Title: LTS dc-SQUID sensors for precision measurements in metrology and fundamental physics

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Abstract:

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

LTS dc-SQUID sensors for precision measurements in metrology and fundamental physics

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PTB Working Group 7.21 Cryosensors

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
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LTS dc-SQUID sensors

- components, operation, parameters
- circuit and design aspects: *signal coupling, SQUID cascades SQUID arrays, flux trapping*
- noise: excess magnetic flux noise at low temperatures

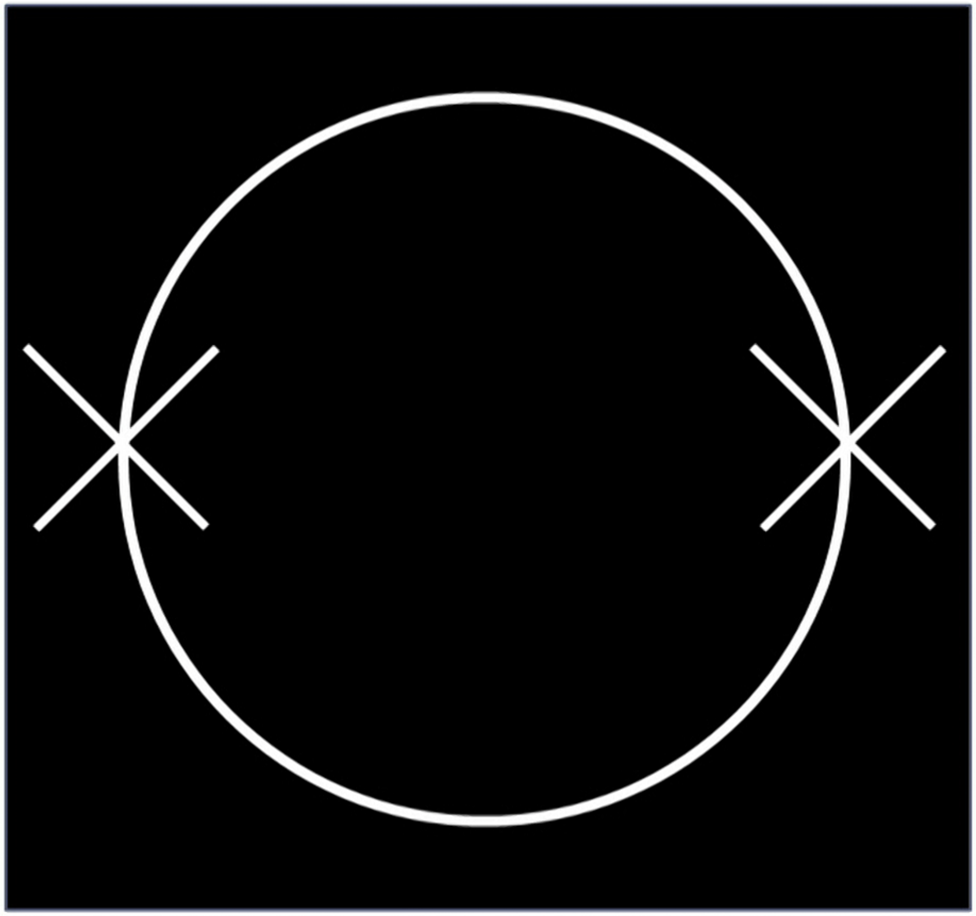
Sensors examples

SQUID readout of TES optical photon counter for ALPS

SQUID sensors for wire-wound magnetometers

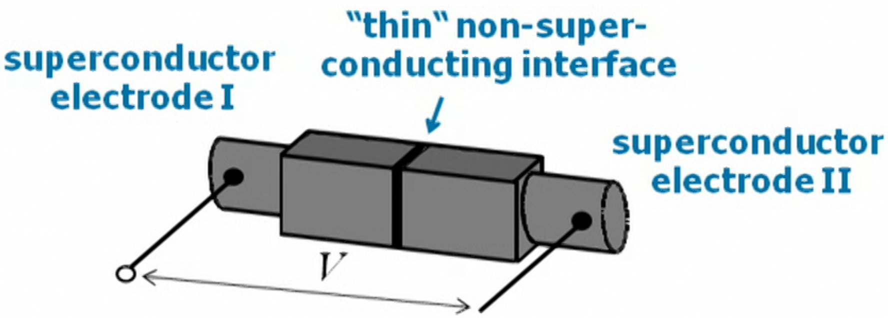
differential SQUID signal booster

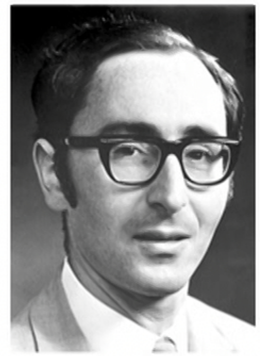
A dc-SQUID – 1 loop, 2 JJs



Superconductive tunneling

- **What happens at a superconducter/superconductor contact?**





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Phys. Lett. **1**, 251

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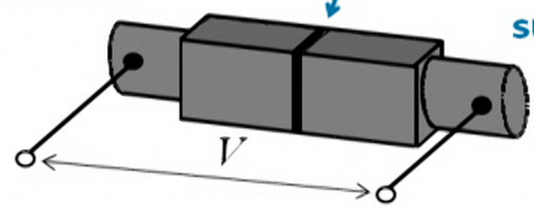

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***Phys. Lett.* 1, 251**

- supercurrent I_c , $V = 0$ → **dc Josephson effect**
- mag. field dependence $I_c(B)$ → **current-phase relation ,** $I_C = I_{Cmax}\sin(\phi)$
- $V \neq 0 \Rightarrow$ ac current I_{ac} , $f_{ac} \propto V$ → **ac Josephon effect ,** $K_{J\text{-}90} = 483.597..\ \mathrm{MHz}/\mu\mathrm{V}$

Superconductive tunneling

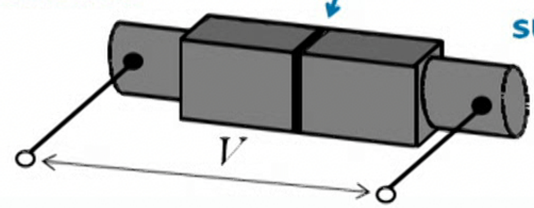
PTB

• What happens at a superconducter/superconductor contact?

superconductor electrode I

"thin" non-super-conducting interface

superconductor electrode II



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Josephson junction – JJ

- configuration of *weakly* coupled superconductors across non-superconductor
- insulator, normal metal, structurally modified superconductor, magnetic material ,...

Superconductive tunneling

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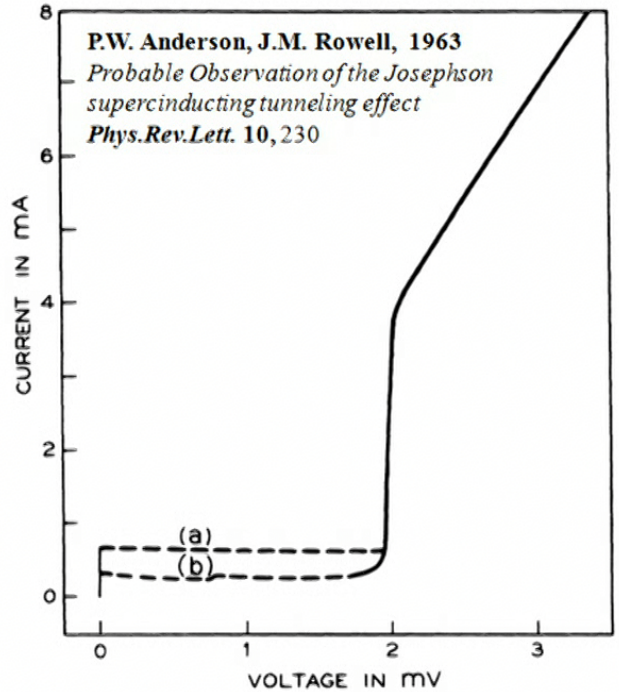

FIG. 1. Current-voltage characteristic for a tin-tin oxide-lead tunnel structure at ~1.5°K, (a) for a field of 6×10^{-3} gauss and (b) for a field 0.4 gauss.

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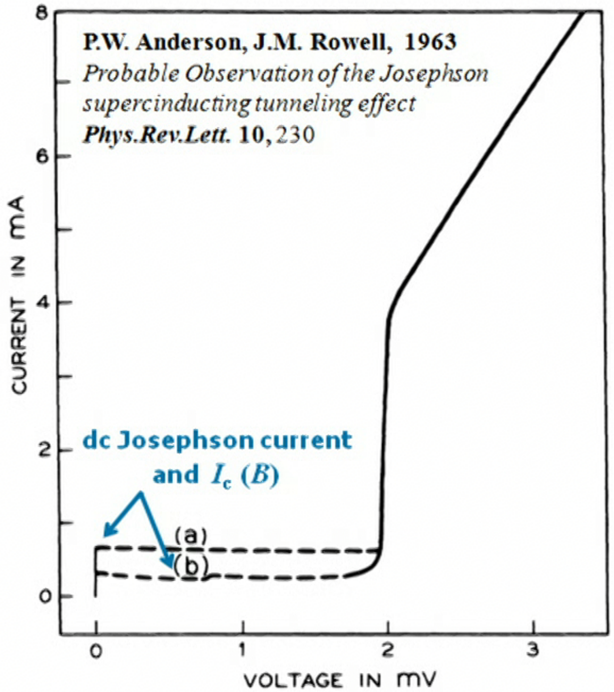

