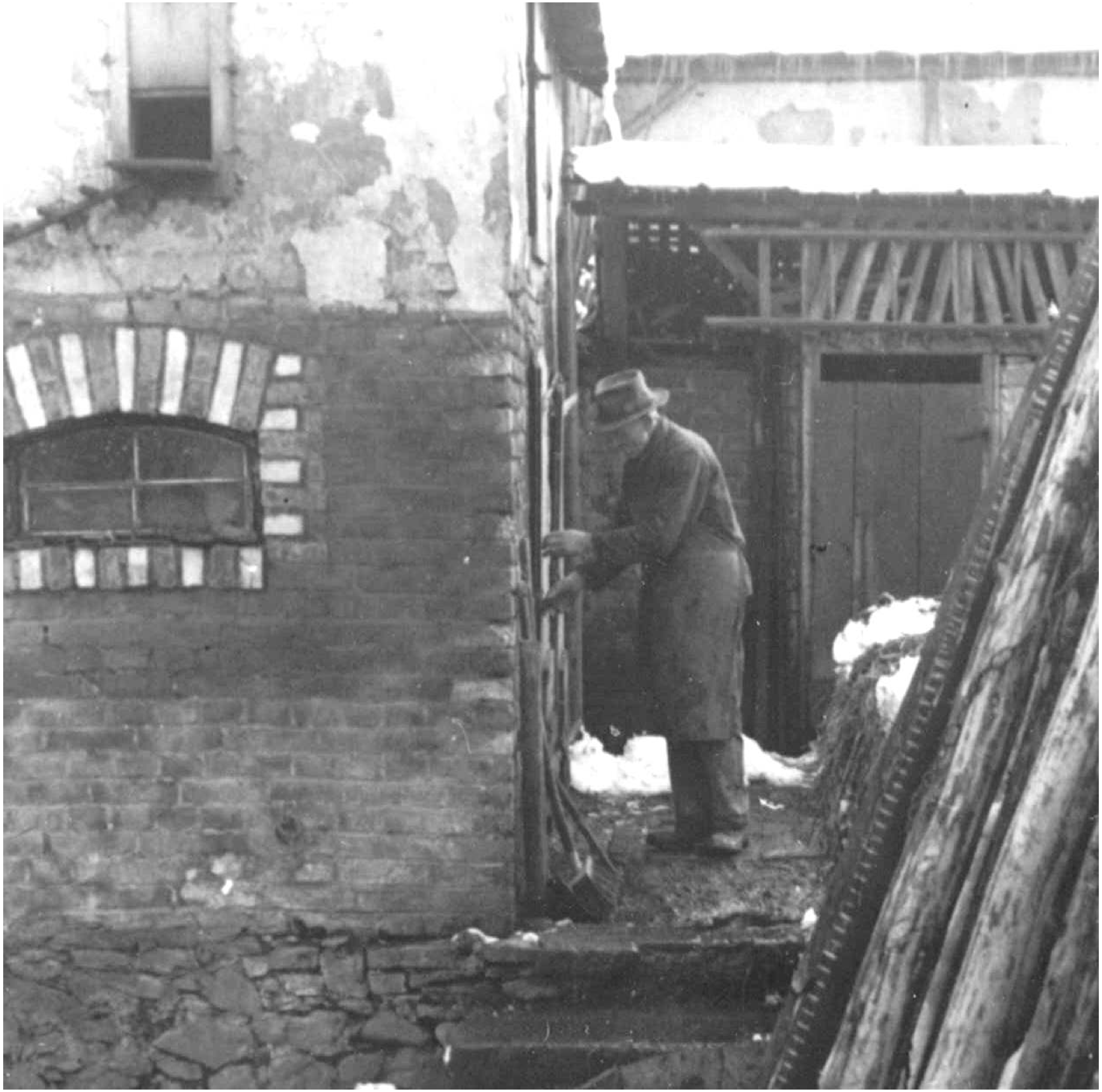
Due to periodic nature of Cooperpair wave function, dependence of voltage on magnetic flux (field) is periodic, too.



Using a special kind of readout electronics employing negative feedback (a so-called flux-locked loop), the periodic transfer function of the SQUID can be linearized, so that the output voltage of this electronics is proportional to the flux in the SQUID

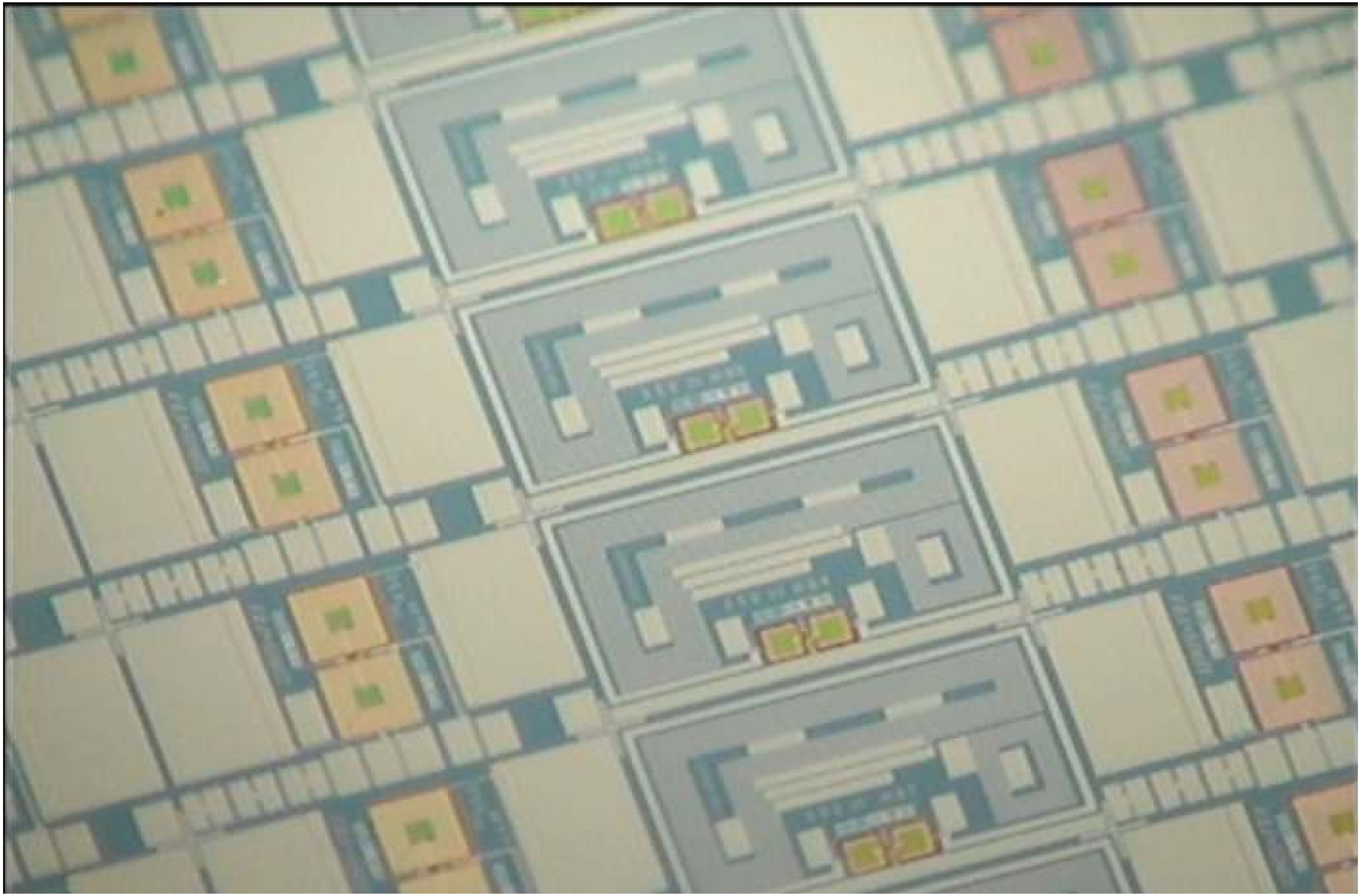


Shunt
Josephson
junctions
SQUID
ring
Input coil
Insulating
layer
Tunnel
junctions
SQUID ring
("washer")
Shunt



Heinrich Georg, about 1930

Part of a Silicon Wafer with SQUIDs



5 mm

ez SQUID

Typical sensitivity of commercially available magnetic field sensors

- Induction (Faraday) coil : 500 pT (1 cm dia., 10 kHz)
- GMR (magnetoresistive) Sensor : 30 pT
- Fluxgate : 10 pT
- Cesium magnetometer : 5 pT
- SQUID, 4K : 1 fT

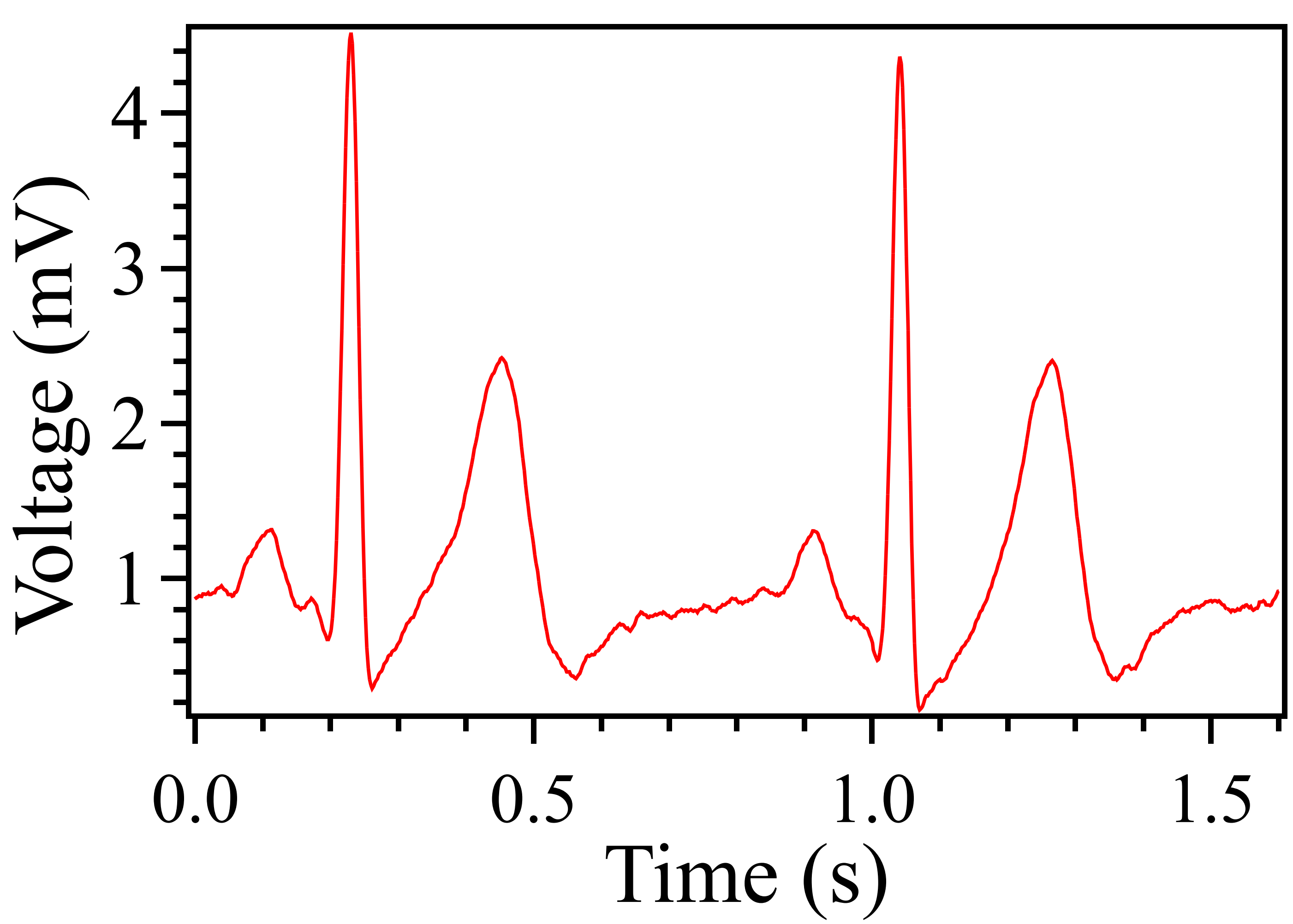
(values for 1 Hz band width)

Medical Diagnostics with SQUIDs

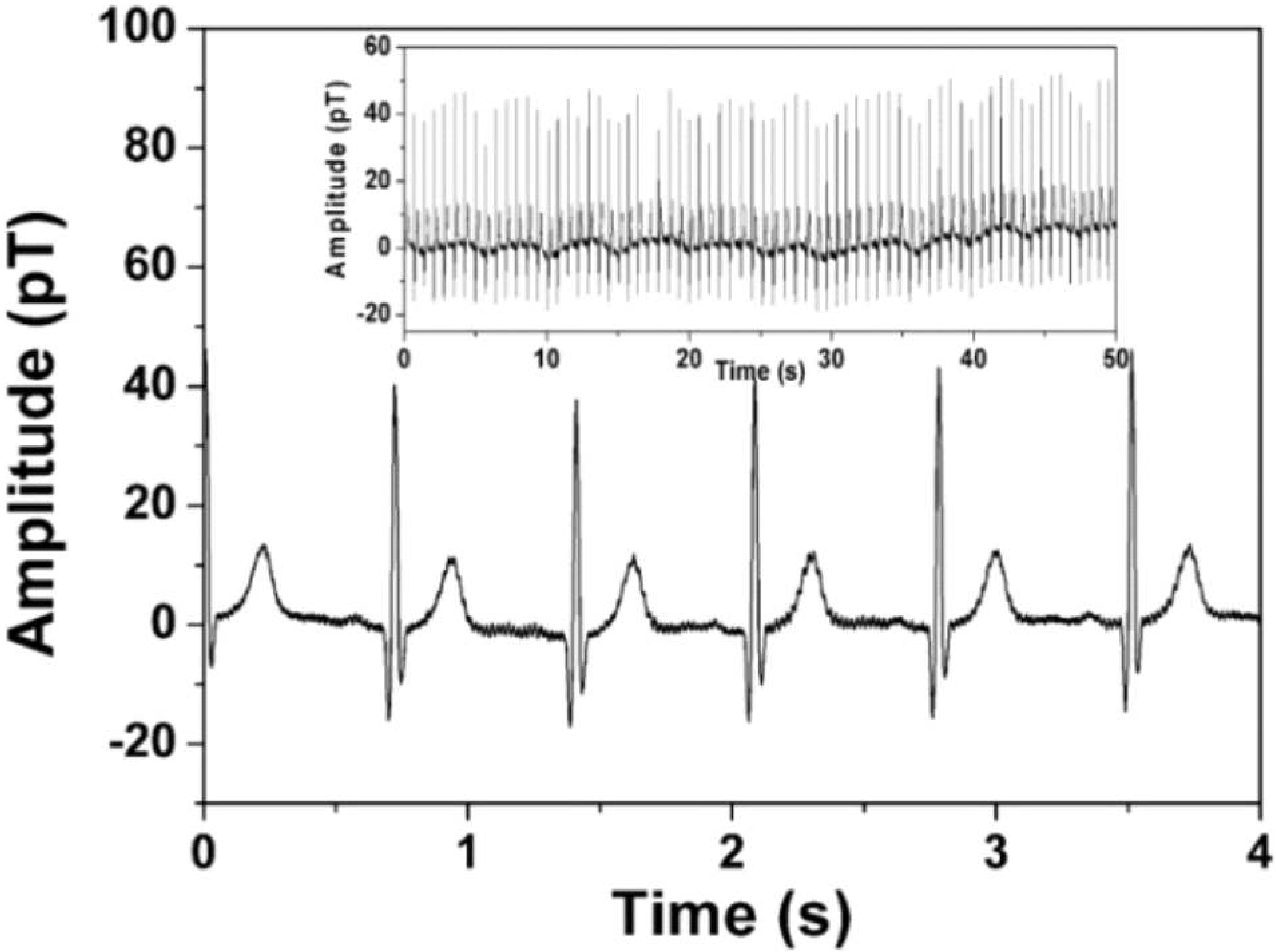
Cell and muscle activity in the human body arises from ionic currents. These currents can be detected outside of the human body by measuring the voltage drop across parts of the body (e.g., when measuring the electrocardiogram and electroencephalogram). The voltages in question are relatively large (millivolts) and can thus be detected by relatively simple electronics.

Electric currents in the body also can be detected by measuring the magnetic field they produce outside of the body. However, these fields are only small. The (ionic) currents flowing in the human heart $I_{ion} \sim 10\ \mu A$. *Thus* $B \sim (\mu_0 \times 10 \mu A) / 0.2 m \sim 30\ pT$.