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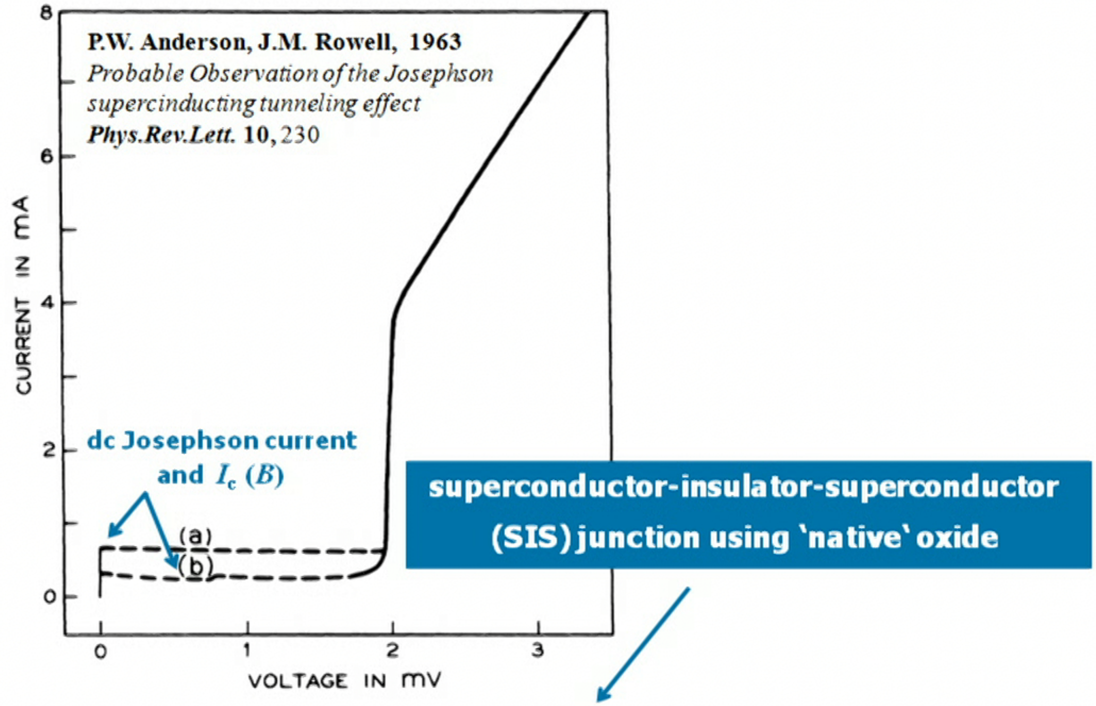

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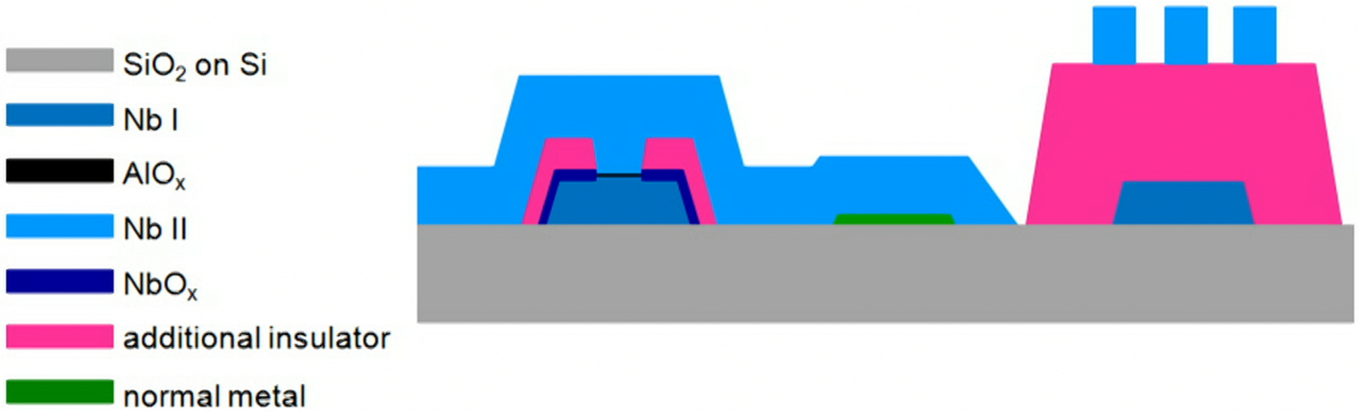
JJs for supercondcting devices

• **Refractory metal SIS junctions – thin film process (PTB)**



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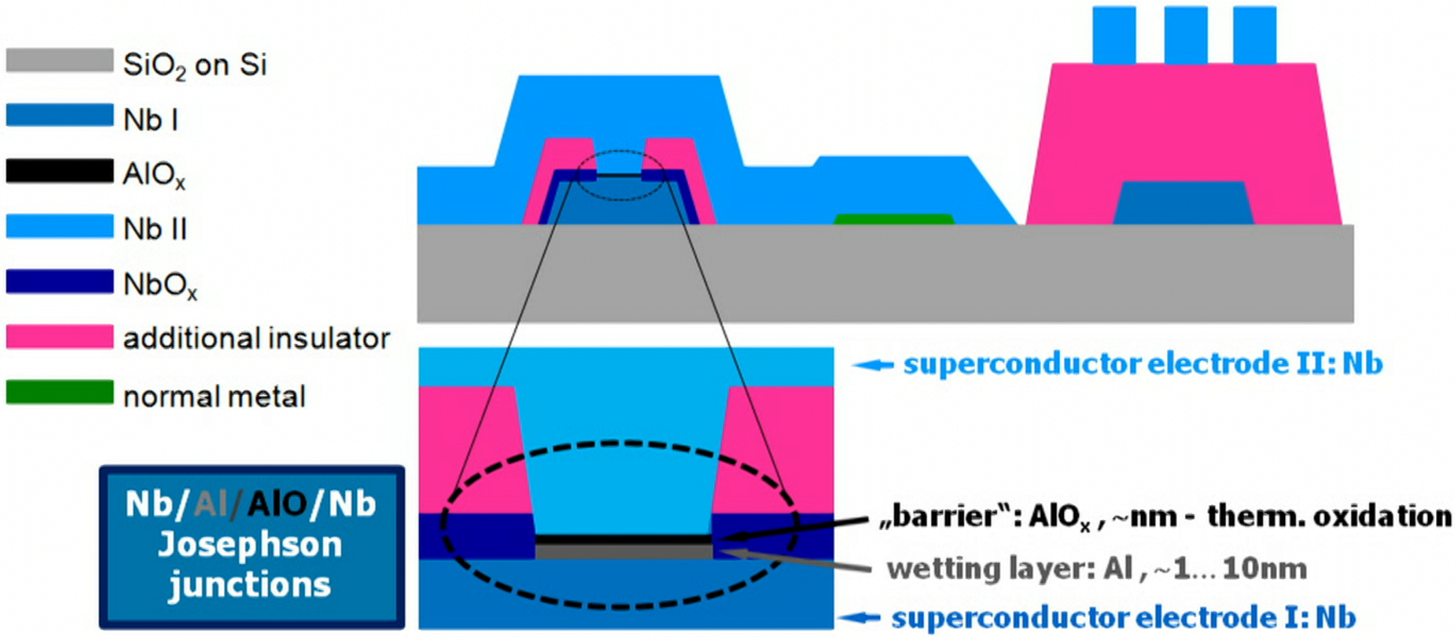
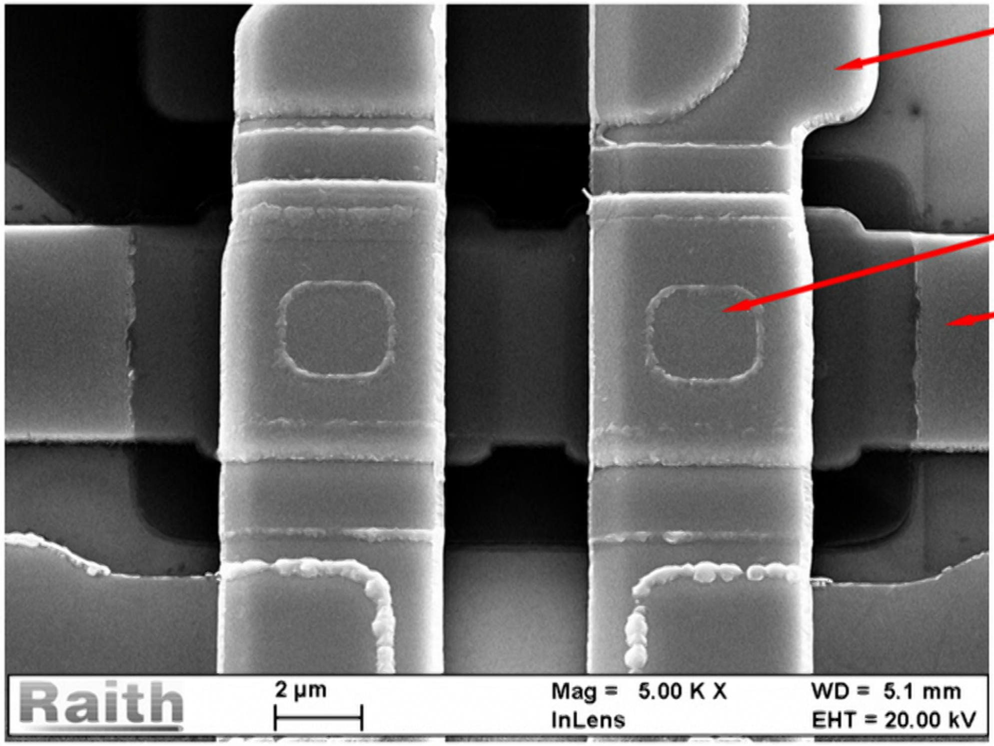


M. Gurvitch et al., 1983
High quality refractory Josephson tunnel junctions utilizing thin aluminium layers
Appl. Phys. Lett. 42, 472

LTS dc-SQUID sensors

- **Example: PTB SQUID fab process, UV contact lithography, min. feature size ≈2μm**



SC-Electrode II: Nb

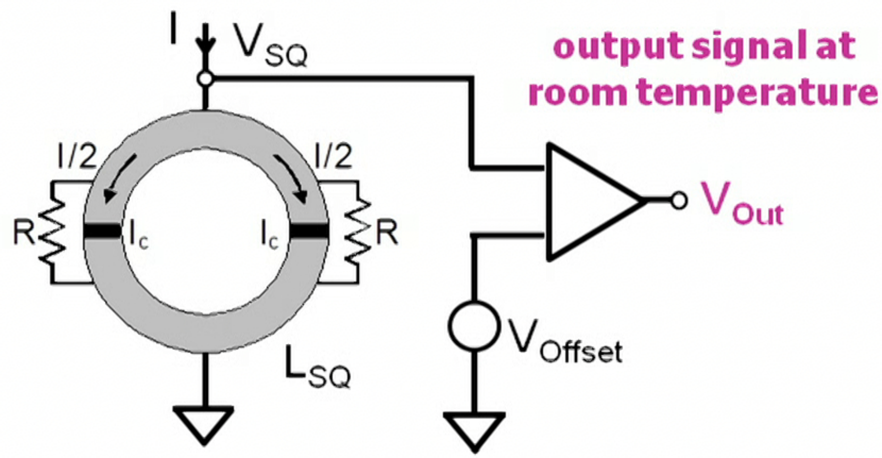
JJ-area, $j_C \approx 100...200\ A/cm^2$

SC-electrode I: Nb

dc-SQUID sensors

PTB

- **superconductor ring interrupted by two Josephson junctions**
  - JJs: regions of weakened superconductivity with a critical current I_C
  - JJs resistively shunted with ohmic resistor R
- **sensor of <u>magnetic flux Φ</u> through the SQUID ring of inductance L_{SQ}**