My ECG

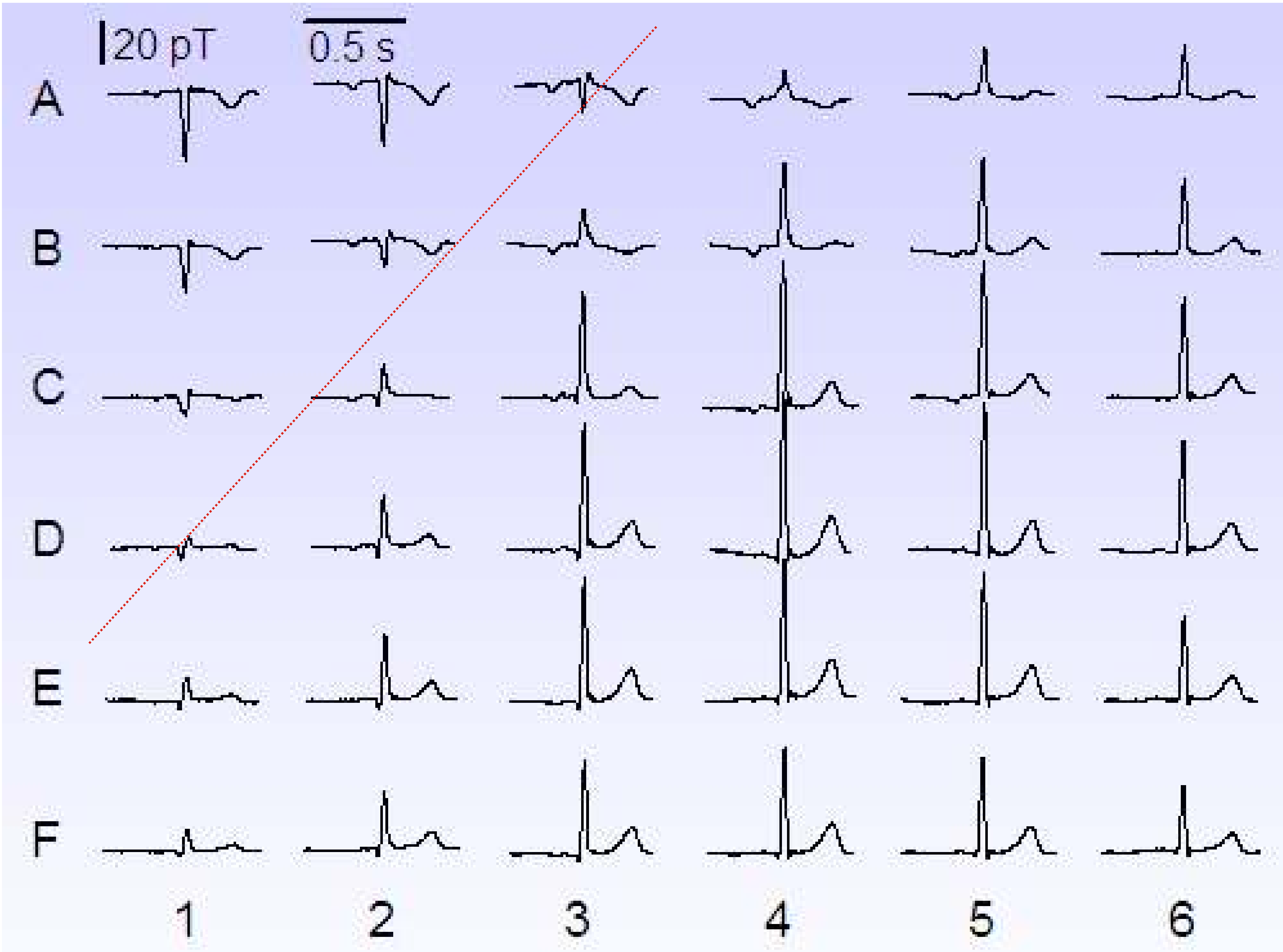


Real Time Magnetocardiogram



Courtesy Dr. X.Y.Kong, SIMIT, Shanghai

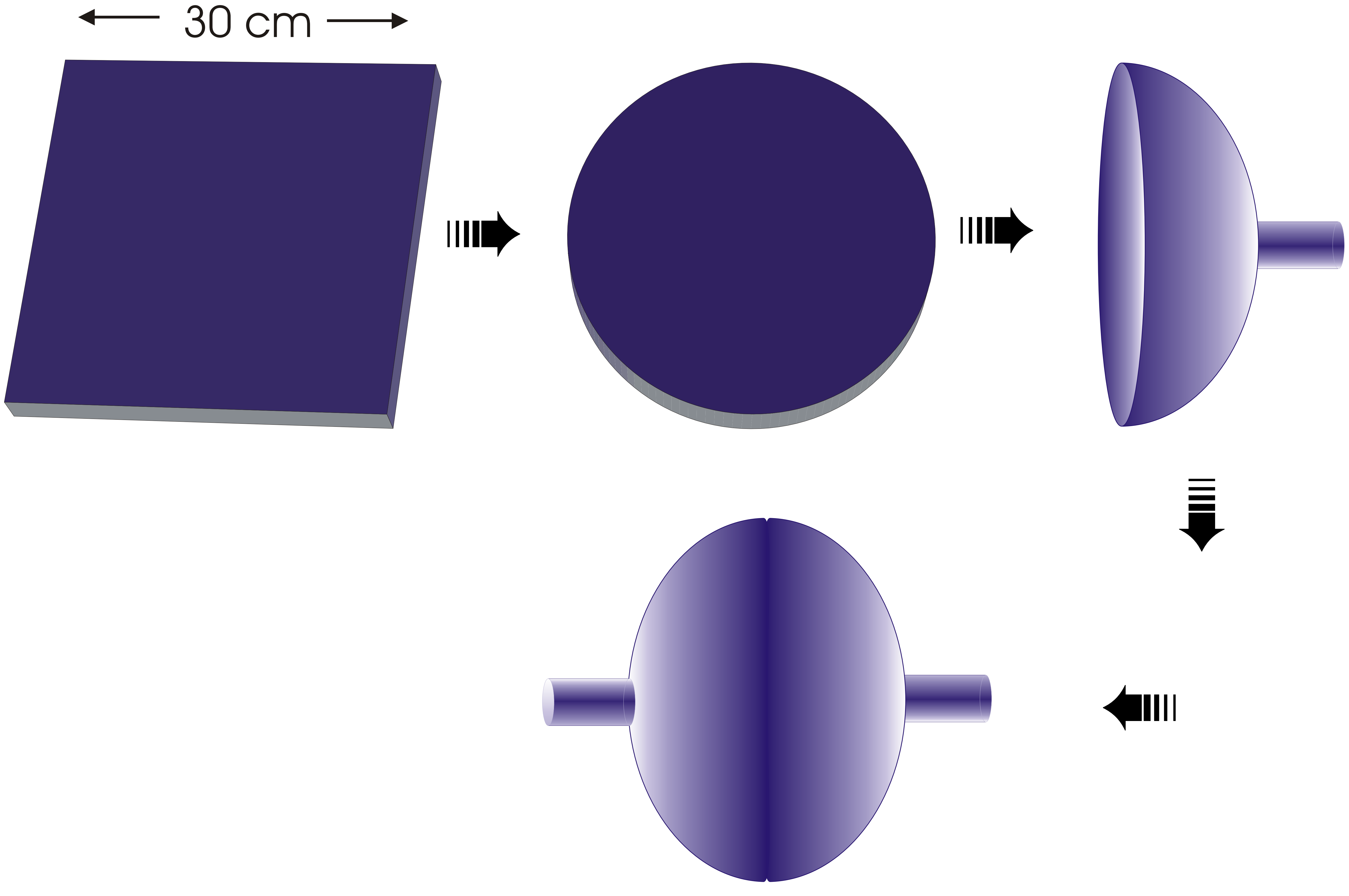
Spatially-Resolved Magnetocardiogram



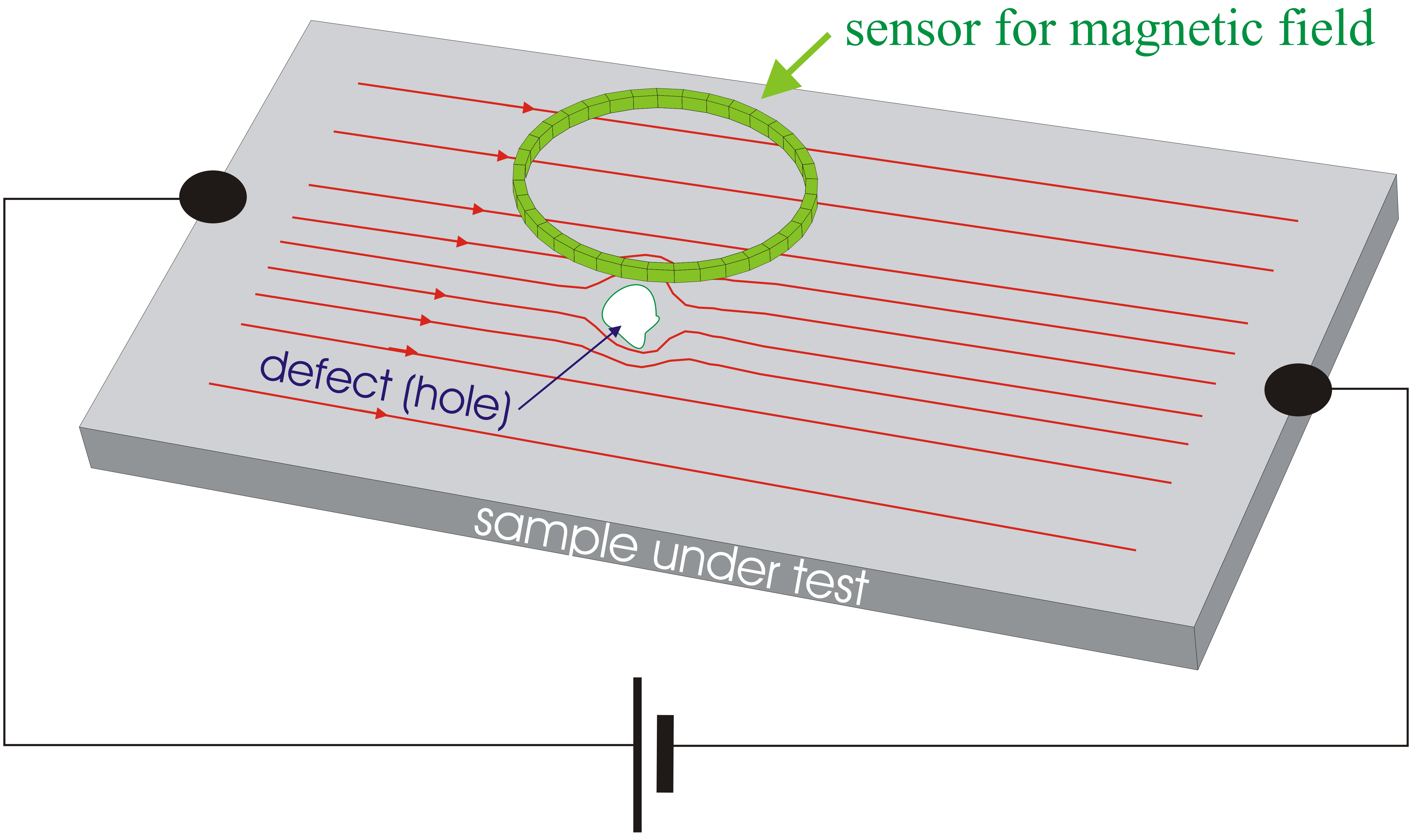
Courtesy of Yi Zhang, FZ Jülich

RF Cavity Used in Particle Accelerators

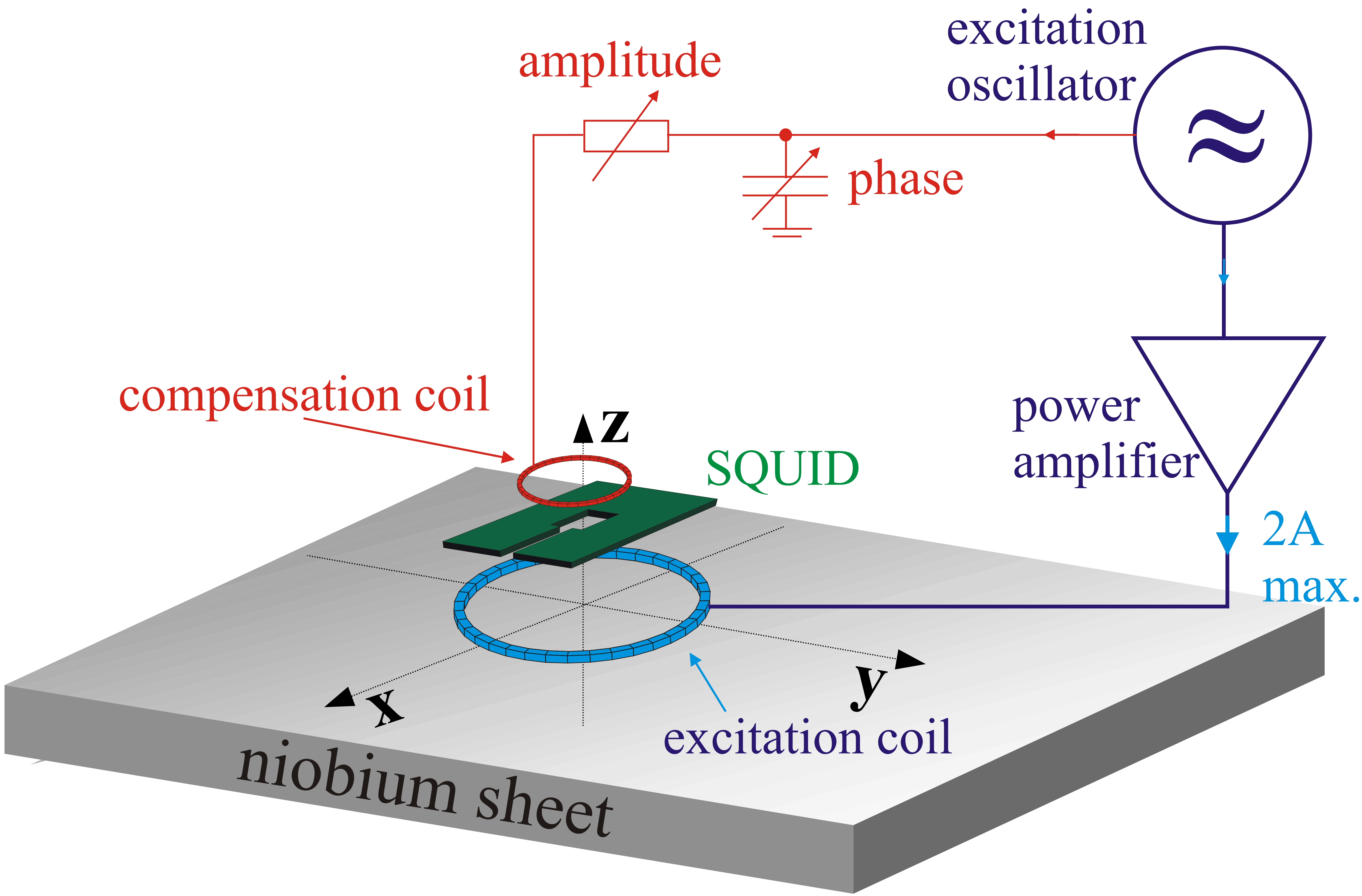
Producing a rf cavity from a niobium sheet

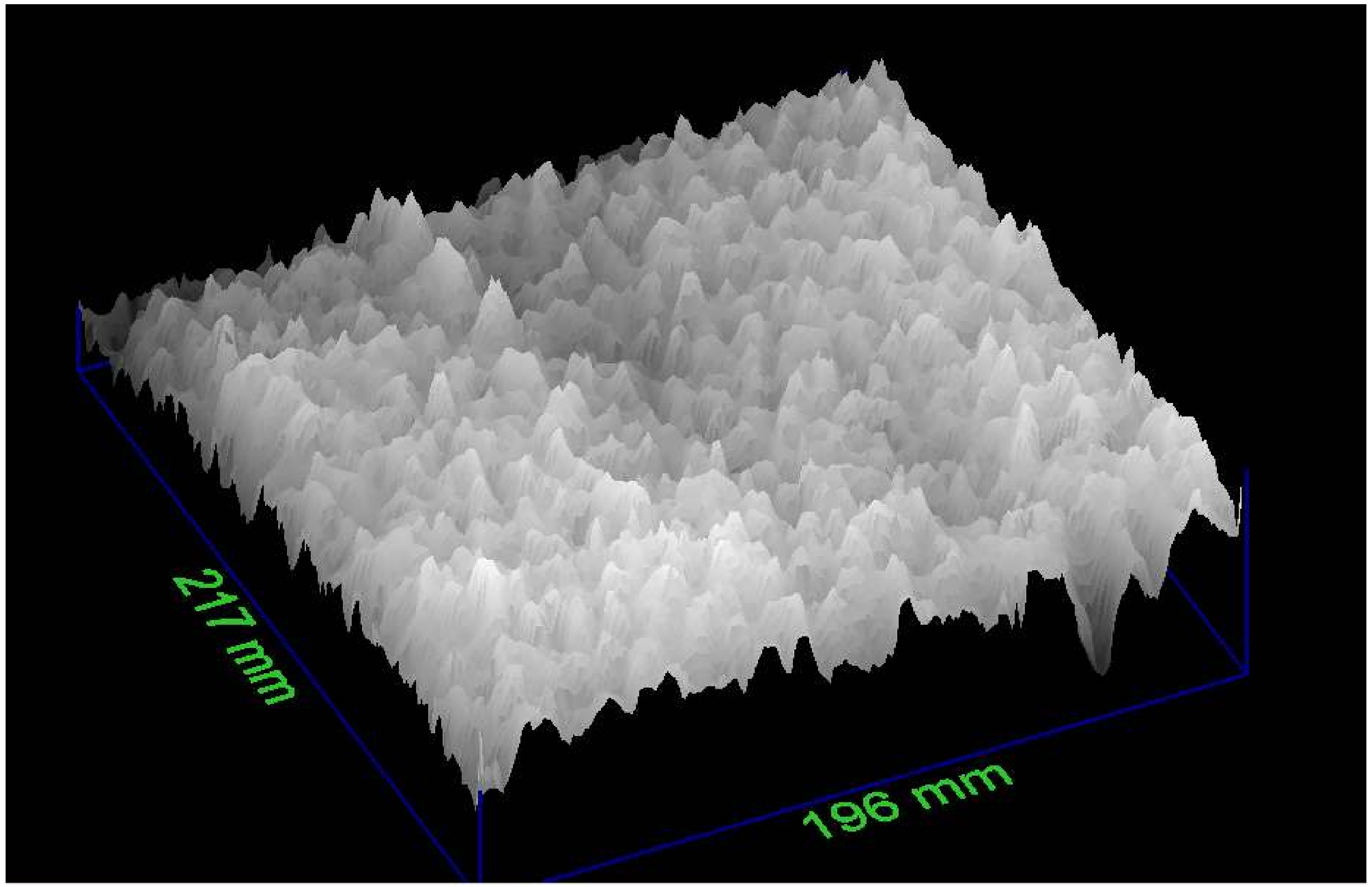


Nondestructive Testing of Conducting Sheets Based on Detecting Local Variations in Current Flow



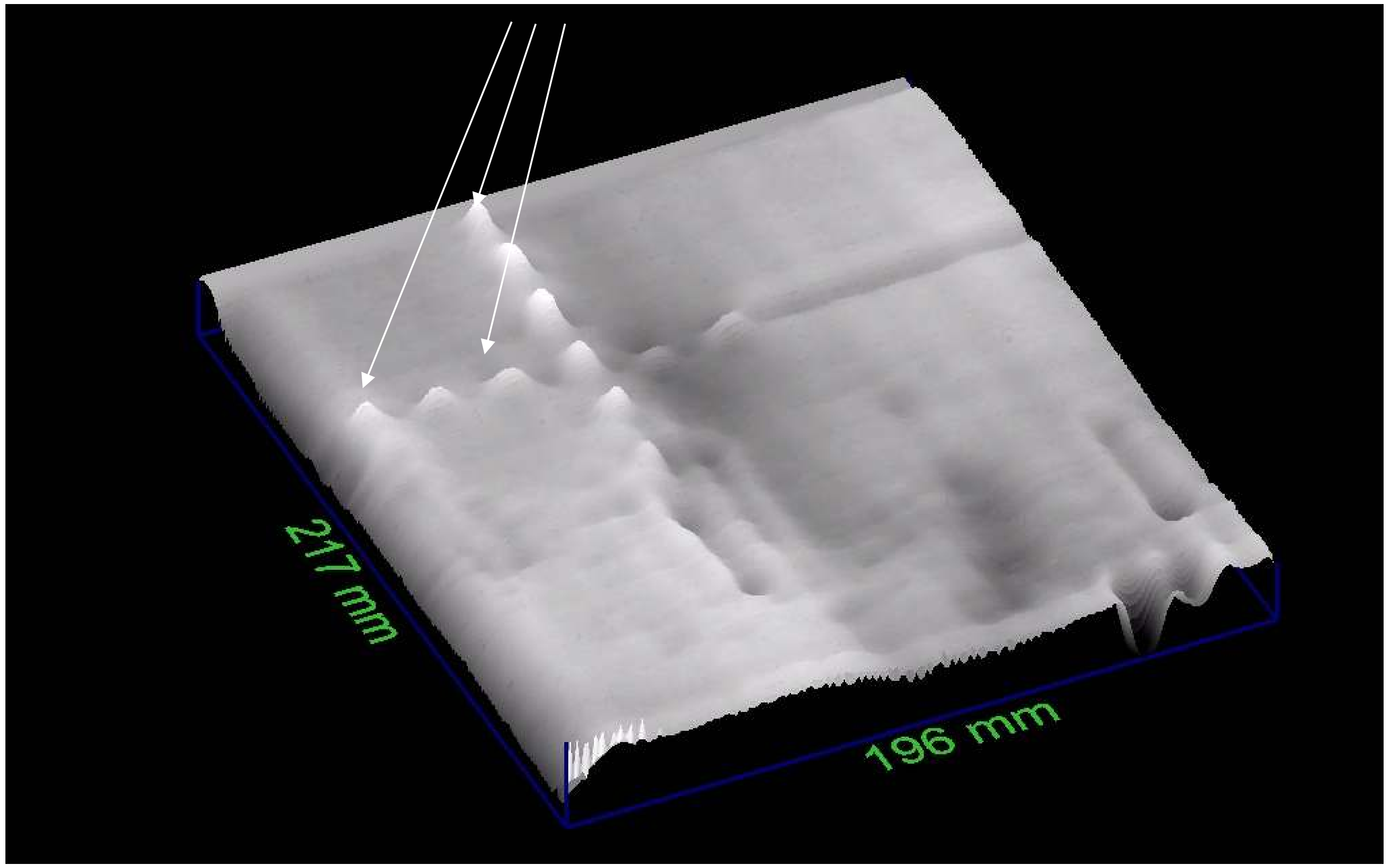
Eddy Current Testing of Niobium Sheets with a SQUID





Conventional Eddy-Current Tester (Measurement Time ~10h)

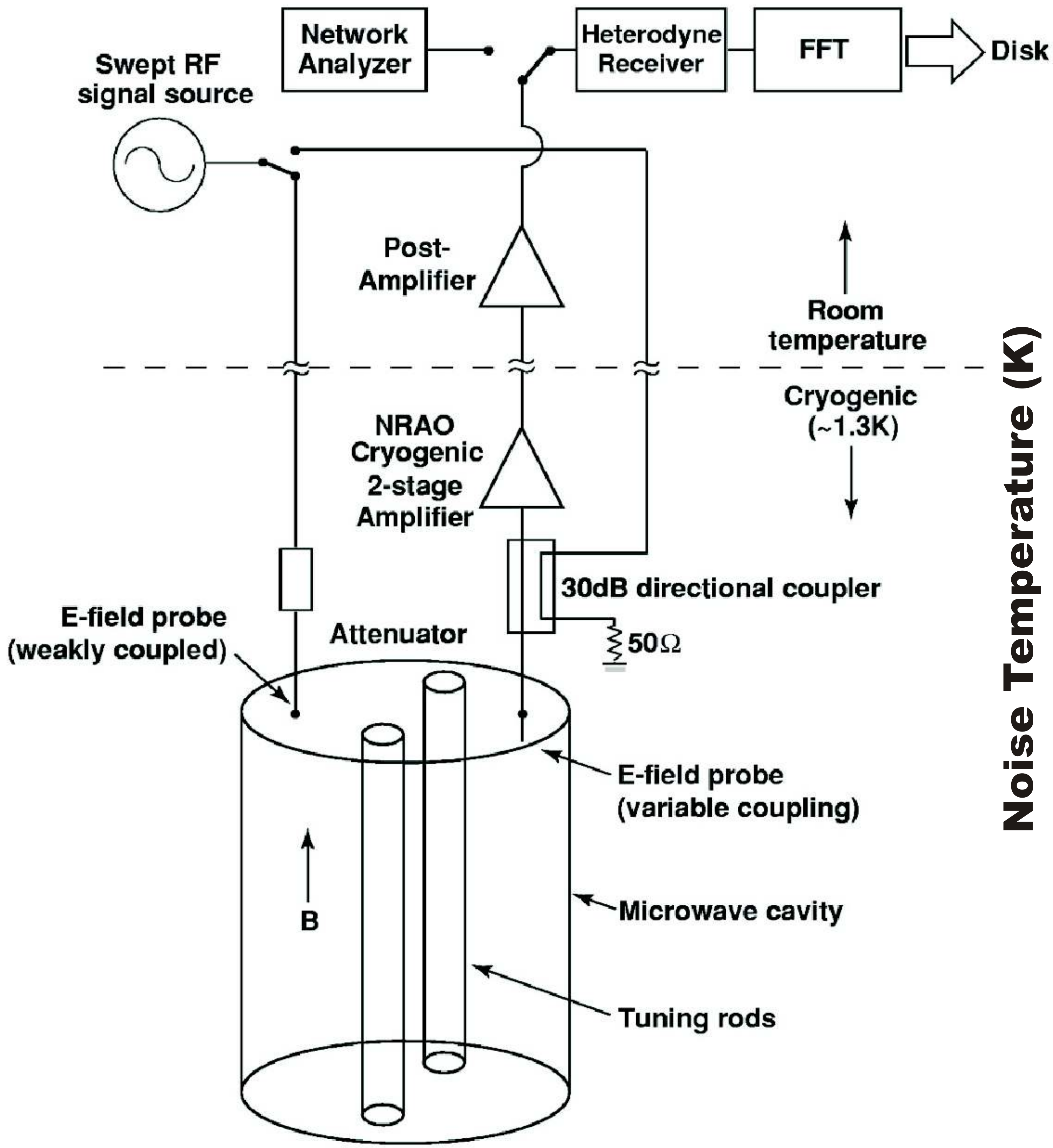
Ta Inclusions

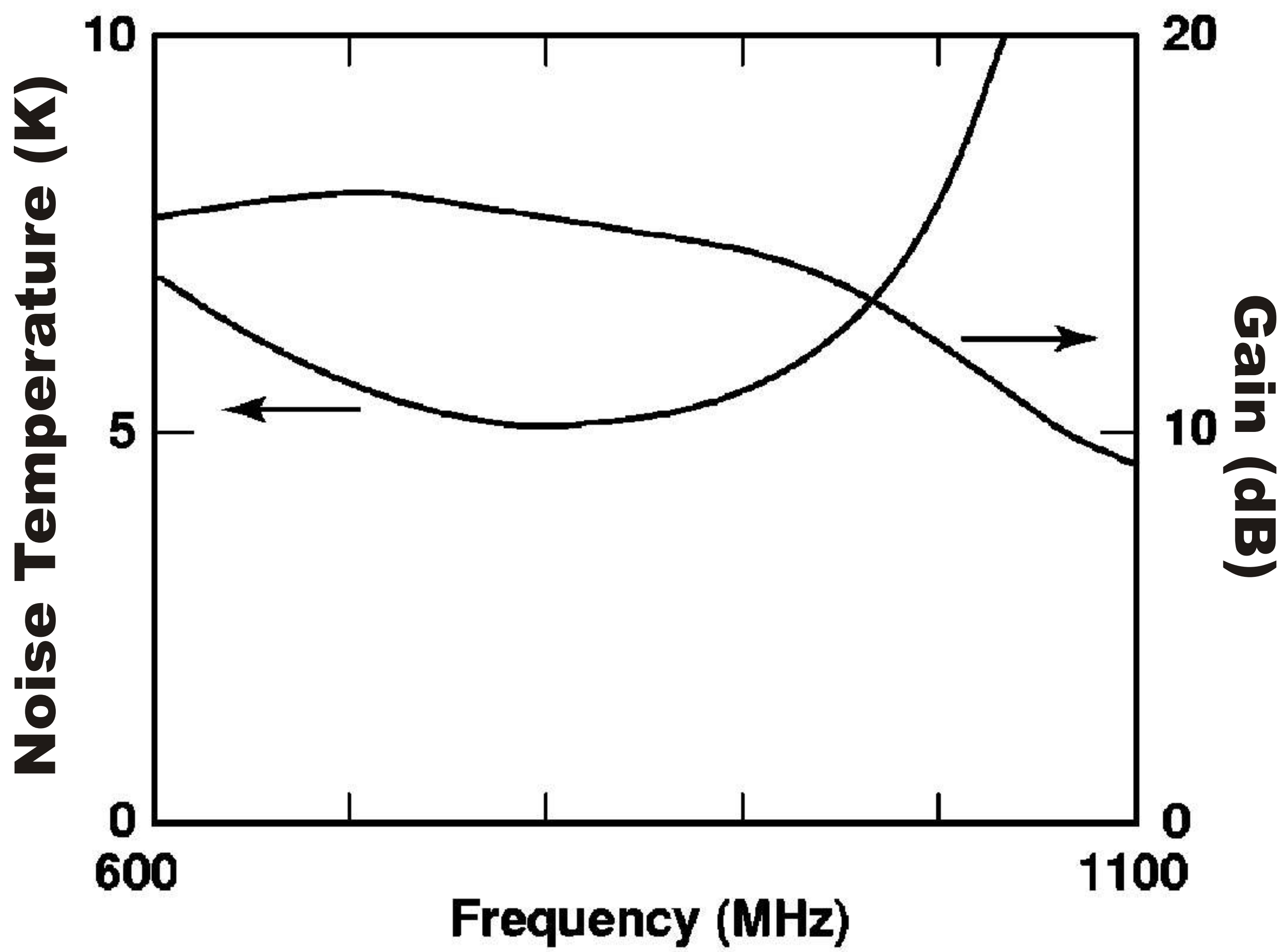


SQUID (Measurement Time: 30 min.)

A high-frequency amplifier based on a dc SQUID

The work was triggered by LLNL requiring a very low noise radio frequency amplifier (~ 500 MHz) for their axion detector project.





S. Asztalos et al.,Large-scale microwave cavity search for dark-matter axions, Phys.Rev. D, 64, 092003.

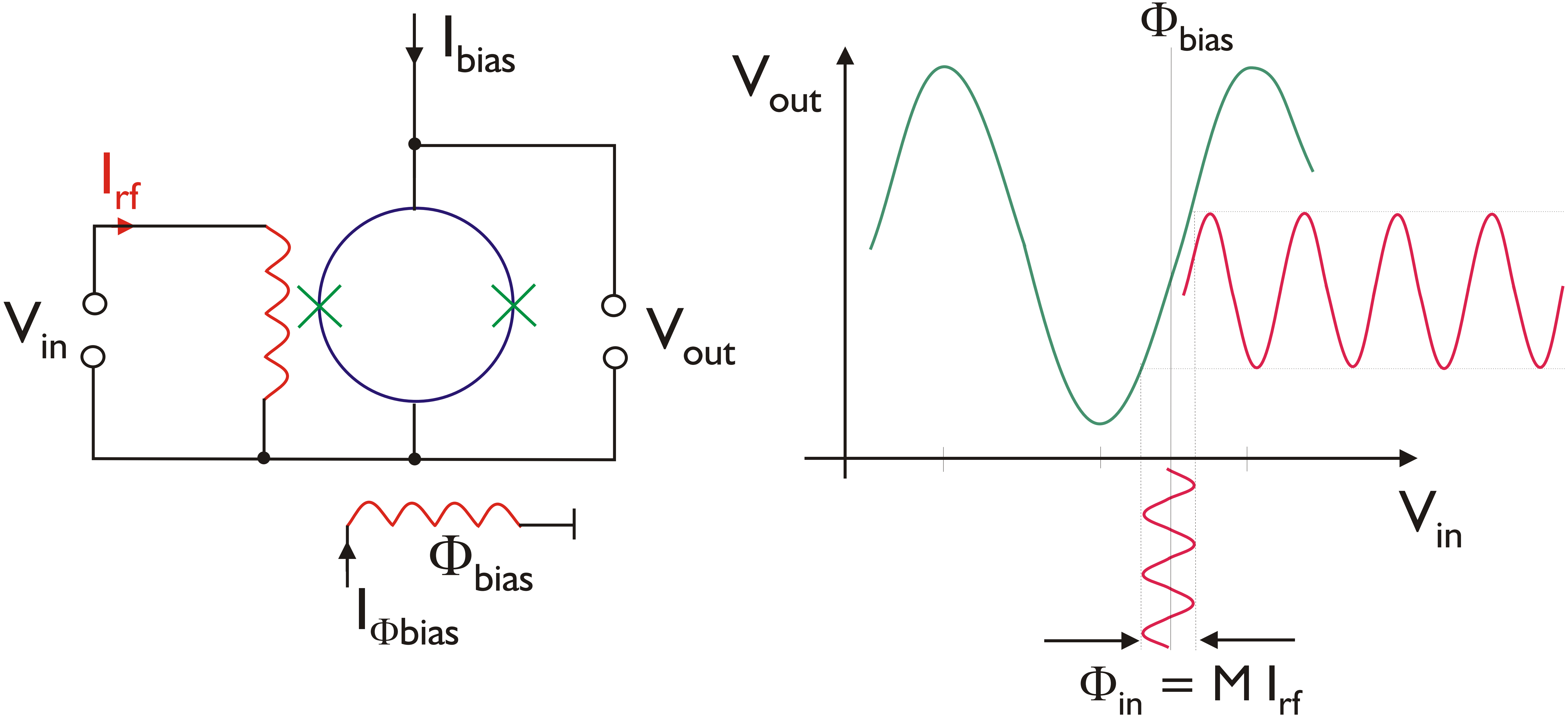
A high-frequency amplifier based on a dc SQUID

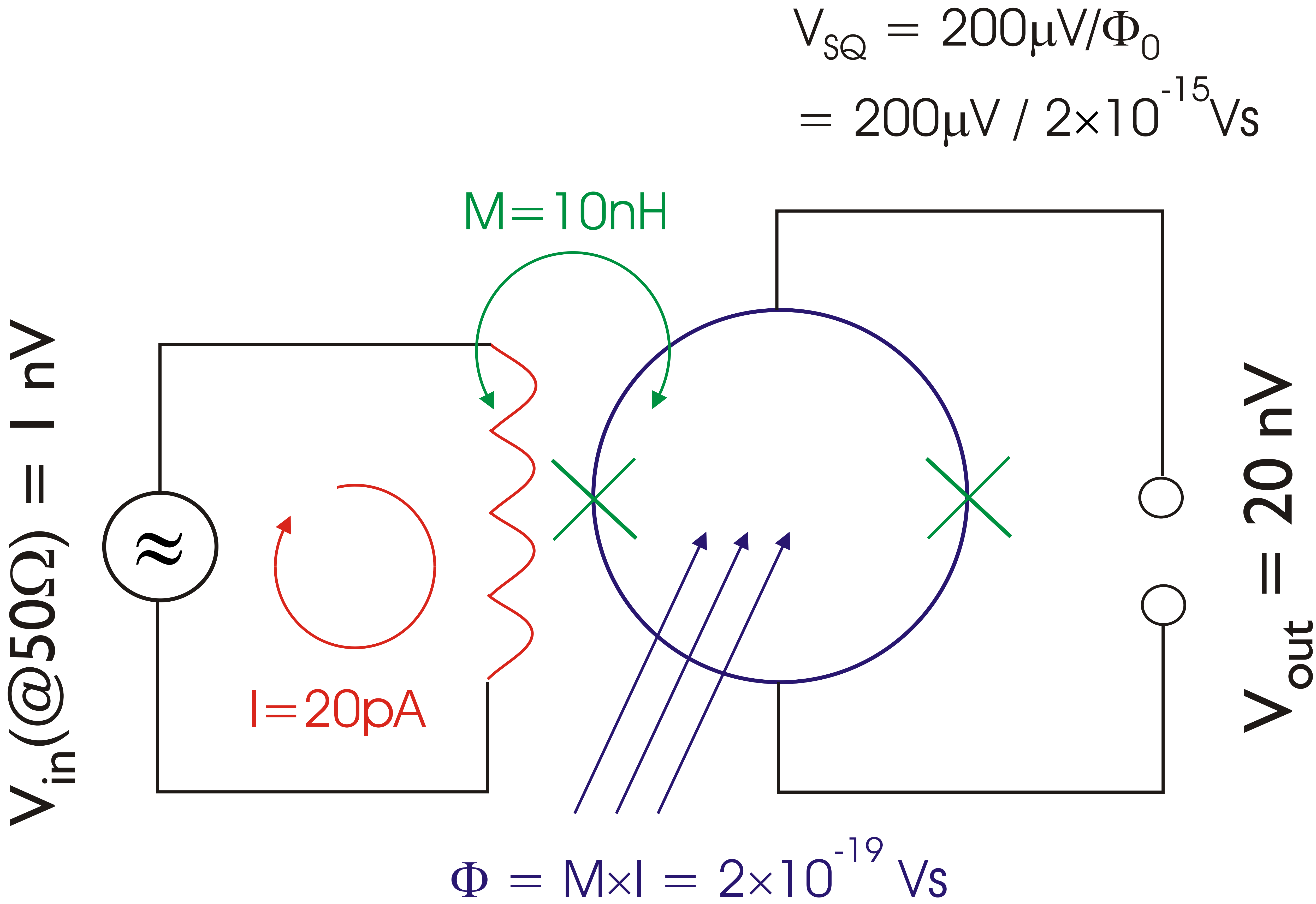
- The noise temperature of a transistor amplifier scales as the physical temperature of the transistor, so cooling the transistor increases sensitivity.
- As a transistor requires currents of $\sim$ mA for low noise, there is a lower limit for the temperature of the transistor chip.
- Idea: Use a superconducting quantum interference device (SQUID) as rf amplifier. Noise temperature scales as SQUID temperature, but dissipation is much lower than in transistor. Physical temperature of SQUID can be 100 mK or lower. $\rightarrow$ Noise could be ten times (or more) lower than noise of transistor.