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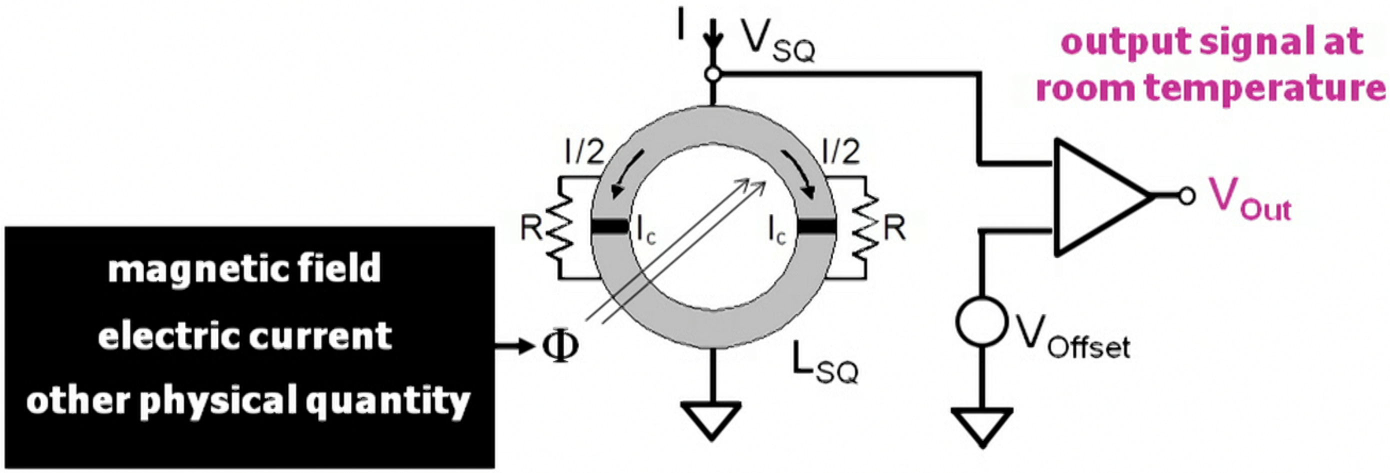

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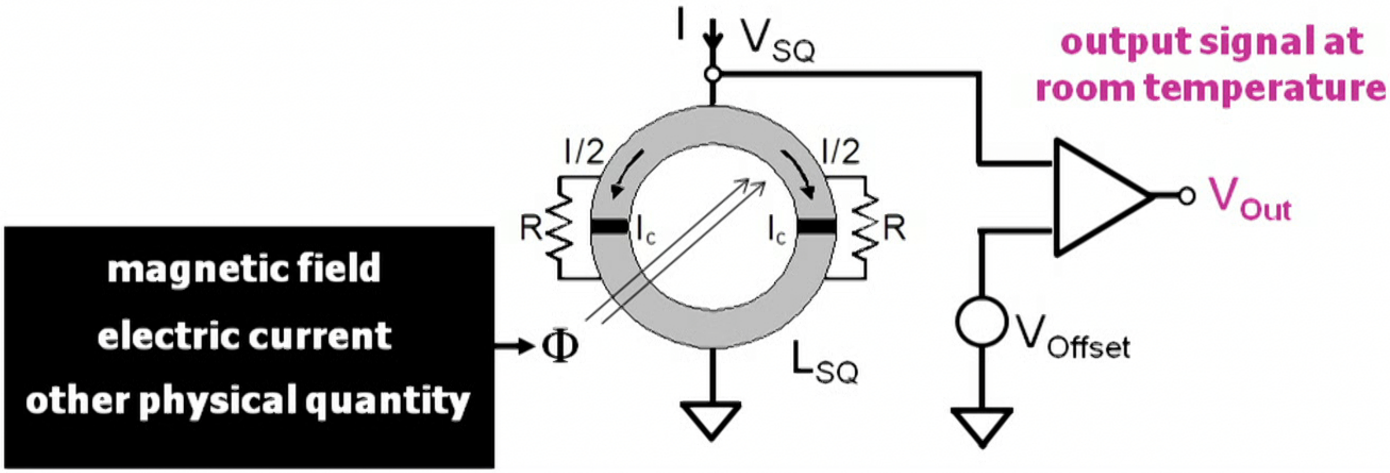

magnetic flux quantization	**Josephson tunneling**
superconductor ring $T < T_c$	SQUID critical current
$\Rightarrow \Phi_{ring} = n \times h/2e = n \times \Phi_0$ $n = 0, 1, 2, 3, \ldots$	$\Rightarrow I_{C,SQ}(\Phi) \propto \lvert\cos(\pi\Phi/\Phi_0)\rvert$

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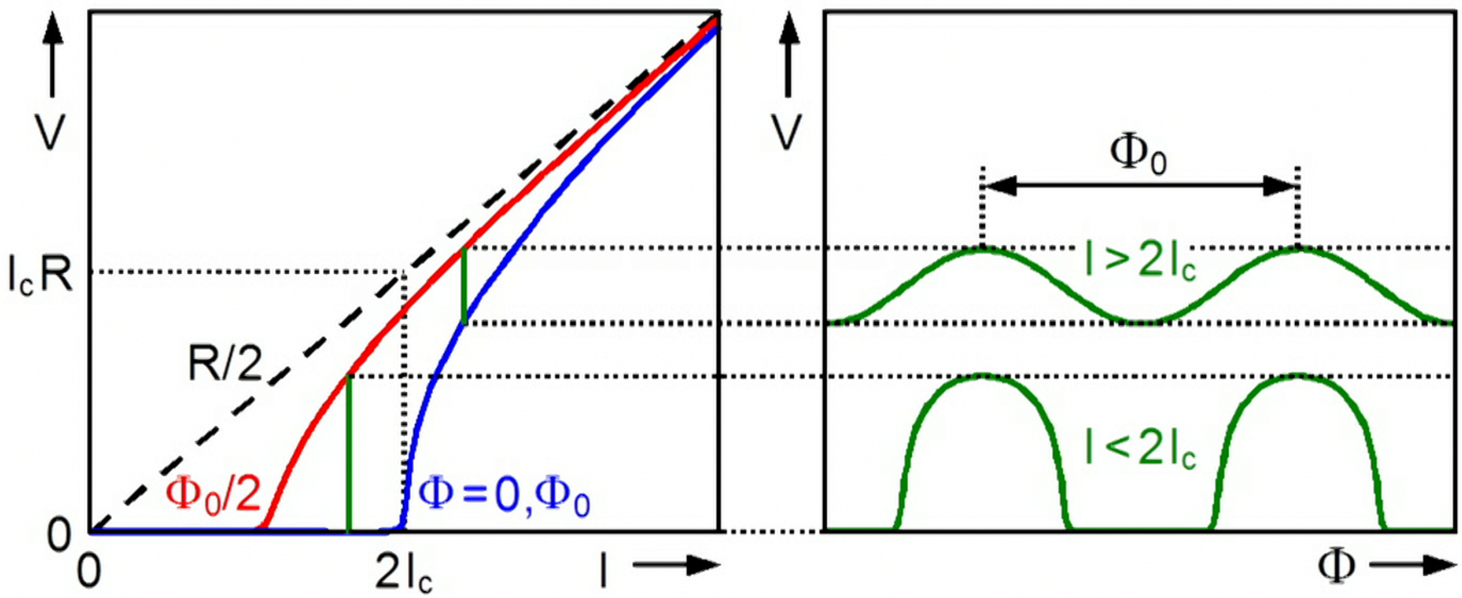

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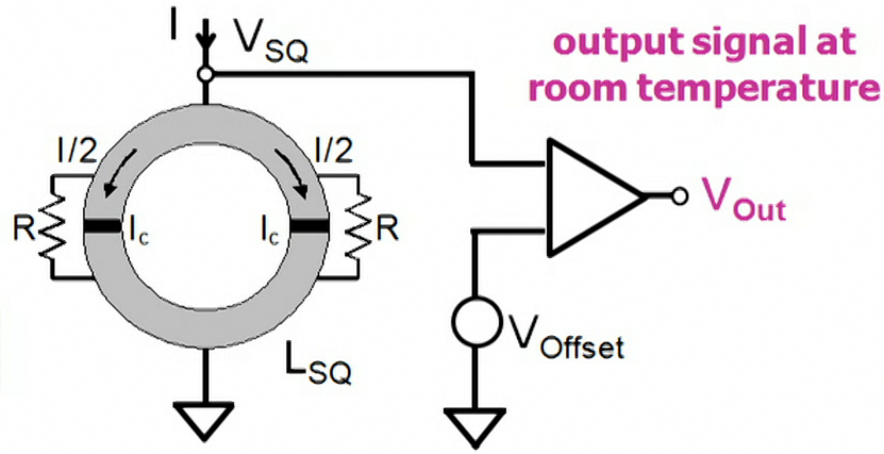


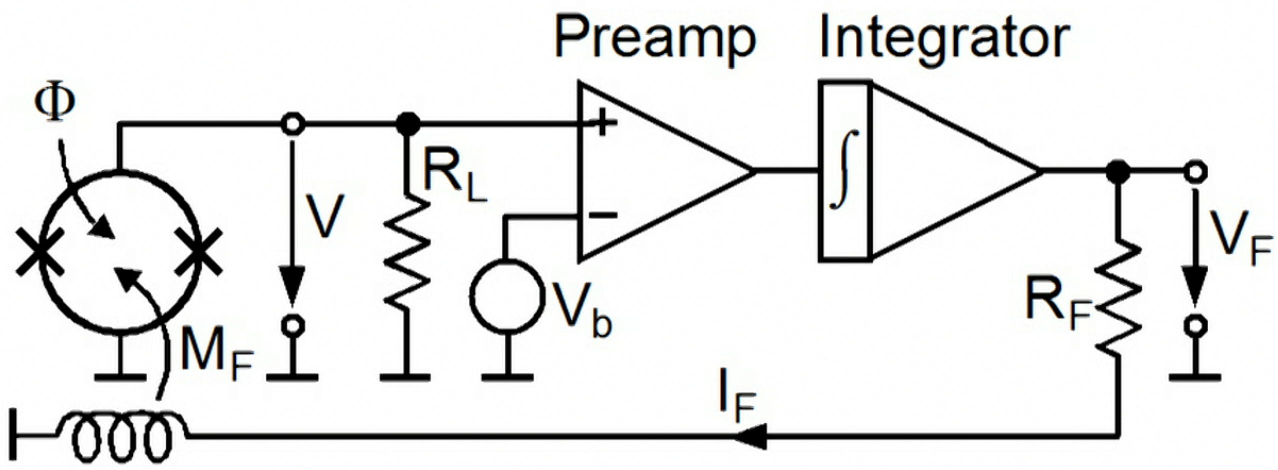
How *fast* is a dc-SQUID?