Using a dc SQUID as a radio frequency amplifier

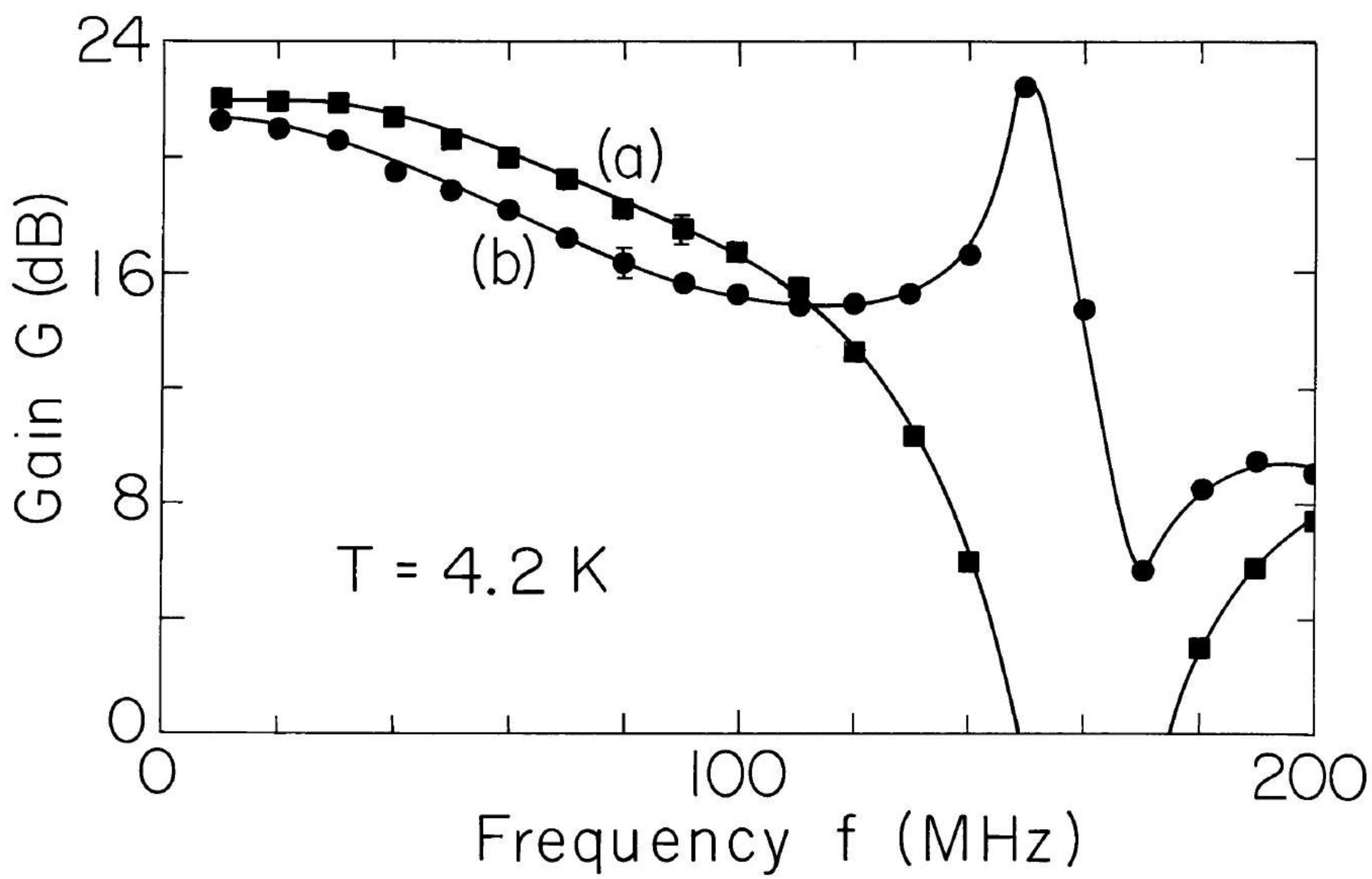
A SQUID measures magnetic flux: use an (integrated) input coil to convert rf current to magnetic flux.

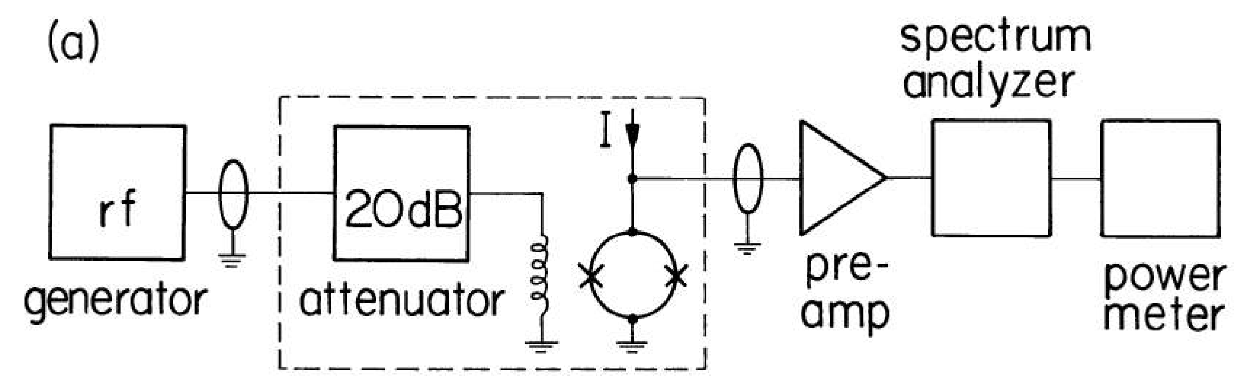
For small input power levels, the amplifier is linear.





$V_{SQ} = 200\mu V/\Phi_0$
$= 200\mu V / 2\times10^{-15} Vs$
M=10nH
$V_{in}(@50\Omega) = 1\ nV$
I=20pA
$V_{out} = 20\ nV$
$\Phi = M\times I = 2\times10^{-19}\ Vs$

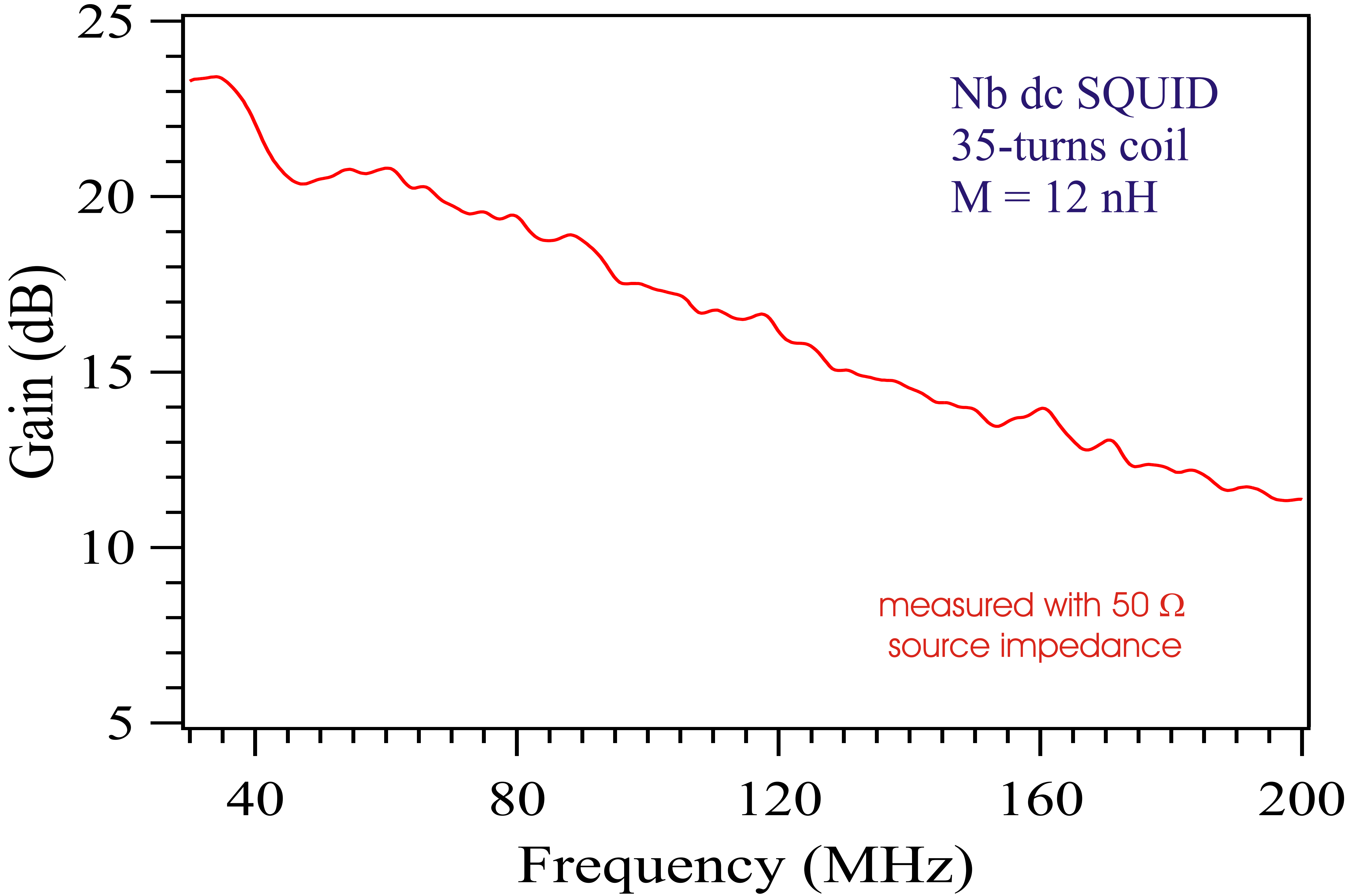




	Frequency (MHz)	G_p (dB)		T_N (K)	
		Measured	Predicted	Measured	Predicted
$T = 4.2$ K (tuned)	93	18.6 ± 0.5	17	1.7 ± 0.5	1.1
$T = 1.5$ K (untuned)	60	24.0 ± 0.5	–	1.2 ± 0.3	–
	80	21.5 ± 0.5	–	0.9 ± 0.3	–
	100	19.5 ± 0.5	18.5	1.0 ± 0.4	0.9
$T = 4.2$ K (untuned)	60	20.5 ± 0.5	–	4.5 ± 0.6	–
	80	18.0 ± 0.5	–	4.1 ± 0.7	–
	100	16.5 ± 0.5	16.5	3.8 ± 0.9	2.5

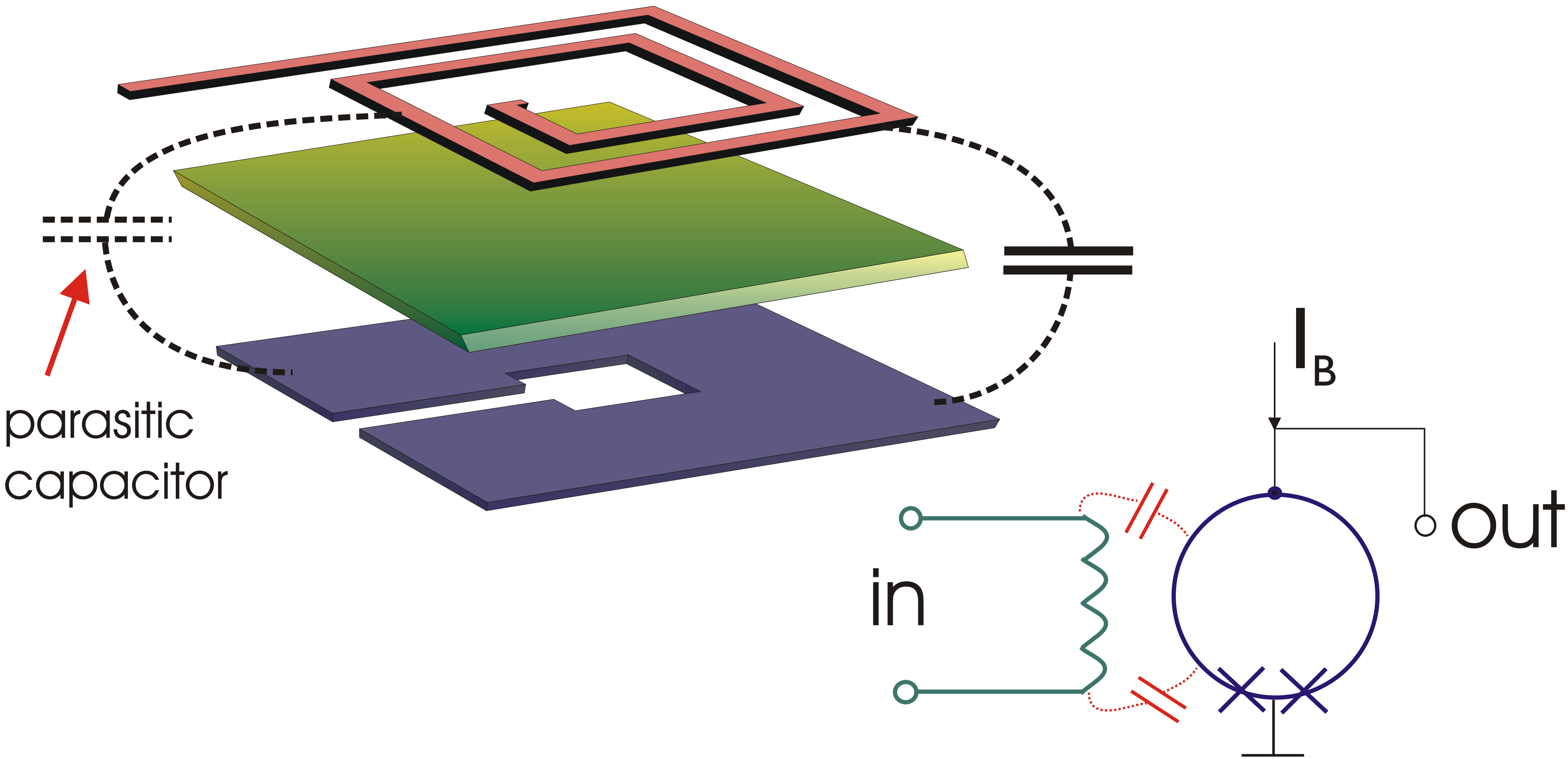
C.Hilbert and J.Clarke, DC SQUIDs as radiofrequency amplifiers, J. Low Temp. Phys. 61, 263–280 (1985).

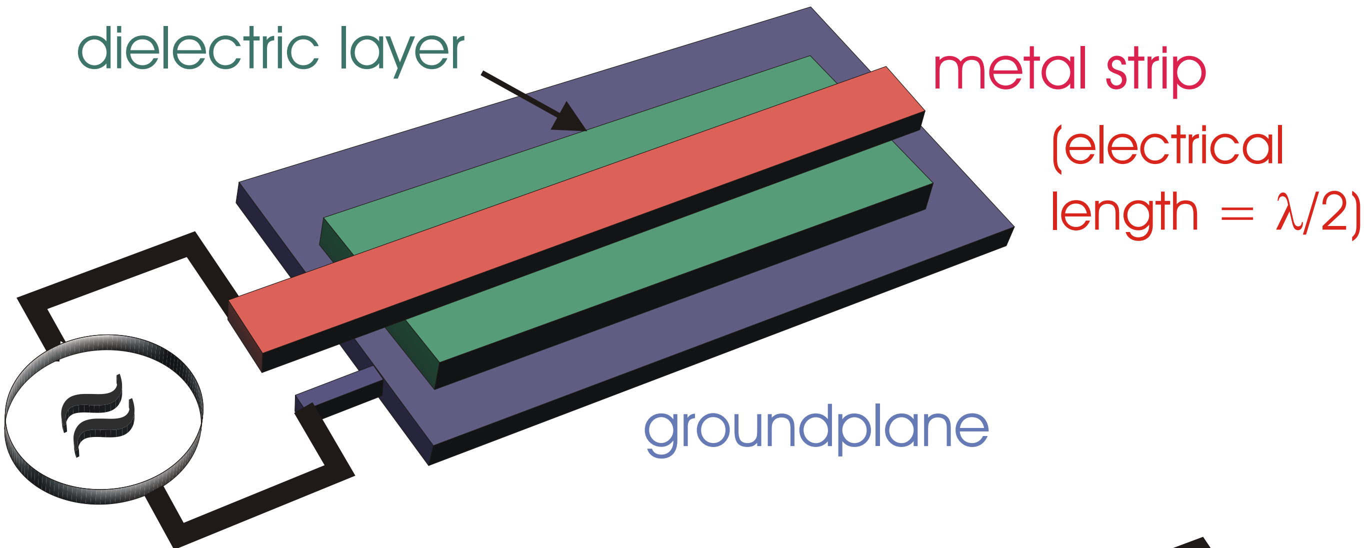
Gain vs frequency of a ‘conventional’ dc SQUID amplifier



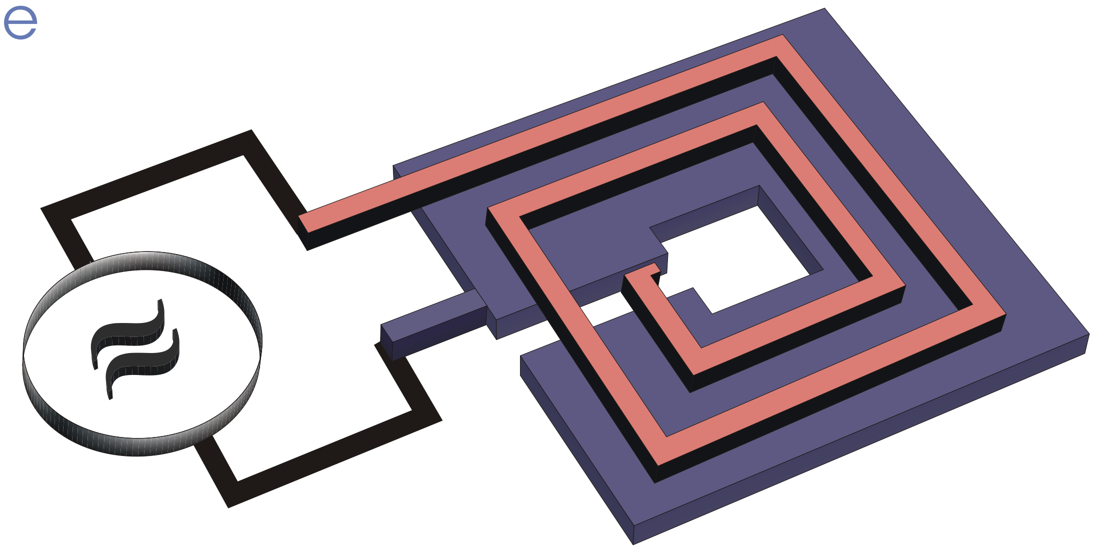
The SQUID rf amplifier

At higher frequencies, parasitic capacitance between the integrated input coil and the SQUID washer reduces the gain substantially.



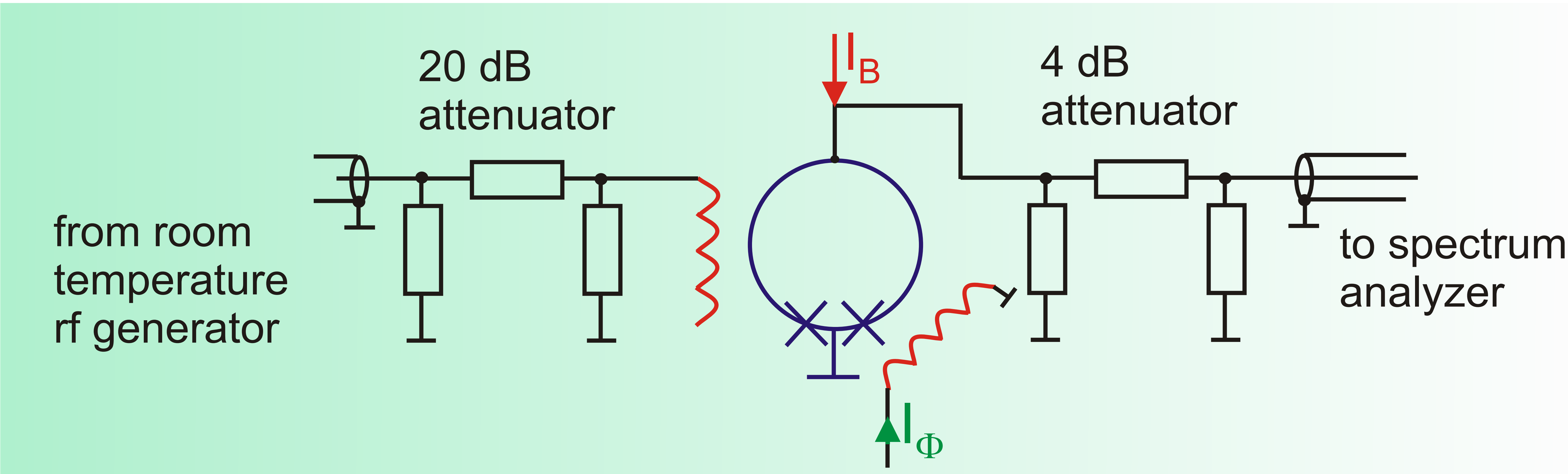


The λ/2 microstrip resonator



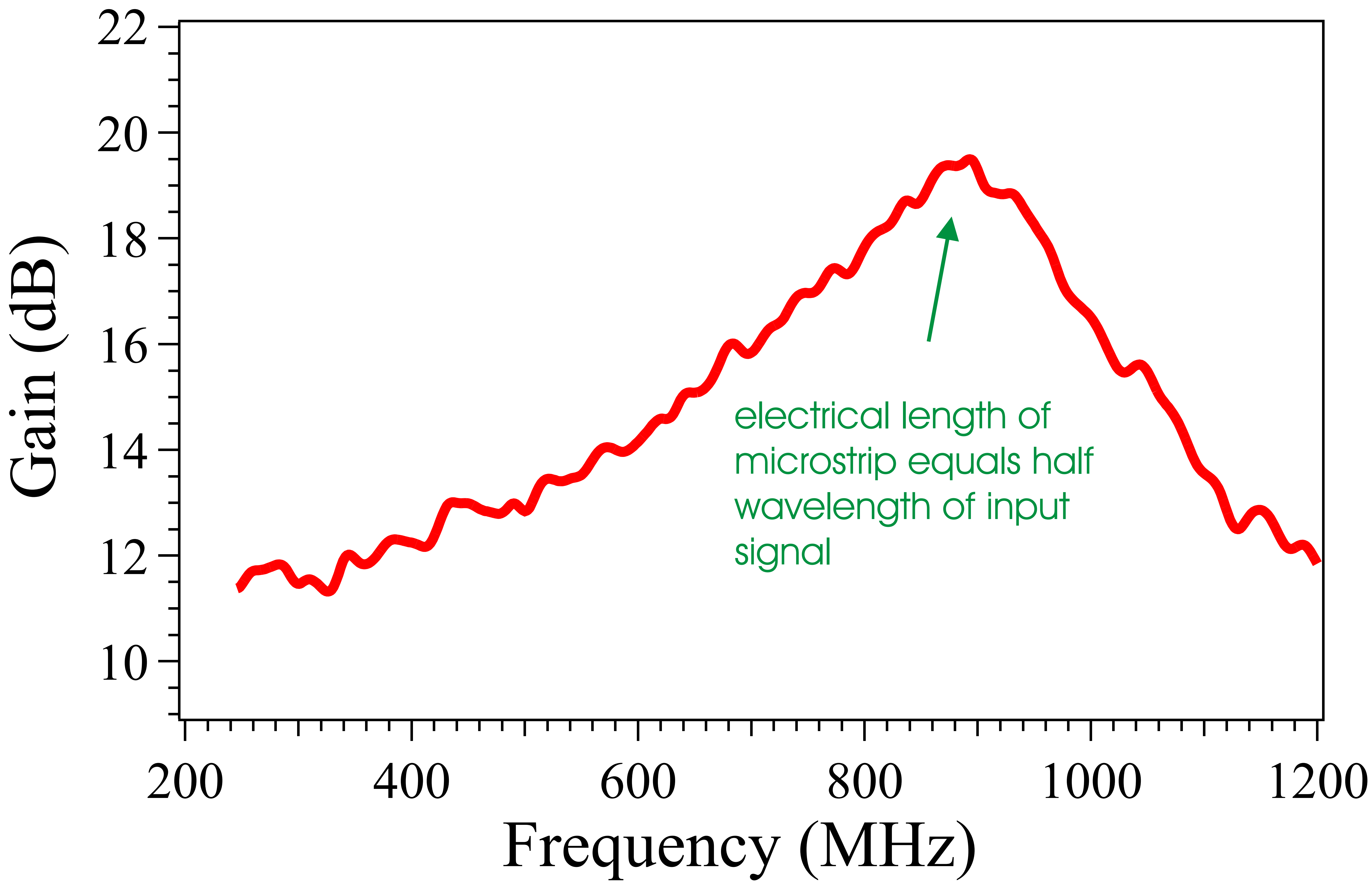
We have taken advantage of the parasitic capacitance by operating the input coil as a microstrip resonator. In a microstrip SQUID amplifier, the input signal is applied between one end of the coil and the SQUID washer; the other end of the coil is left open. The SQUID washer acts as a groundplane for the microstrip resonator.

Gain Measurement Configuration

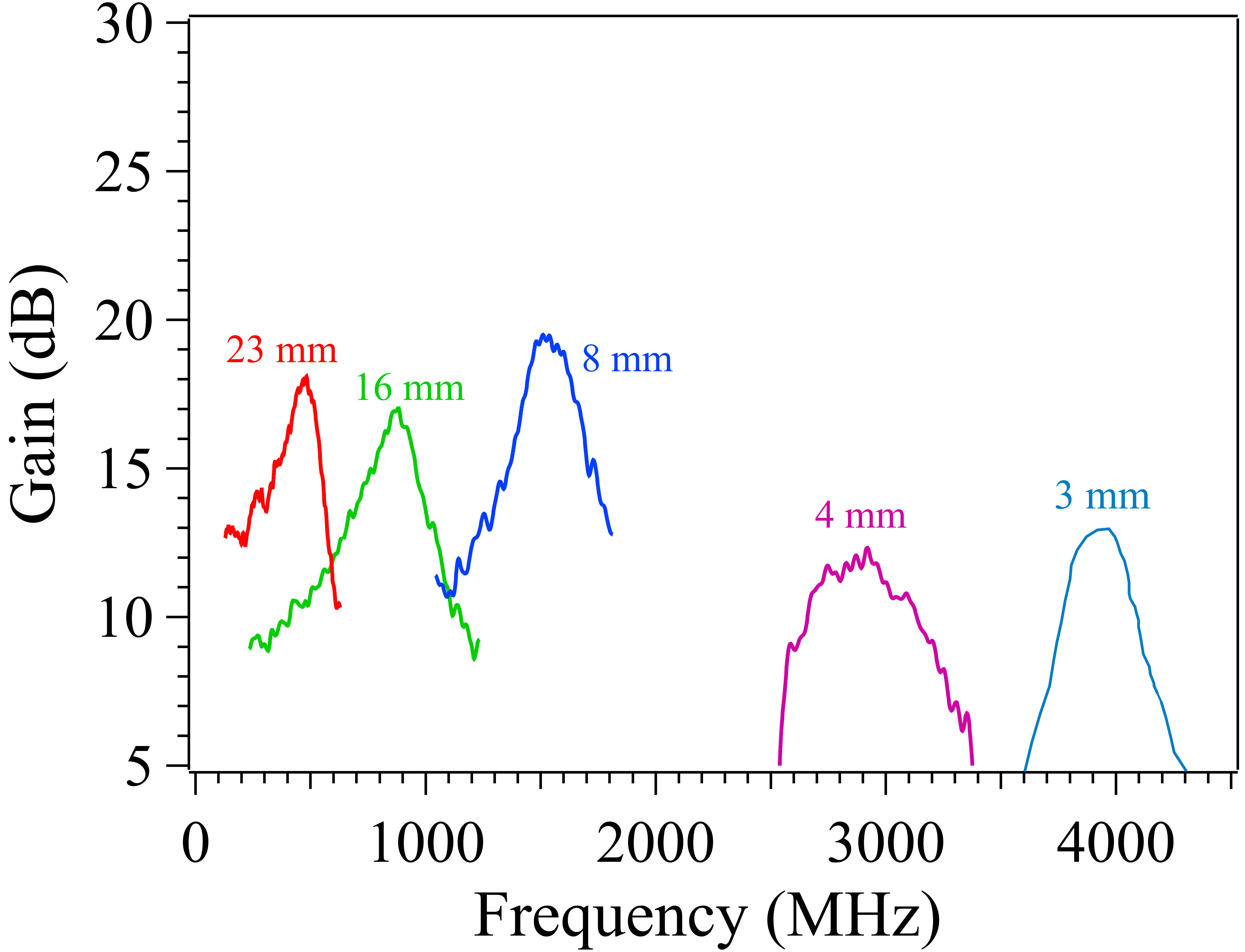


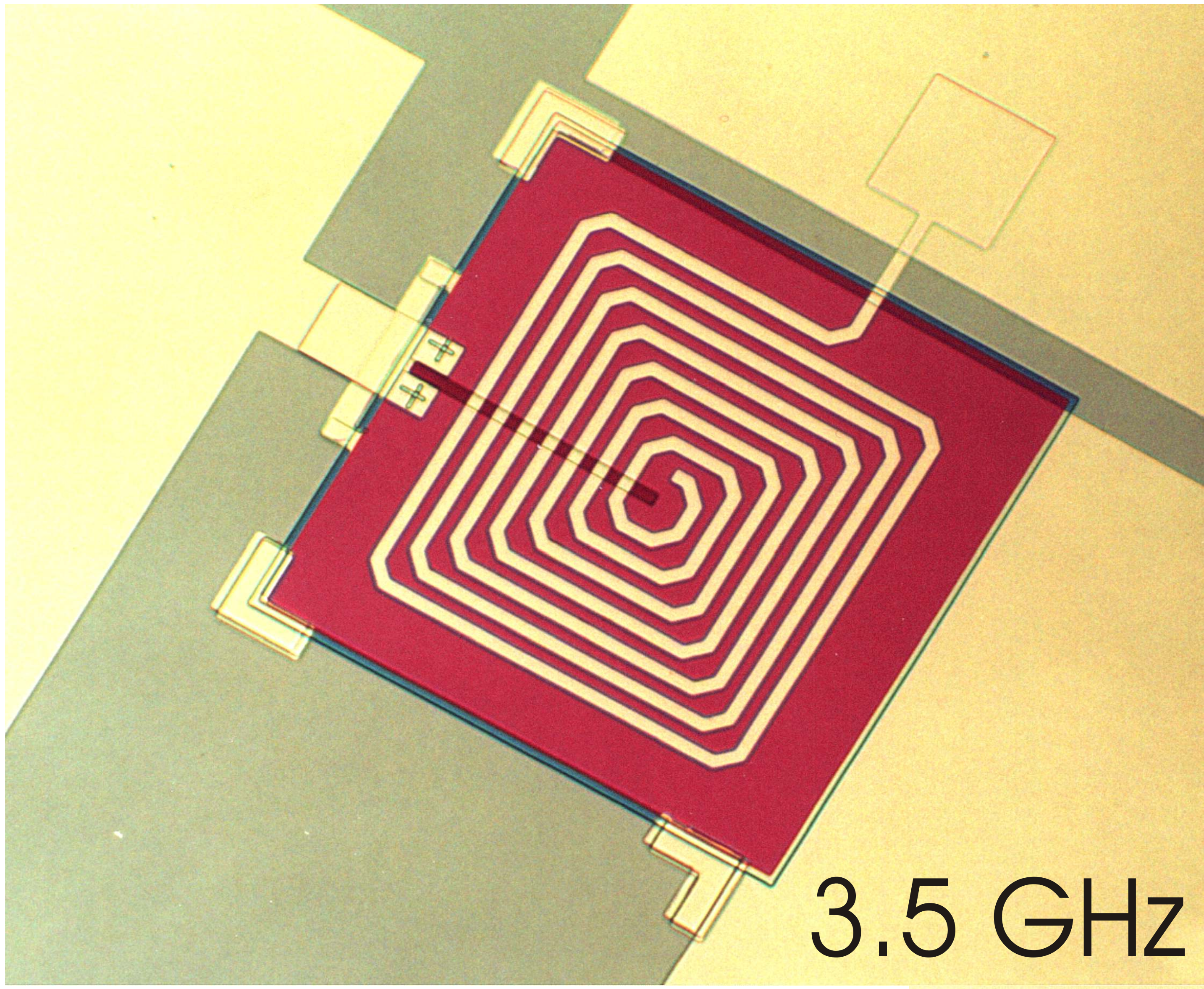
Configuration used to measure gain. The two attenuators prevent noise from the room temperature equipment to saturate the SQUID.