$$\tau \approx L_{SQ}/2R$$

$$L_{SQ} \approx 100\ \text{pH},\ R \approx 10\ \Omega$$
$$\rightarrow \approx 5\text{ps}$$

dc-SQUID sensors

○ **almost always:** operation in negative feedback („**F**lux-**L**ocked **L**oop")



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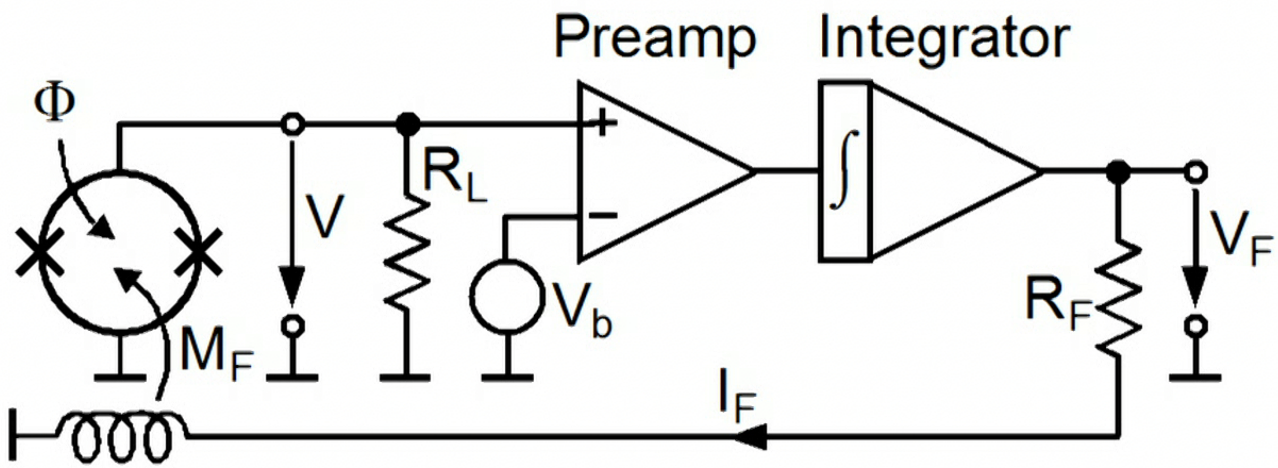
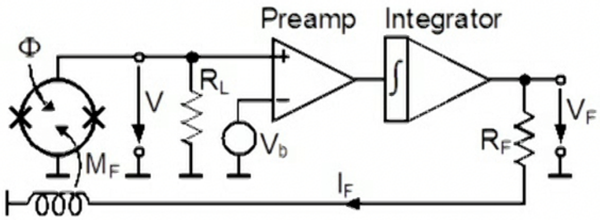


- FLL transfer coefficient $\partial V_F / \partial \Phi = -M_F / R_F$
- flux changes $<<1\Phi_0$ can be measured
- no relevant noise degradation, **but BW limitation**

FLL dynamics - ideal



- **FLL bandwidth f_{3dB}**
  What is the maximum output signal frequency?

- **System slew rate $\partial\Phi_F / \partial t$**
  how fast can the feedback signal change?

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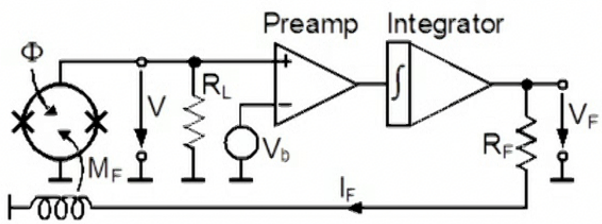

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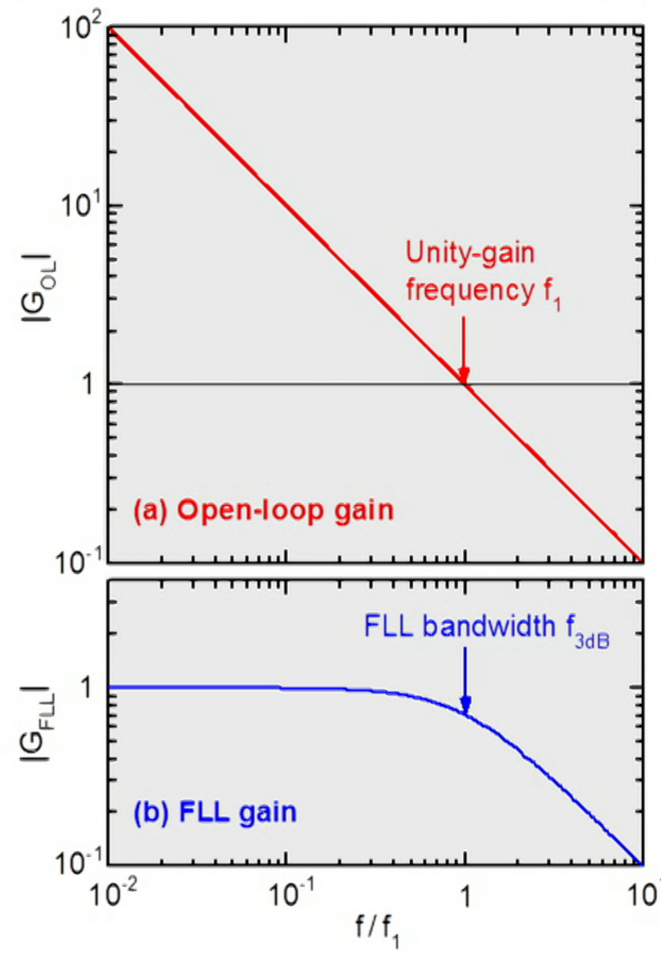
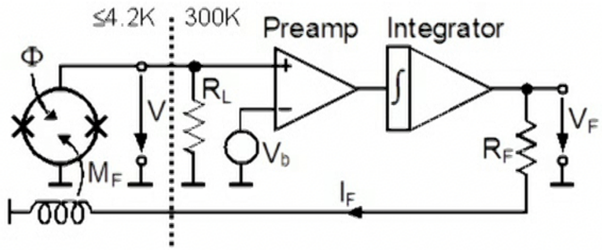
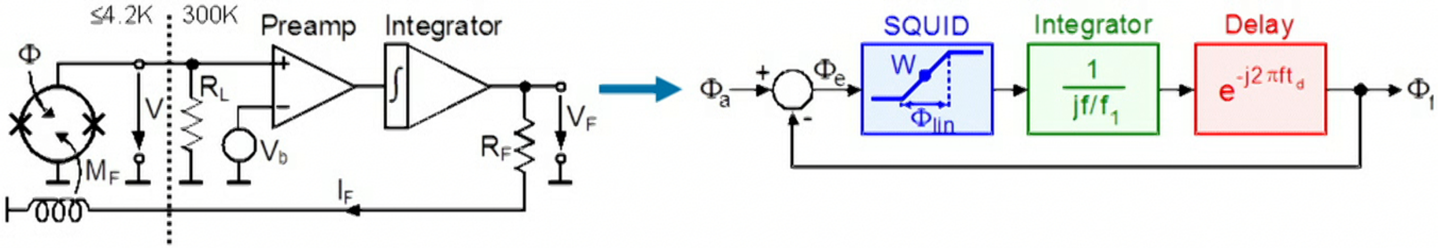


FLL dynamics – delay limit



- 1m cable → $t_d \approx 10$ ns

FLL dynamics – delay limit



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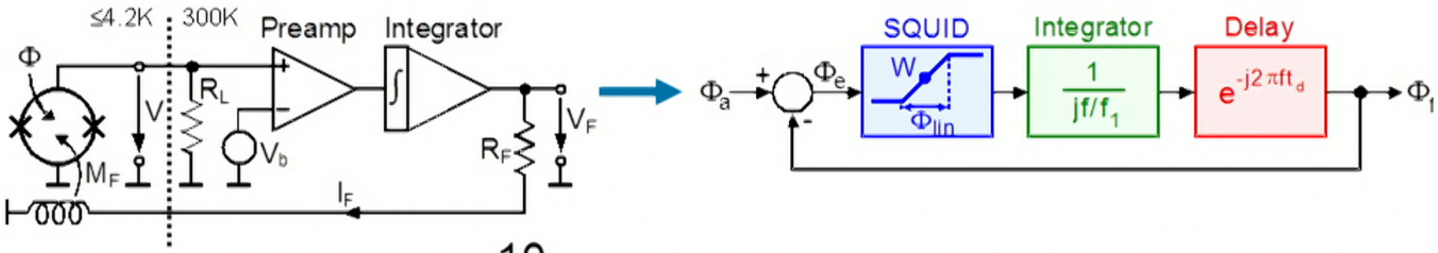

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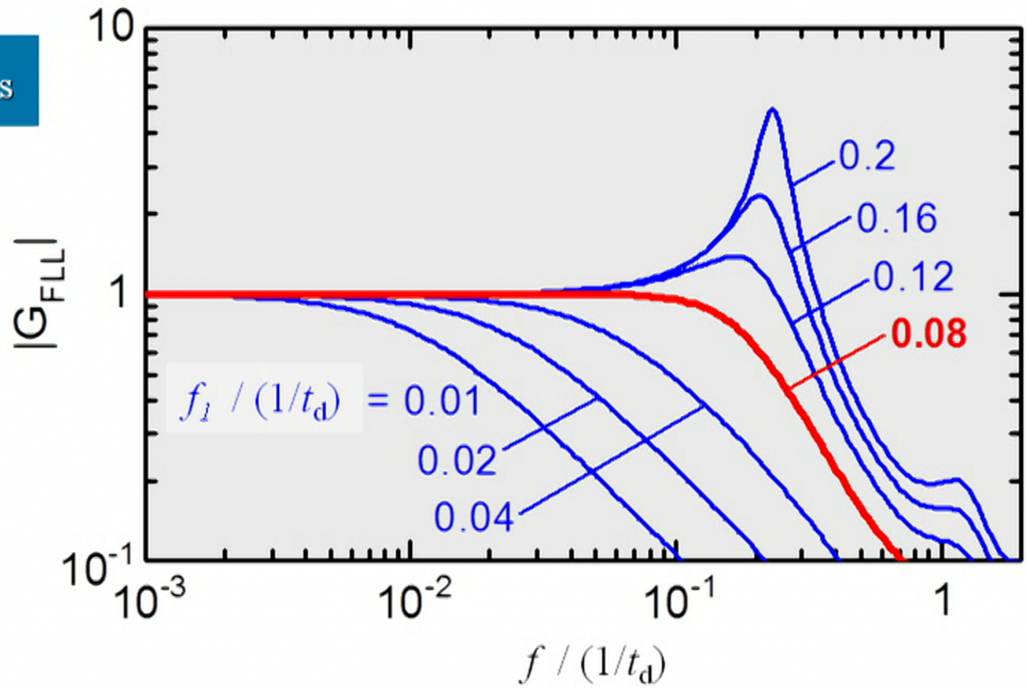