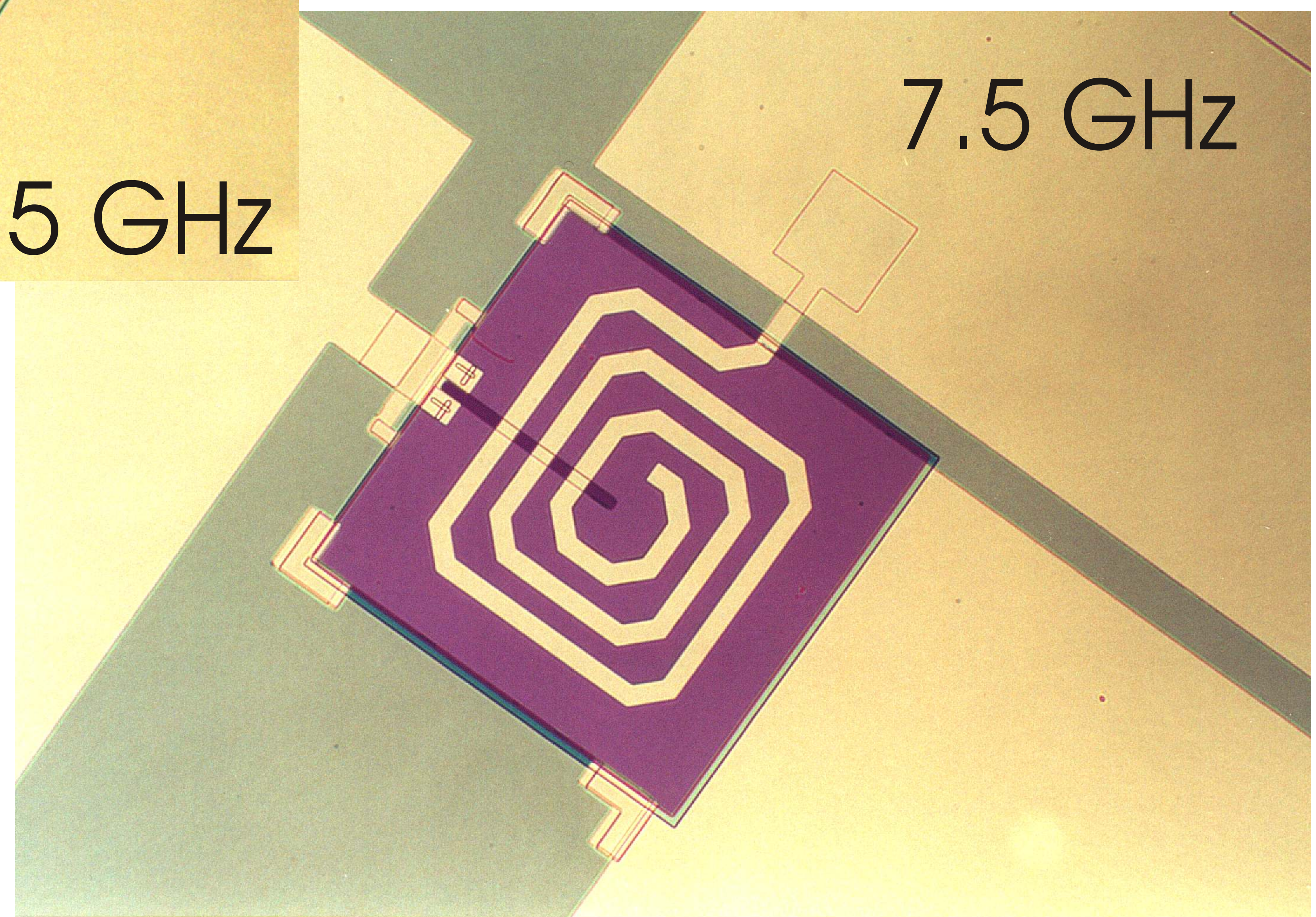
Gain of a microstrip SQUID amplifier



Gain of microstrip SQUID amplifier vs length of input resonator (coil)




3.5 GHz


7.5 GHz

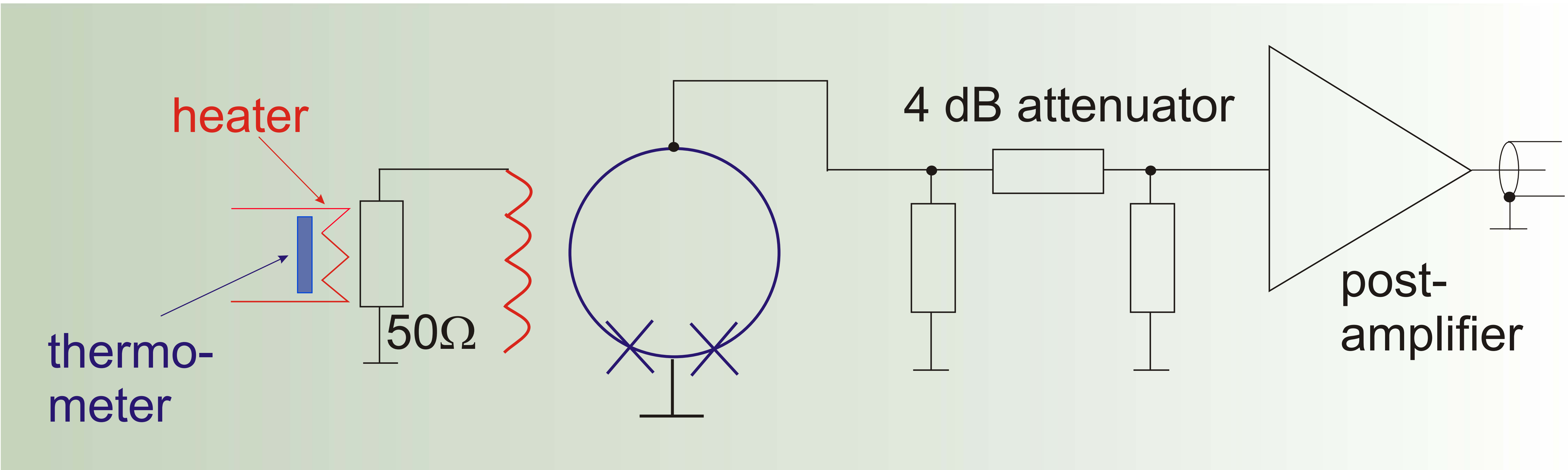
The Sensitivity and Noise Temperature of SQUID Amplifiers

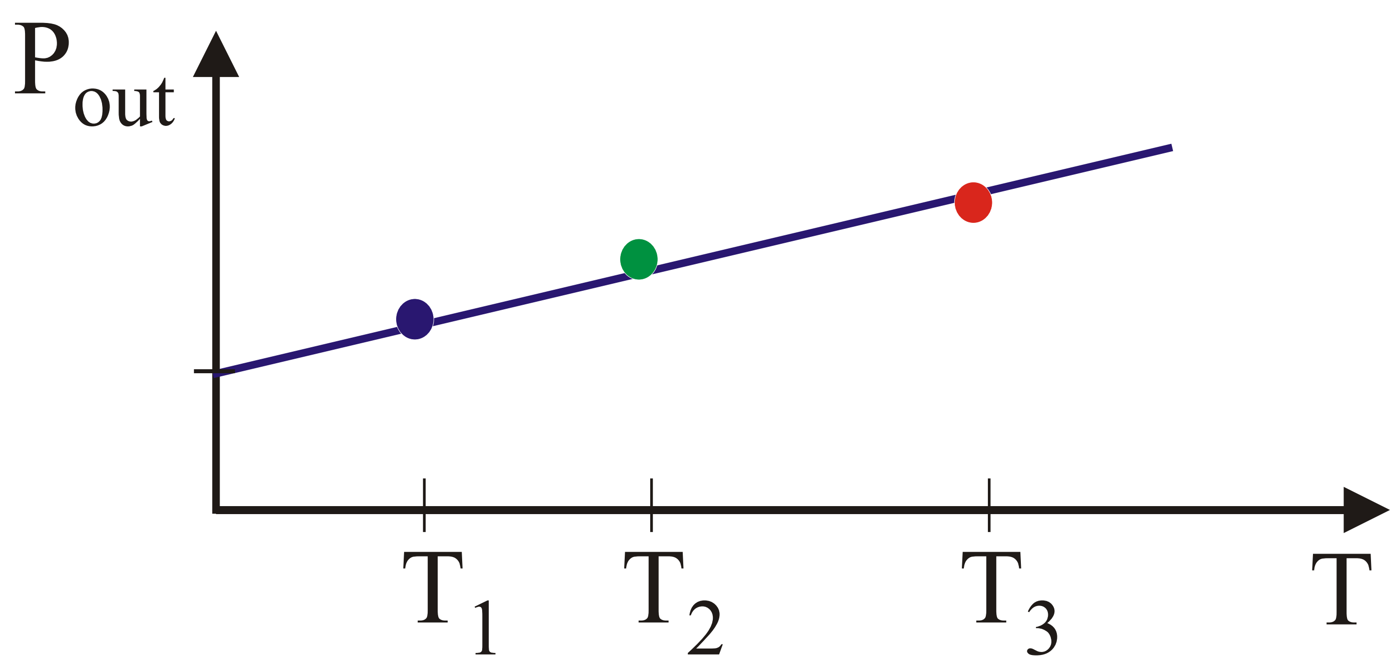
To characterize the sensitivity of an amplifier at high frequencies, its noise temperature is specified. One assumes the noise of the amplifier is produced by a virtual resistor at the input of the amplifier.

The temperature at which that resistor had to be in order to produce the same noise as the amplifier is the noise temperature of the amplifier.

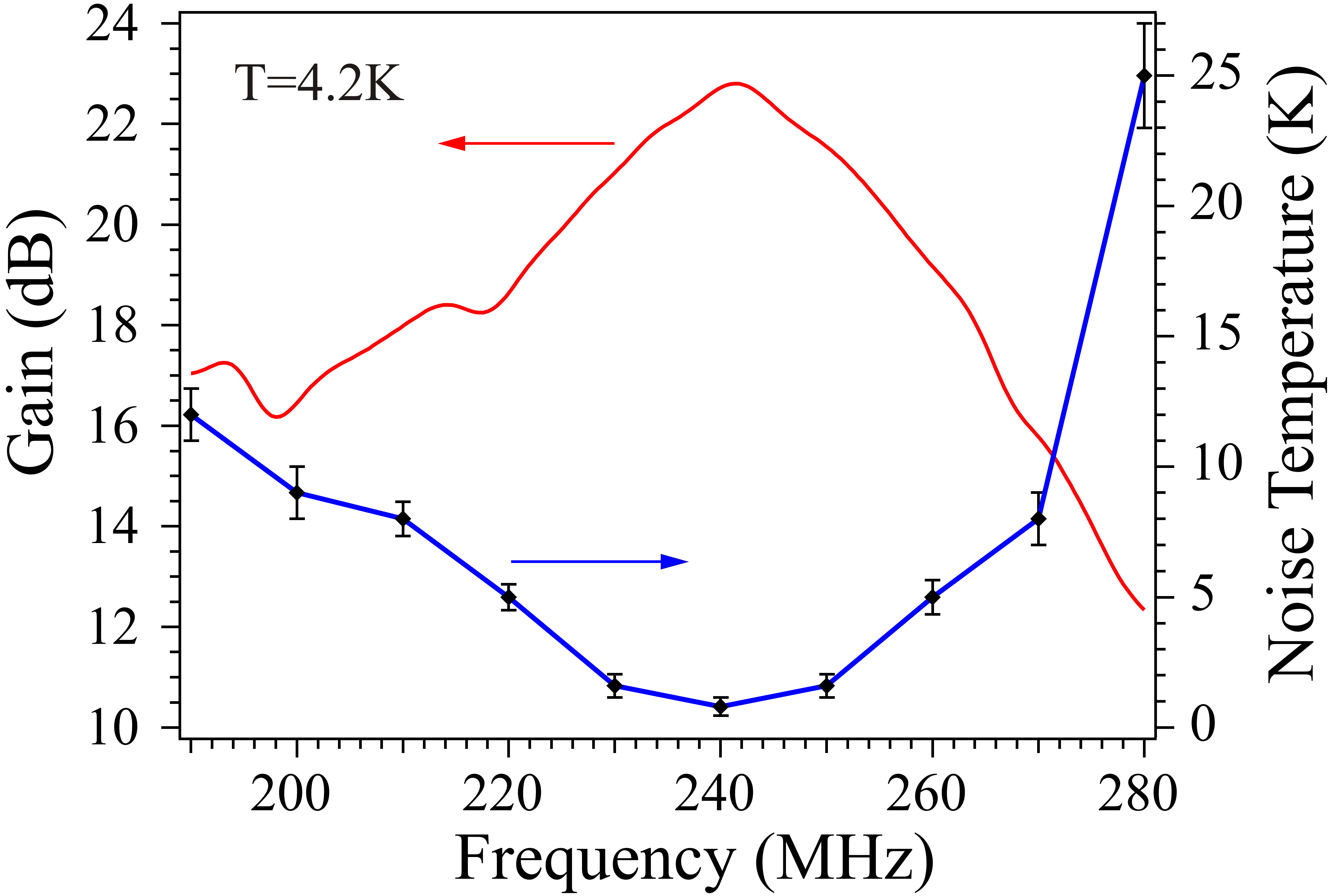
An amplifier producing a voltage noise referred to its input of 0.1 $nV/Hz^{1/2}$ and having an input impedance of 50 Ω has a noise temperature of 4 K.

Configuration used to measure the noise temperature T_N. A 50 Ω resistor acts as noise source; by comparing the noise powers at the output of the SQUID for different resistor temperatures, one can calculate T_N.



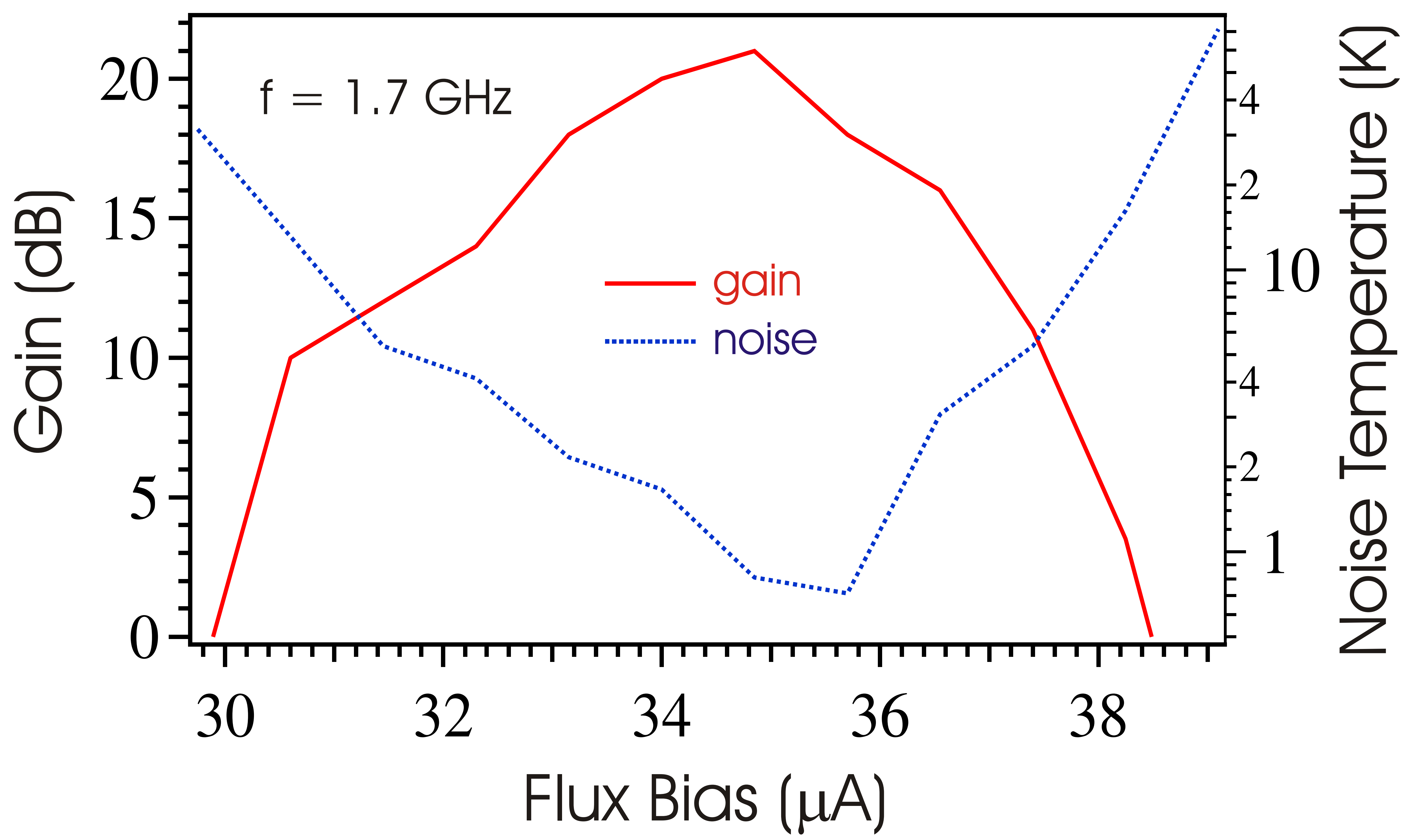


Noise Temperature Measurements: 4.2 K

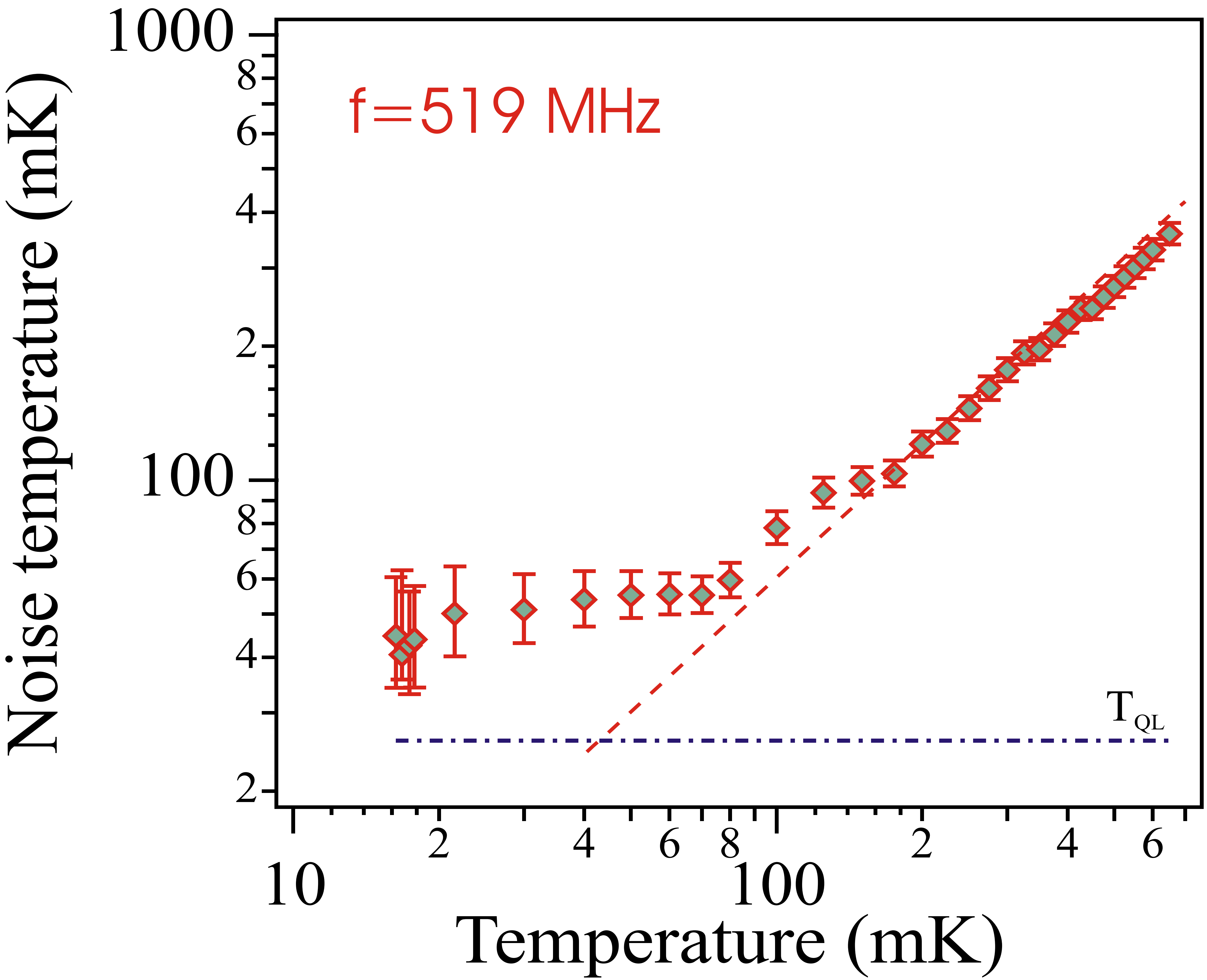


Gain and noise temperature vs frequency of
a microstrip SQUID with 71 mm long microstrip resonator.