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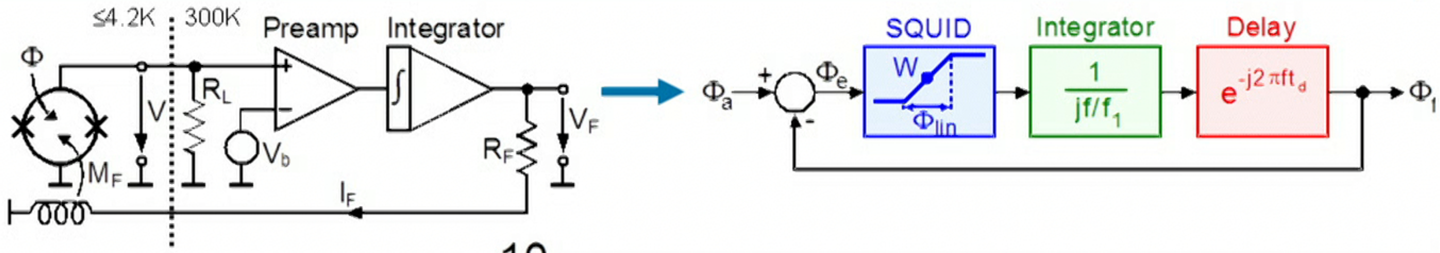
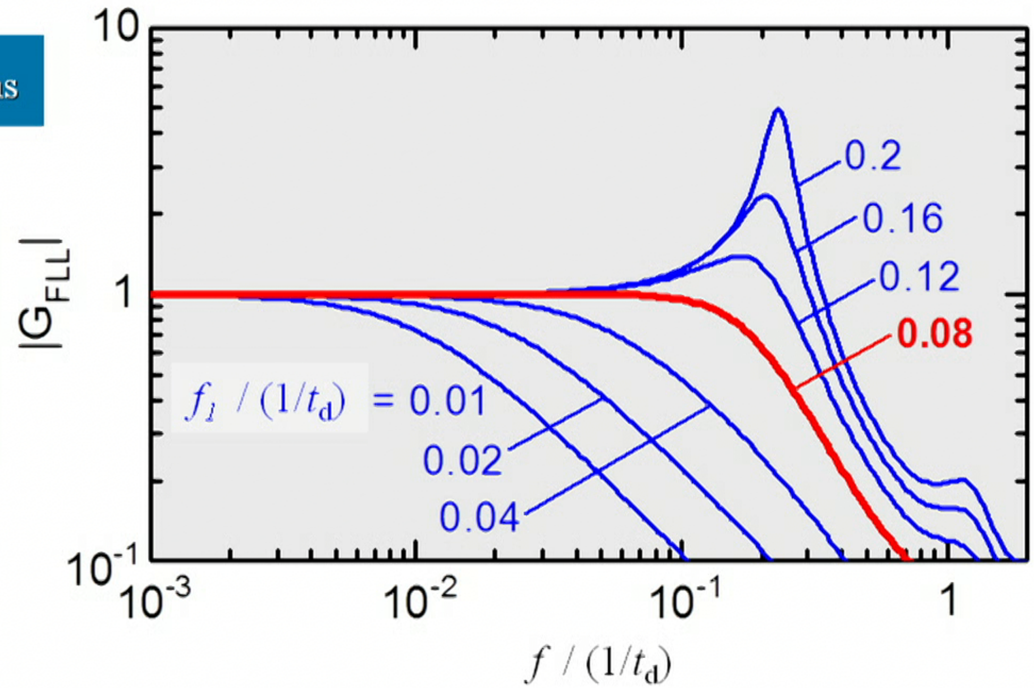


- 1m cable → $t_d \approx 10$ ns

$f_1 = 0.08 / t_d$
≈ 8 MHz

$f_{3dB} = 2.25\ f_1$
≈ 18 MHz



SQUID sensor types

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- ***Magnetometer***

SQUID sensor types

PTB

• *Magnetometer*

Measurand: **magnetic flux density B**

SQUID sensor types

• *Magnetometer*

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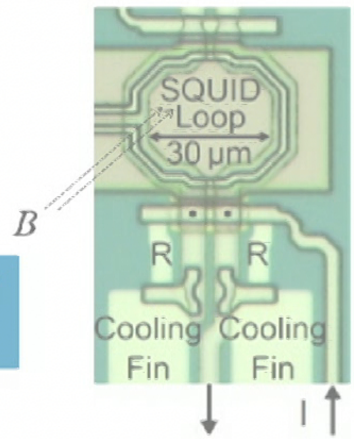
Signal coupling: **"direct"**



Sensitivity
$\delta B / \delta\Phi = 2\ \mu T/\Phi_0$

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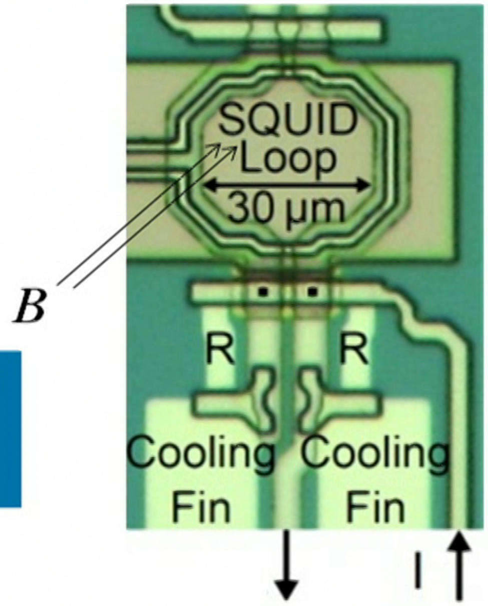

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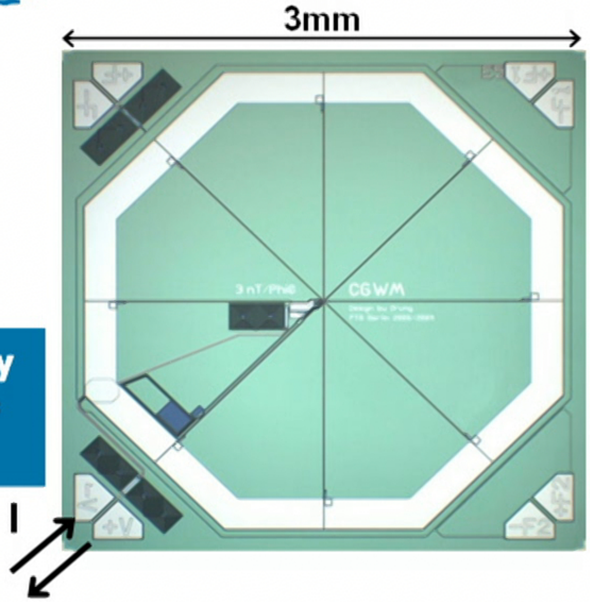

Sensitivity
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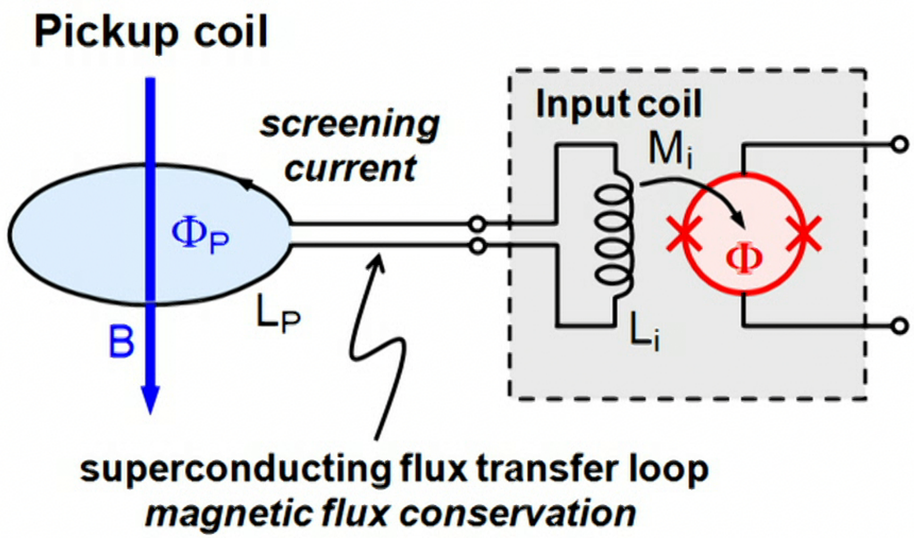

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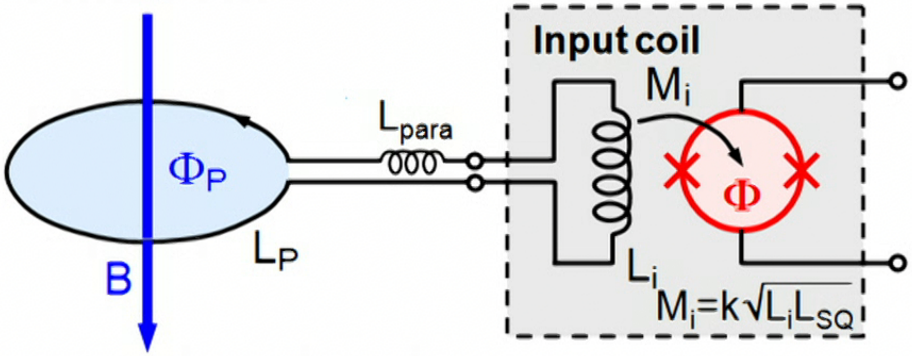
Pickup coil