Noise Temperature Measurements: 4.2 K



Noise Temperature Measurements: 20 mK to 1 K



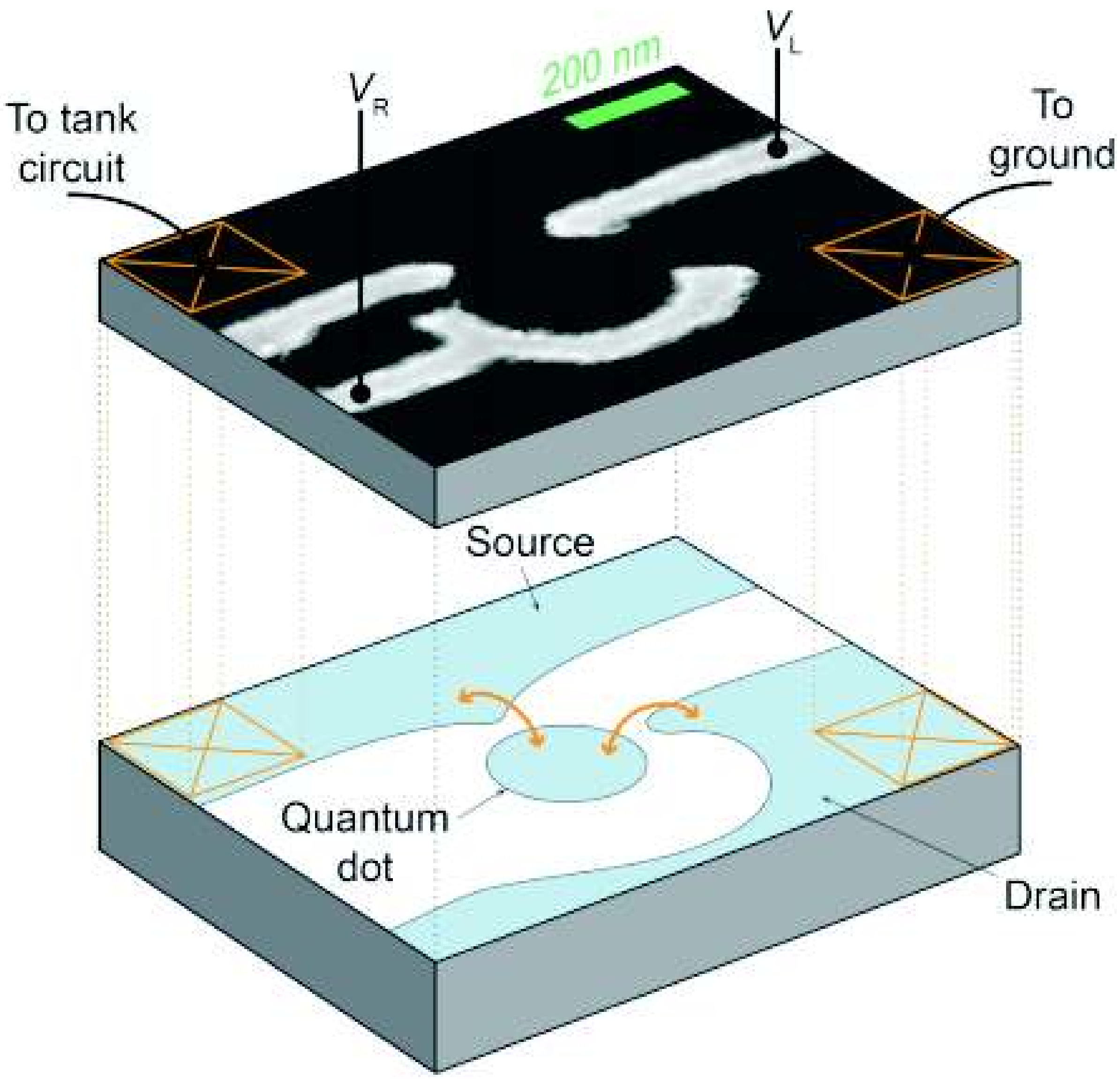
Some Recent Work Employing Microstrip SQUID rf Amplifiers

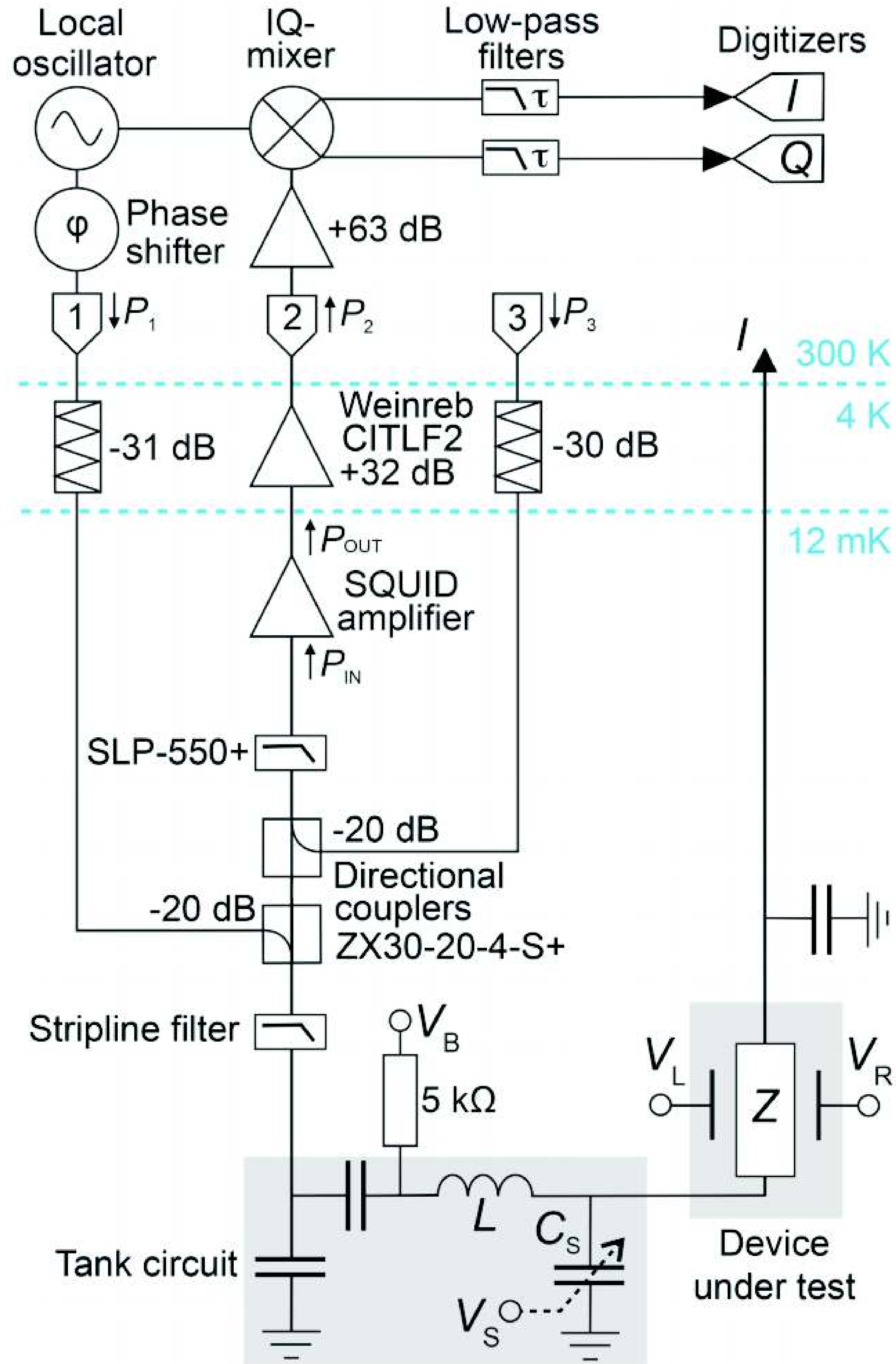
- S. J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, and K. van Bibber, M. Hotz, L. J Rosenberg, and G. Rybka, J. Hoskins, J. Hwang, P. Sikivie, and D. B. Tanner, R. Bradley, J. Clarke, SQUID-Based Microwave Cavity Search for Dark-Matter Axions, PRL104,041301 (2010).

- S. Michotte, Qubit dispersive readout scheme with a microstrip superconducting quantum interference device amplifier, Appl. Phys. Lett. 94, 122512 (2009).

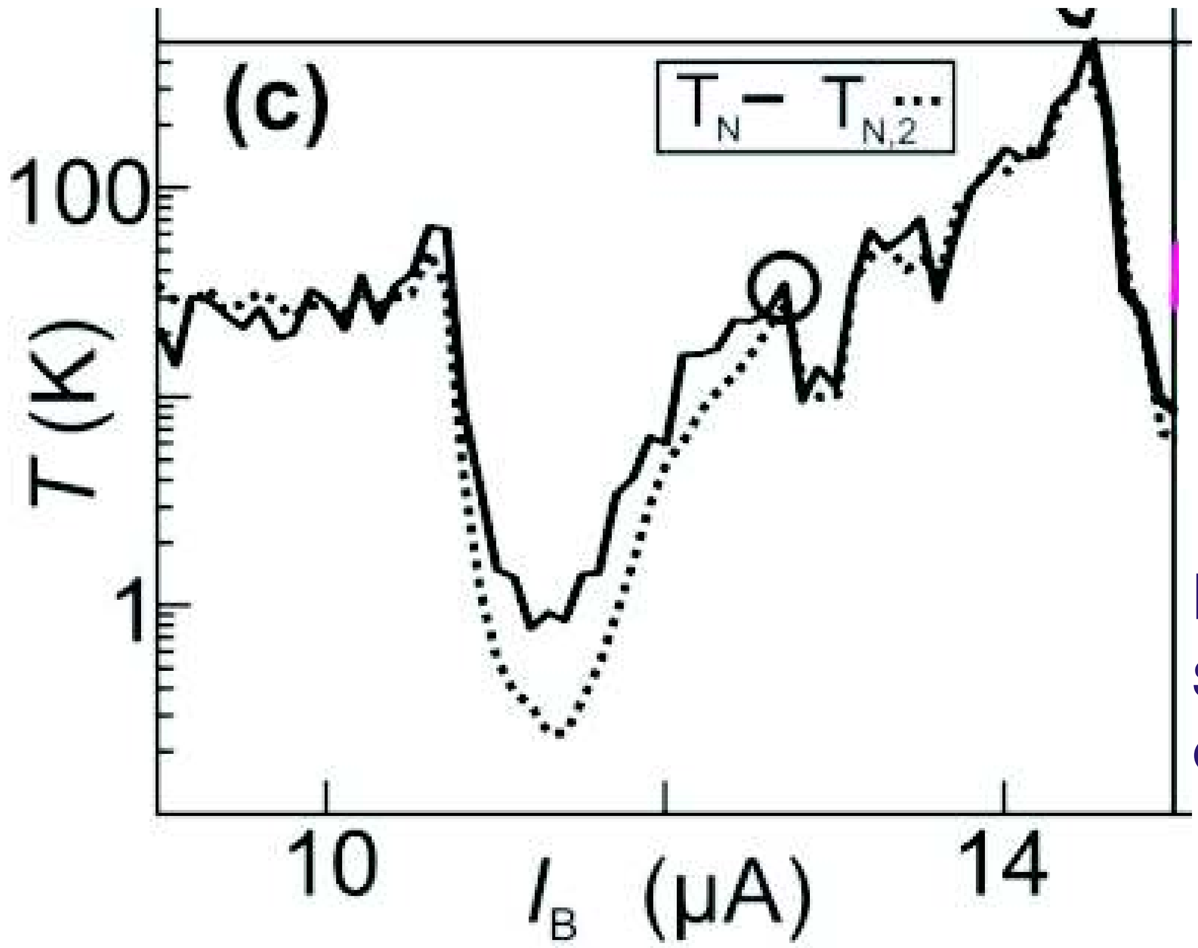
- F. J. Schupp, F. Vigneau, Y. Wen,A. Mavalankar,J. Griffiths, G. A. C. Jones, I. Farrer, D. A. Ritchie,C. G. Smith, L. C. Camenzind,L. Yu,D. M. Zumbühl,G. A. D. Briggs, N. Ares, and E. A. Laird, Sensitive radiofrequency readout of quantum dots using an ultra-low-noise SQUID amplifier, J. Appl. Phys.127, 244503 (2020).

- Xing Fan, An Improved Measurement of the Electron Magnetic Moment, Dissertation, Harvard University, Cambridge, Massachusetts, August 2022.



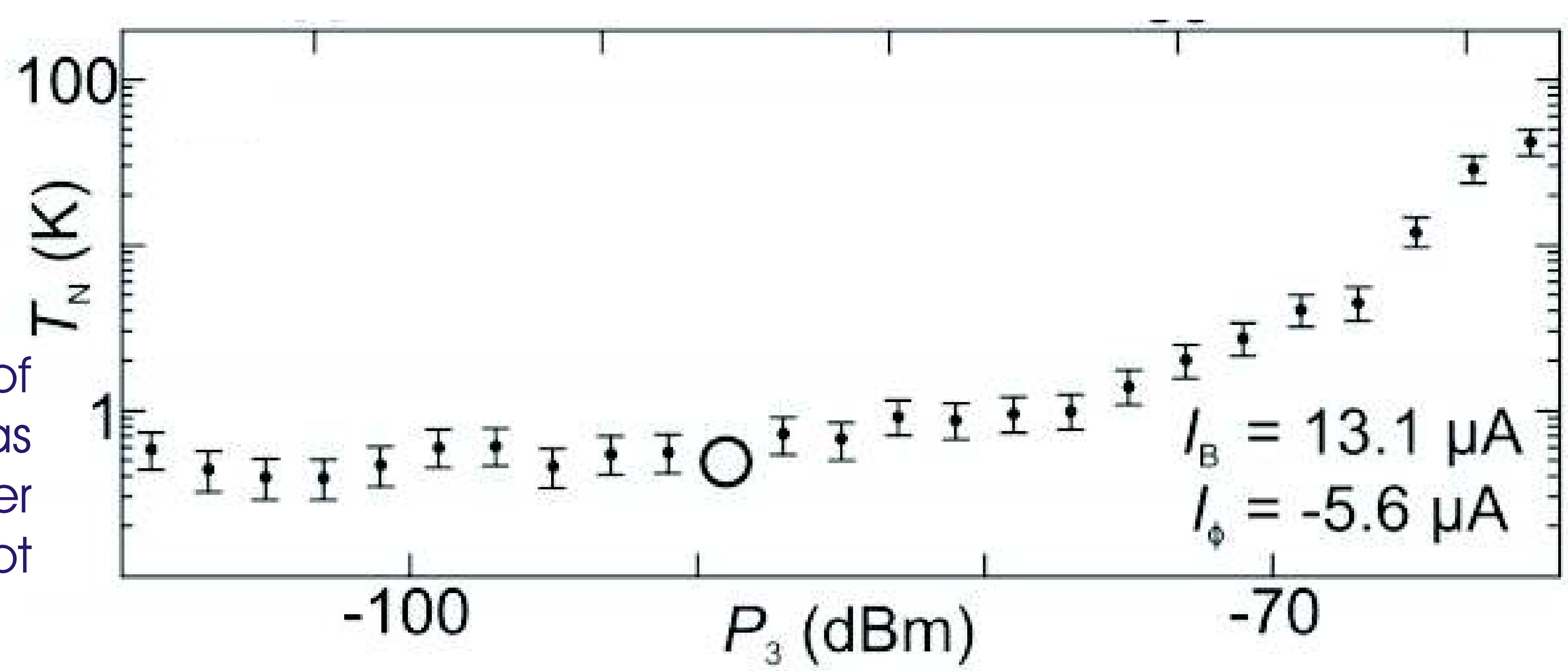


F. J. Schupp *et al.*, Sensitive radiofrequency readout of quantum dots using an ultra-low-noise SQUID amplifier, J. Appl. Phys.127, 244503 (2020).