• optimal signal coupling:

$$\partial\Phi_{SQ} = \frac{1}{2}\frac{k\sqrt{L_{SQ}}}{\sqrt{L_P}}\,\partial\Phi_P$$

$$L_P = L_i\,,\ k \to 1$$
$$L_{para} = 0$$

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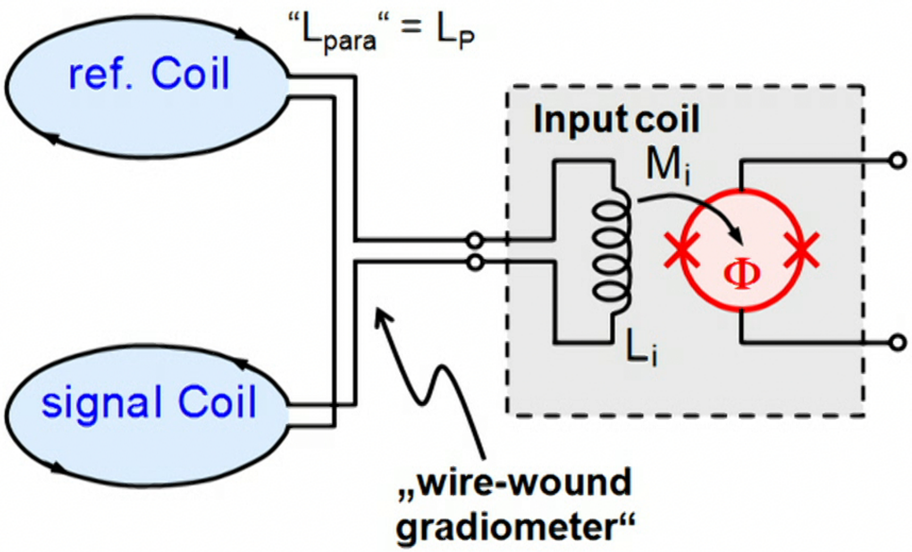
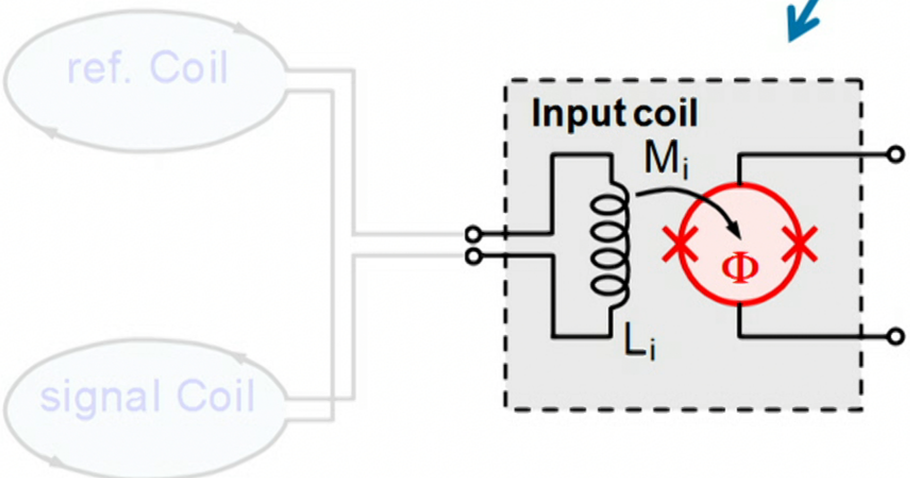


SQUID sensor types

	• *Magnetometer*	• *Current sensor*
Measurand:	magnetic flux density B	electric current I
Signal coupling:	via pick-up coil (often superconducting wire)	via input coil L_i



SQUID sensor types

	• *Magnetometer*	• *Current sensor*
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Signal coupling:	via pick-up coil or direct	via input coil L_i
Sensitivity parameter:	$[A_{eff}^{-1}] = T/\Phi_0$	$[\delta I / \delta\Phi_{Sq}] = A/\Phi_0$
Sensor noise parameter:	mag. flux density noise $[\sqrt{S_B}] = T/\sqrt{Hz}$	current noise density $[\sqrt{S_I}] = A/\sqrt{Hz}$

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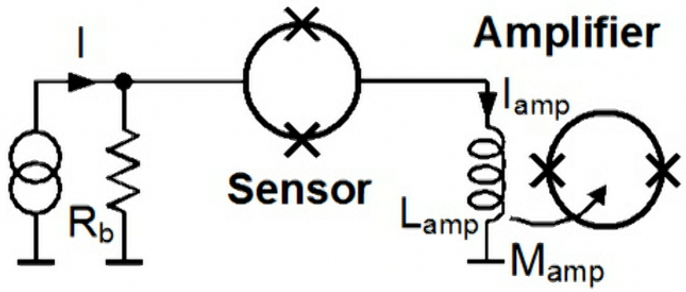
coupled energy sensitvity $[\varepsilon] = h$	$\varepsilon = ½ (A_{eff}^2 / L_{Sq}) S_B$	$\varepsilon = ½ L_i S_I$

SQUID cascades

- **Voltage-biased front-end SQUID read out by following SQUID stage(s)**



advantage

- reduce noise contribution from room temperature electronics

disadvantage

- more complex wiring and response curve
- higher dissipation power and heat load

SQUID cascades

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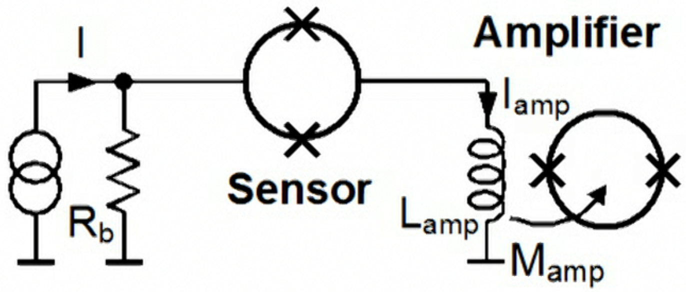

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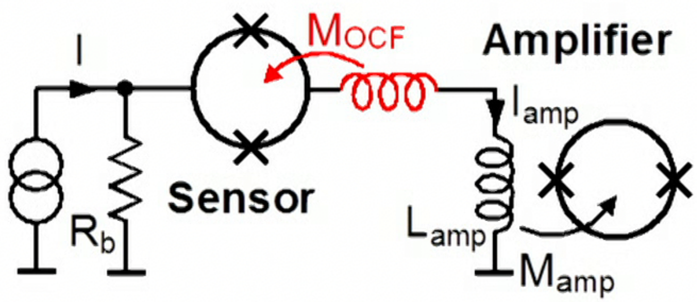
- sensor SQUID output current fed back to sensor SQUID



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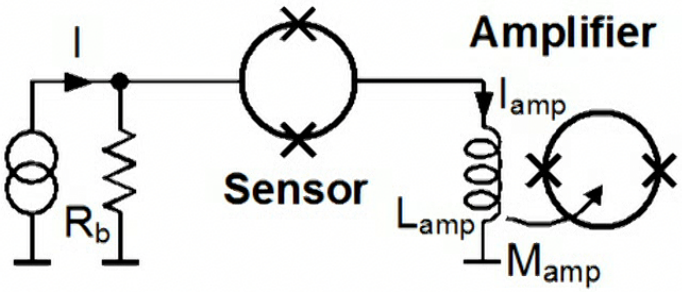

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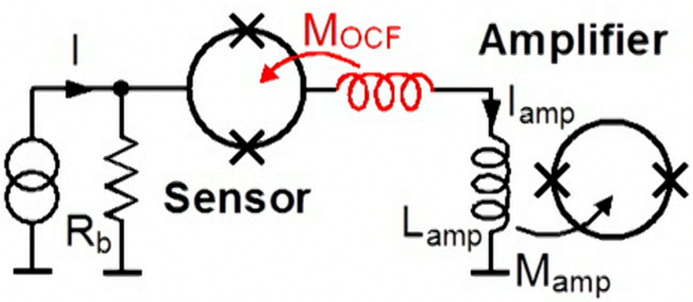

advantage
- increases sensor-to-amp flux gain
- reduces noise contribution of amp to sensor

disadvantage
- SQ1 dynamic range is somewhat reduced

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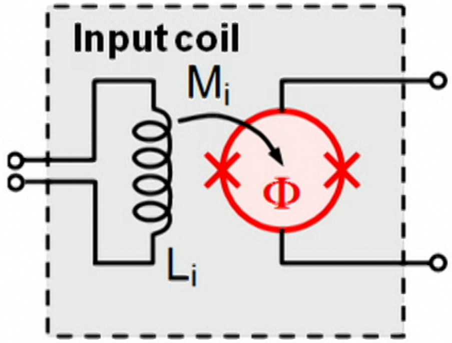
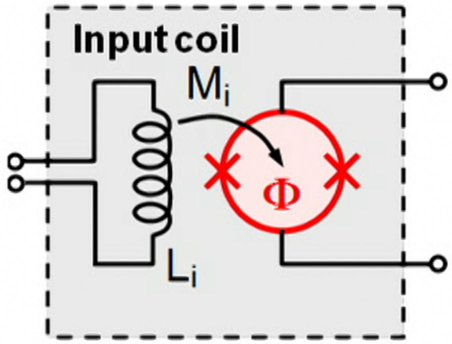
Current sensor input coupling



- **required L_i determined by source of signal current to be measured**
  - minimal L_i of order of SQUID inductance ≈ 10pH…1nH
- **when larger input inductances required**
  → (1) double transformer input

Current sensor input coupling

PTB



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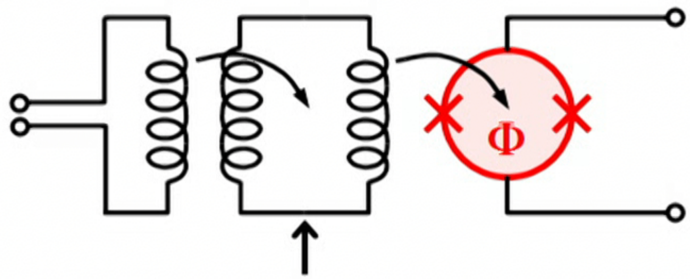
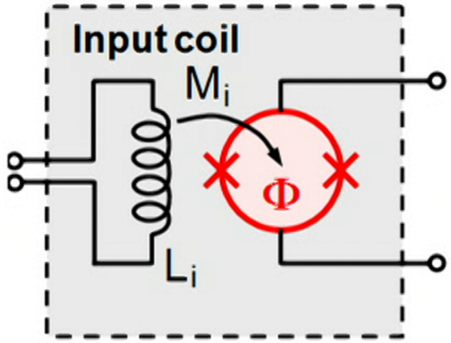


- ○ susceptible to magnetic interference
- ○ affects L_i and S_I
- ○ parasitic resonances can occur
  → **more complex sensor design**

Current sensor input coupling



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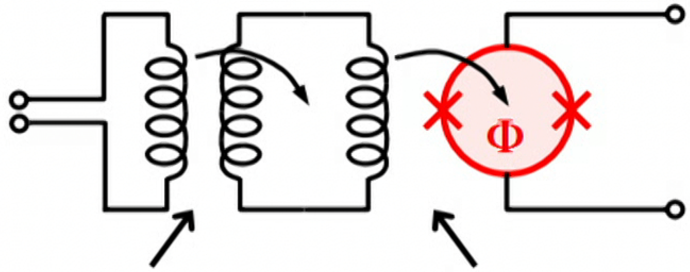

→ current sensor with "double-transformer input"

- ○ susceptible to magnetic interference
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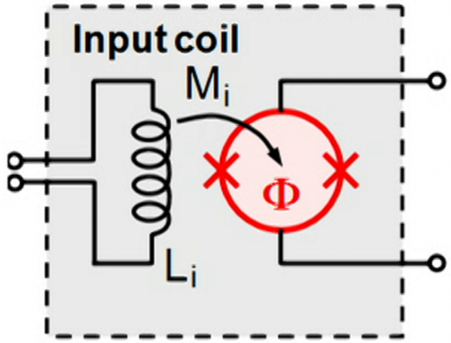
  → more complex sensor design

Input coupling



- **required L_i determined by source of signal current to be measured**
  - minimal L_i of order of SQUID inductance ~10pH…1nH
- **when larger input inductances required**
  → (2) SQUID arrays with serial input

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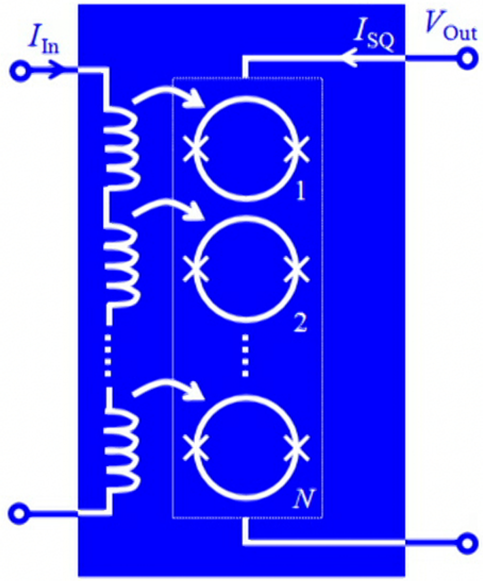

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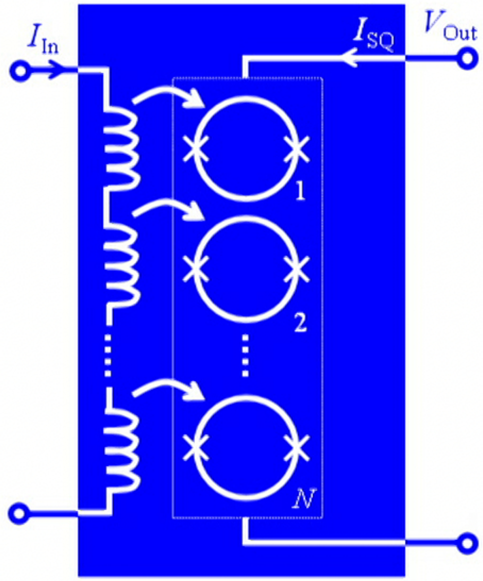
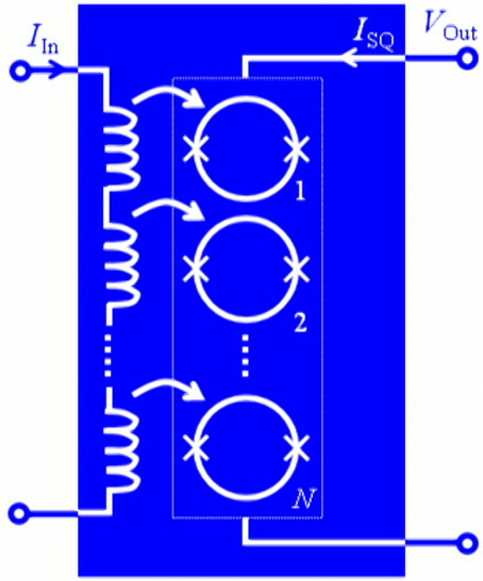
SQUID arrays



- **input coils of array elements all in series**
  → signal correlated, but intrinsic noise of array elements uncorrelated

Single SQUID	N SQUID series array	N SQUID parallel array
ε_c	ε_c	ε_c
S_I	S_I / N	S_I / N
D	$\sqrt{N} \times D$	$\sqrt{N} \times D$

SQUID arrays



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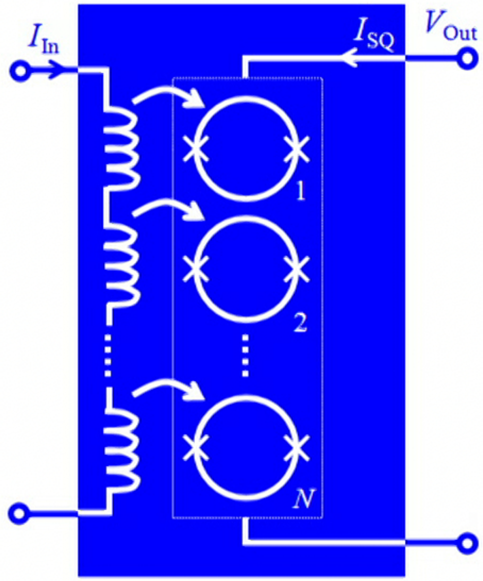
ε_c	ε_c	ε_c
S_I	S_I / N	S_I / N
D	$\sqrt{N} \times D$	$\sqrt{N} \times D$

- **series, parallel or serial/parallel arrays**
  → flexible dimensioning of array output & transimpedance

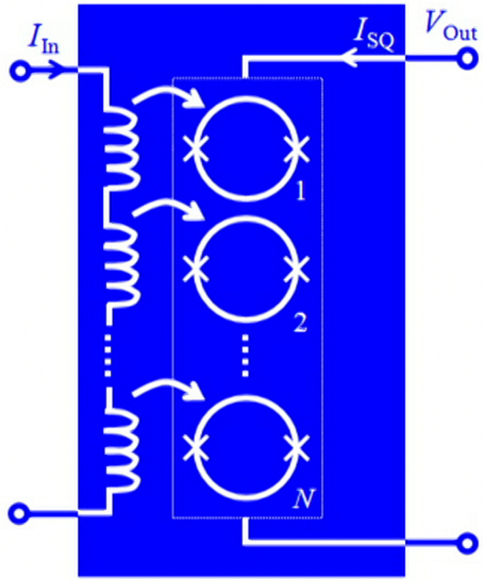
Single SQUID	N SQUID series array	N SQUID parallel array
R_{dyn}	$N \times R_{\text{dyn}}$	R_{dyn} / N
R_{trans}	$\approx N \times R_{\text{trans}}$	$\approx R_{\text{trans}} / N$
P_{Diss}	$N \times P_{\text{diss}}$	$N \times P_{\text{Diss}}$

SQUID arrays – flux trapping



- *single-SQUID-like* array behavior requires identical flux (offsets) in each array element

SQUID arrays – flux trapping



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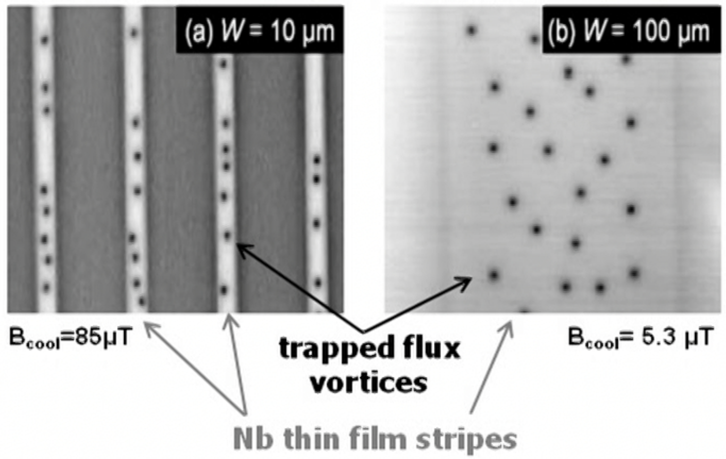
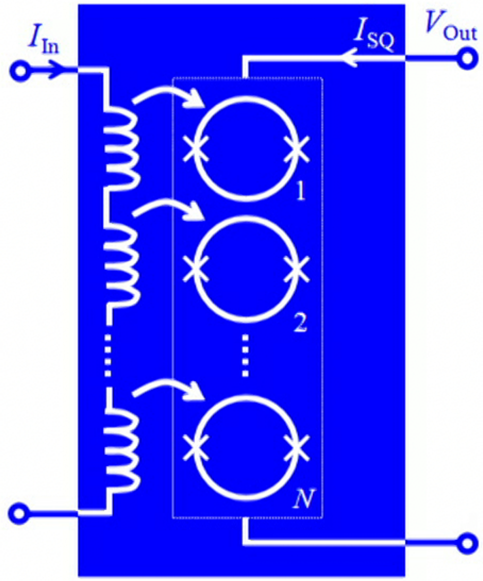
Cooling in or exposure to 'large' magnetic fields of type-2 superconductor Nb

from G. Stan, et. al., Phys. Rev. Lett. 92, 097003 (2004)



SQUID arrays – flux trapping



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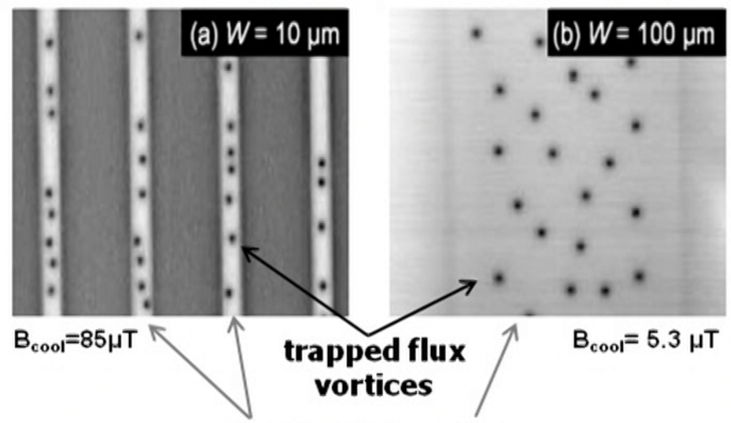
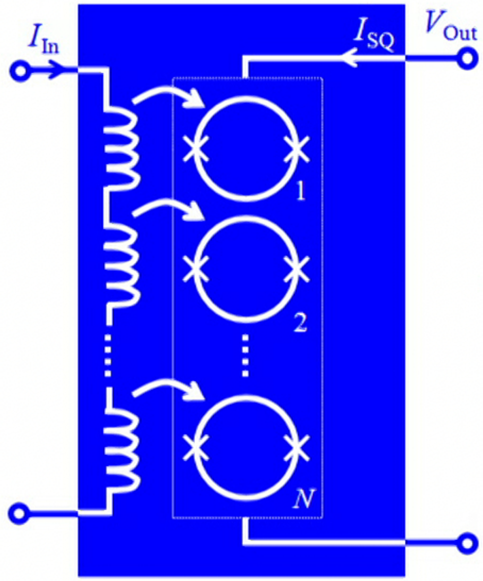