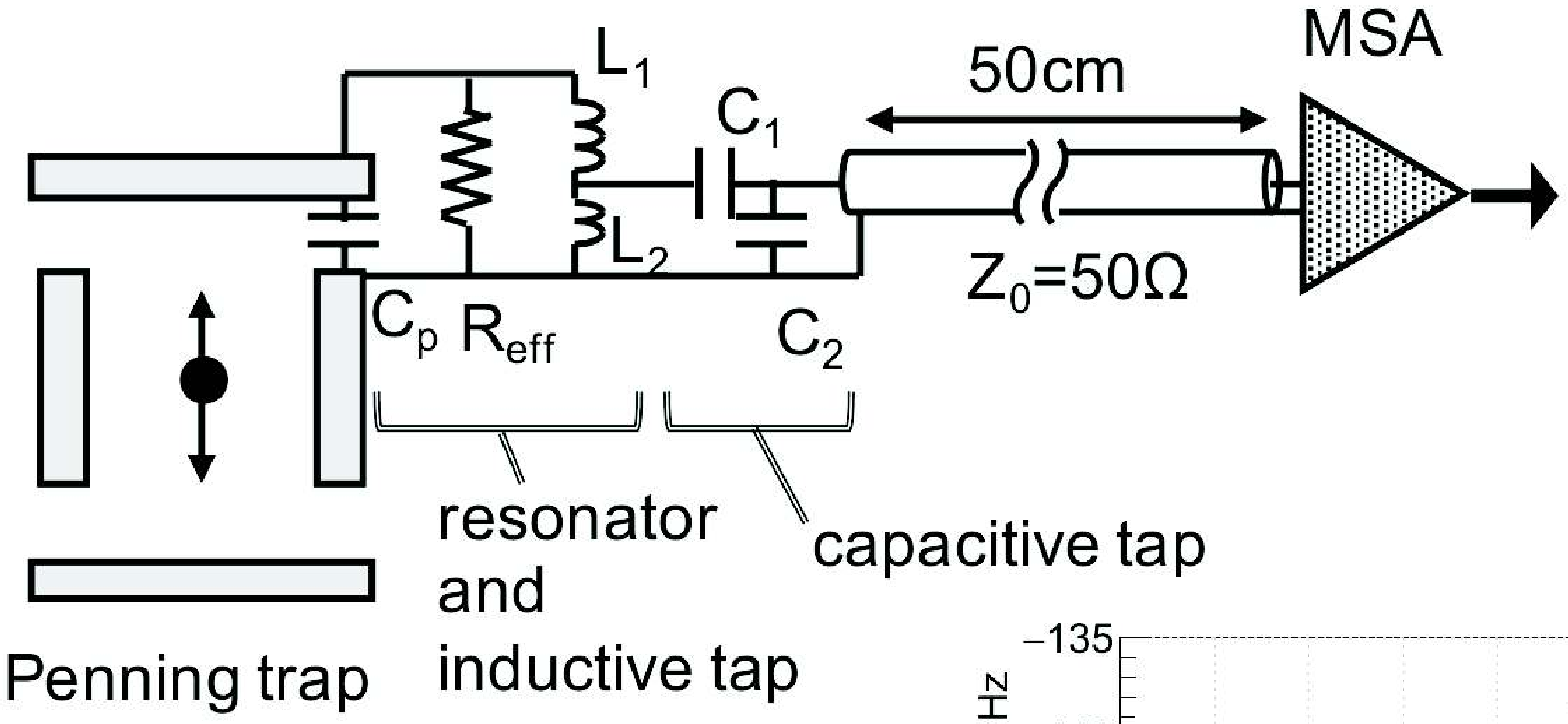
F. J. Schupp *et al.*, Sensitive radiofrequency readout of quantum dots using an ultra-low-noise SQUID amplifier, J. Appl. Phys.127, 244503 (2020).

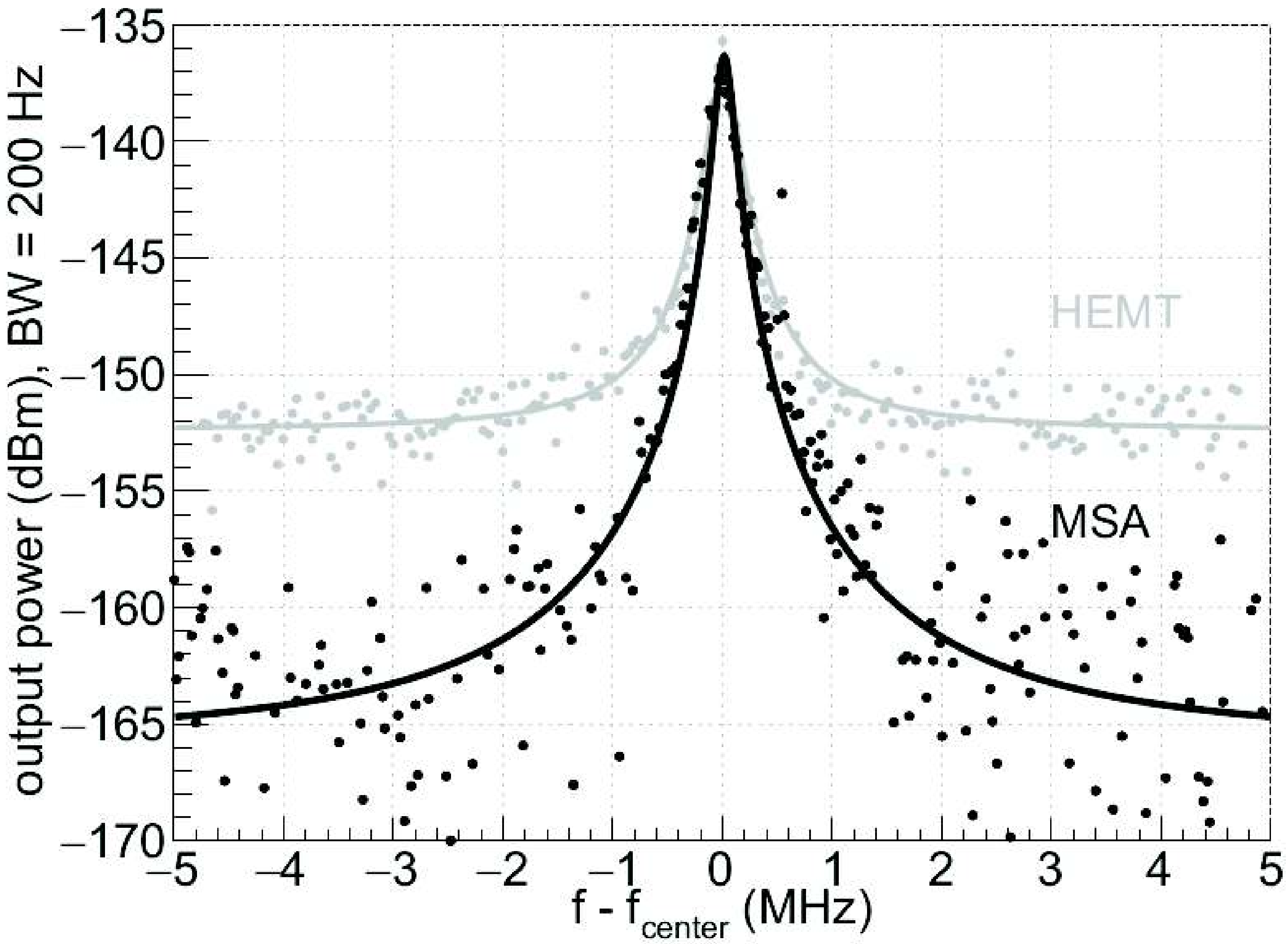
Noise temperature of SQUID amplifier (dots) and system (solid line) as function of SQUID dc bias current



Noise temperature of SQUID amplifier as function of rf power applied to quantum dot

Measurement configuration for an improved measurement of the electron magnetic moment

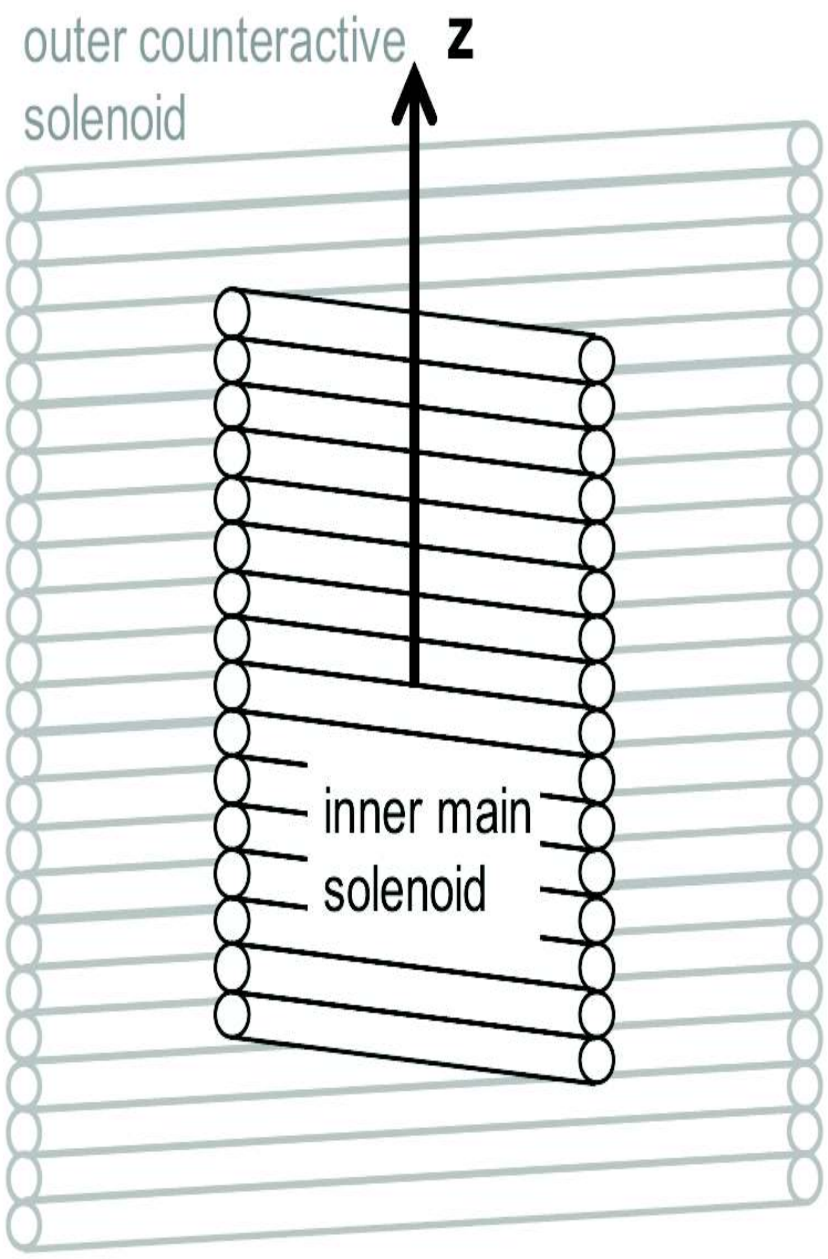


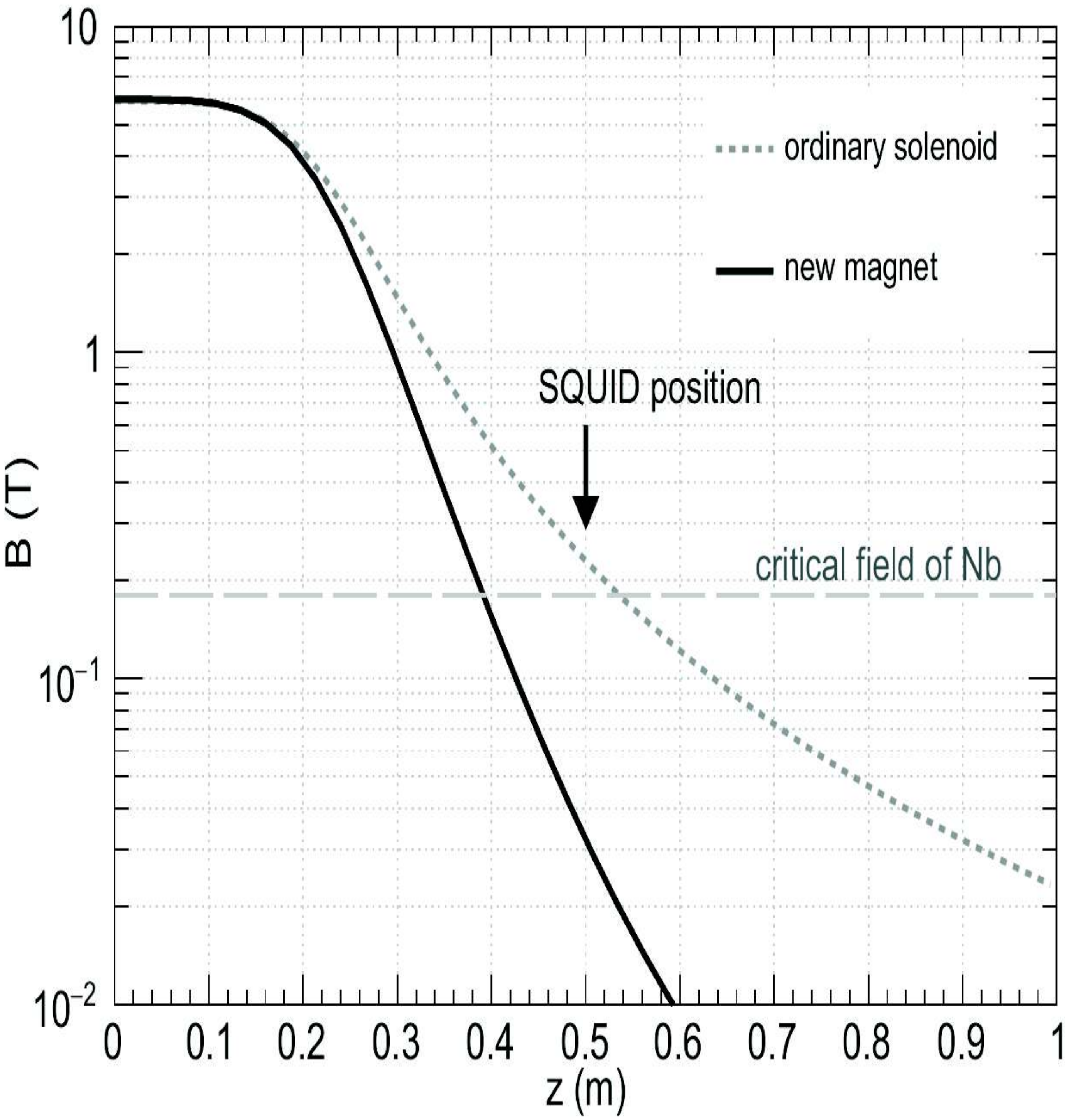


Noise peak of resonator of Penning trap

Xing Fan, An Improved Measurement of the Electron Magnetic Moment, Dissertation, Harvard University, Cambridge, Massachusetts, August 2022.

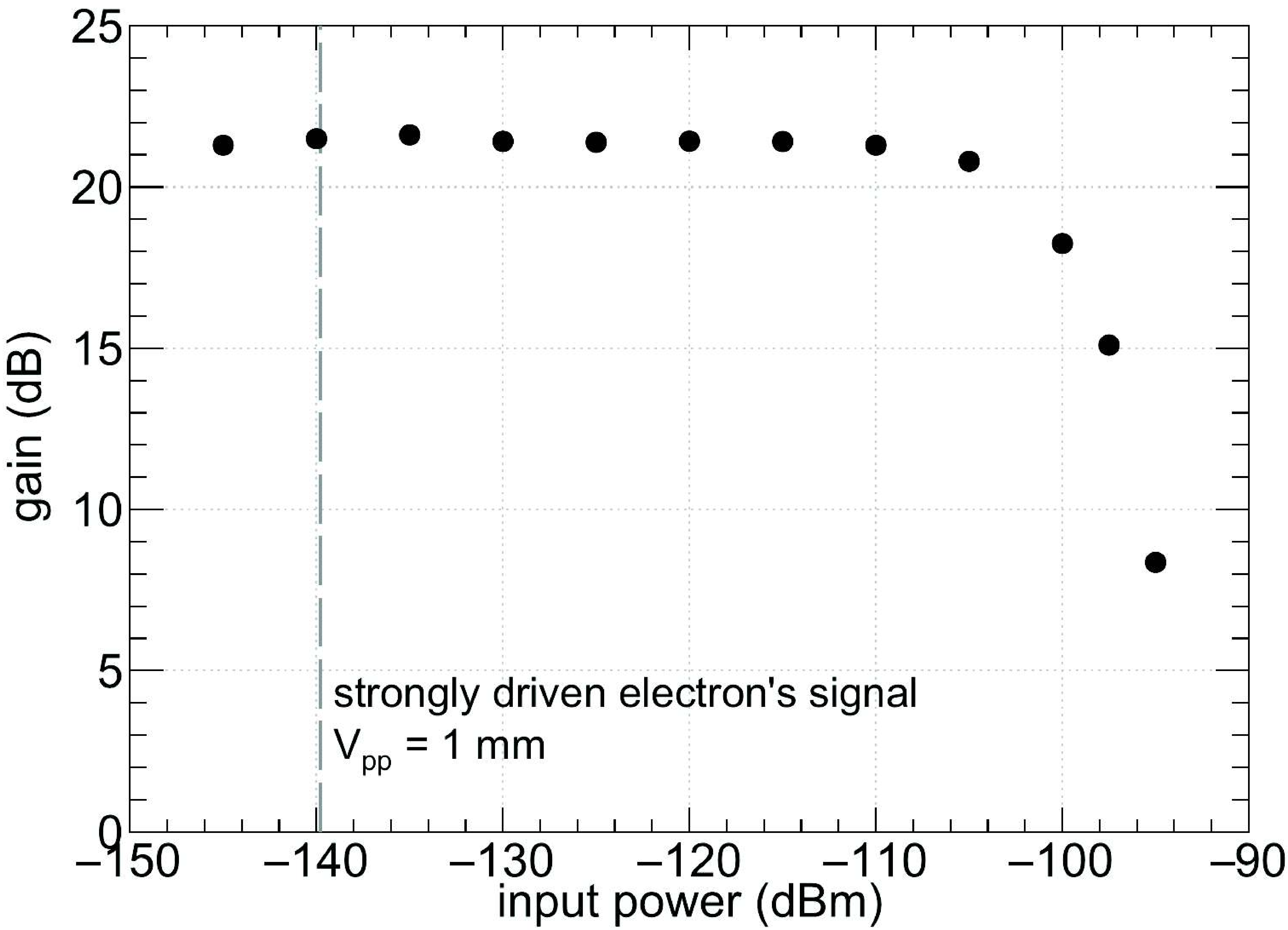
Compensating the stray field of a 6-T magnet at the location of the SQUID amplifier by a second solenoid





Xing Fan, An Improved Measurement of the Electron Magnetic Moment, Dissertation, Harvard University, Cambridge, Massachusetts, August 2022.

Gain of microstrip SQUID amplifier as function of input-signal level.



Xing Fan, An Improved Measurement of the Electron Magnetic Moment, Dissertation, Harvard University, Cambridge, Massachusetts, August 2022.

Conclusion

A dc SQUID can be employed as a very sensitive detector fpr mahnetic flux, magnetic field, and any other physical quantity, which can be converted to magnetic flux (such as voltage, current etc.).

It can also be used as an amplifier in the frequency range from dc at least up to several GHz.

Power gains of $\sim$ 100 (20 dB) can be achieved with noise temperatures (in the optimum case at mK temperatures) of slightly above the quantum limit.

The gain of a SQUID amplifier is usually high enough to render the noise of a semiconductor post amplifier negligible. However, the input signal to a SQUID amplifier should not exceed $\sim$ -100 dBm (0.1 pW).

The SQUID has to be sufficiently shielded from external magnetic fields to avoid changes in gain with that interference.