- **cooling field w/o trapped flux:**

$$B_{ffc} \approx \Phi_0 / W^2$$

SQUID arrays – flux trapping



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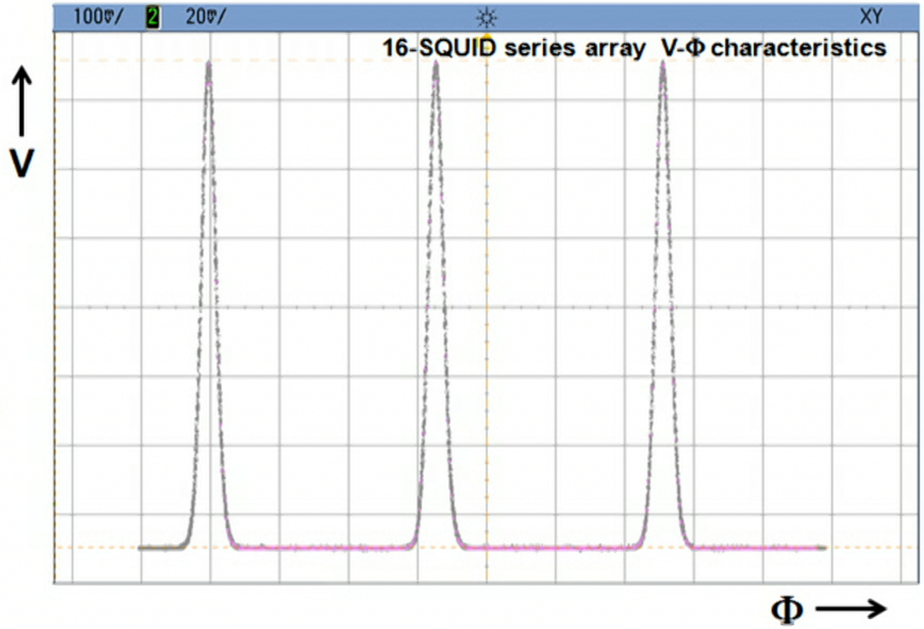
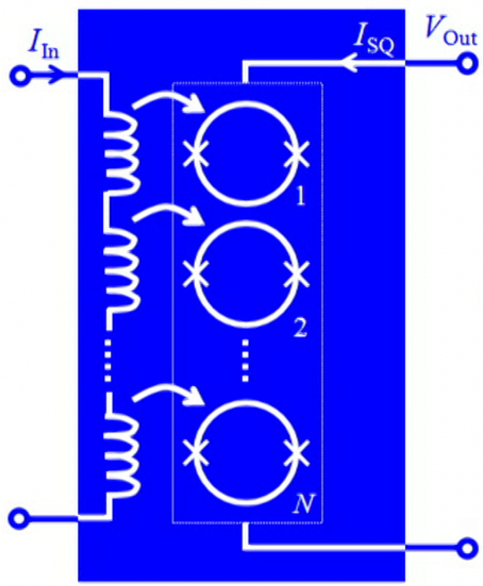


SQUID arrays – flux trapping



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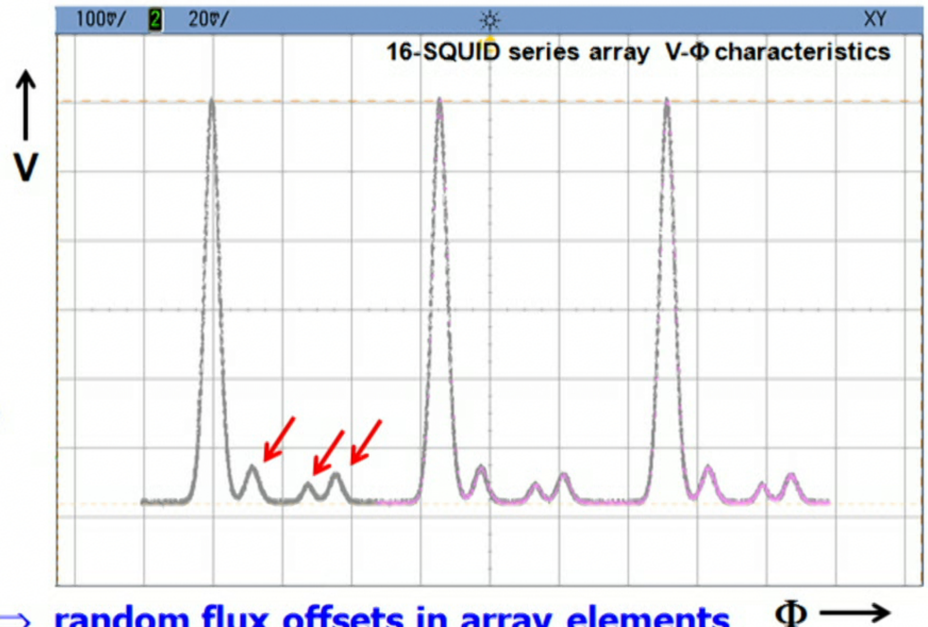


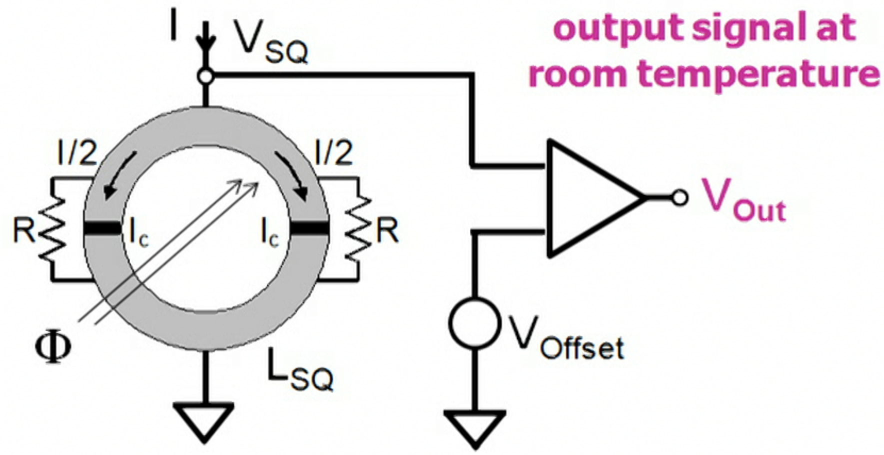
⇒ random flux offsets in array elements

⇒ degraded SQUID array performance

⇒ also, noise from vortex motion

Magnetic flux noise

- sensor of magnetic flux Φ through the SQUID ring



$$\Rightarrow \varepsilon_{theor} \equiv \frac{S_\Phi}{2L_{SQ}} \approx \frac{2(1+\beta_L)\,\Phi_0\,k_B T}{I_C R}$$

$$\beta_L = 2 I_C L_{SQ} / \Phi_0 \approx 1$$

for optimum LTS-SQUID noise

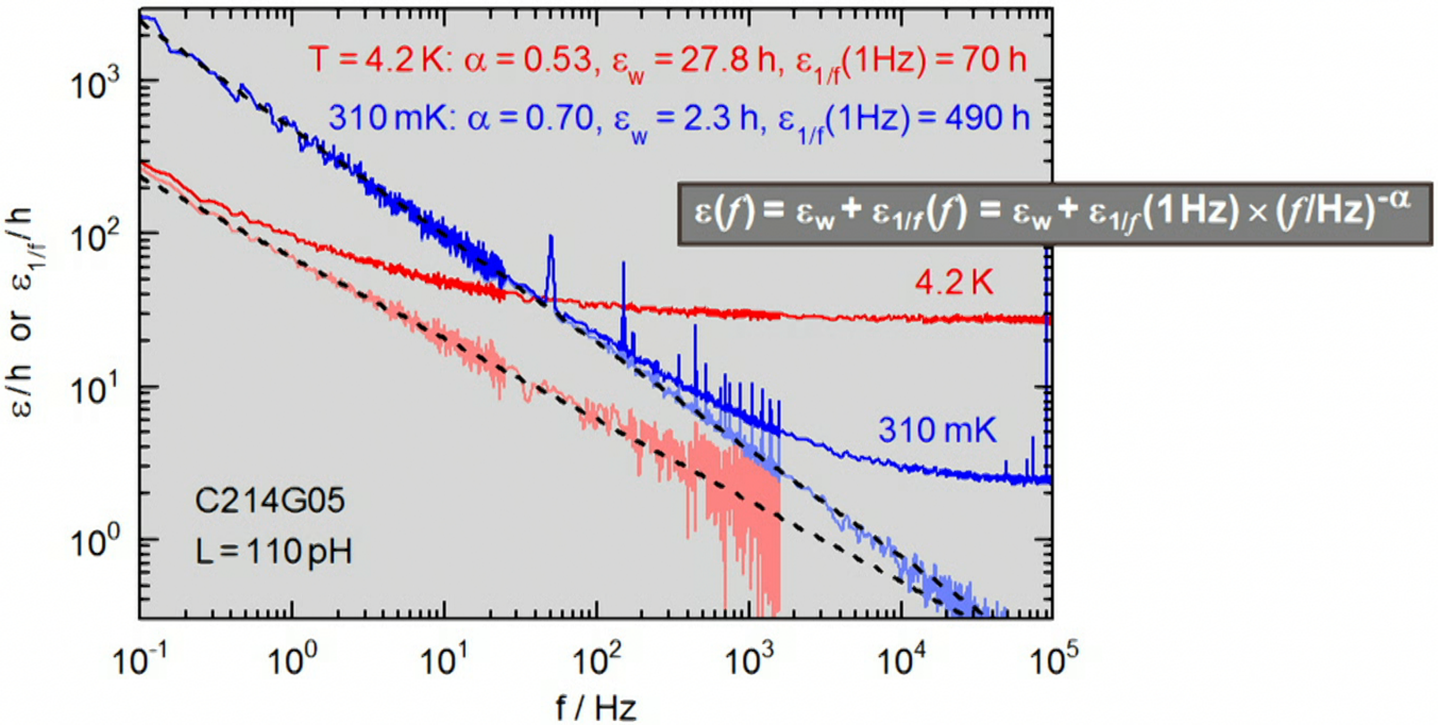
Chesca B, Kleiner R and Koelle D 2004, *SQUID Theory*
in *The SQUID Handbook* ed J Clarke and A I Braginski
(Weinheim: Wiley)

Magnetic flux noise

- ***cool down your SQUID sensor to lowest possible*** T_{Op}

Magnetic flux noise

- increase in "real" excess magnetic flux noise upon cooling, while white noise decreases with lowering temperature T_{Op}



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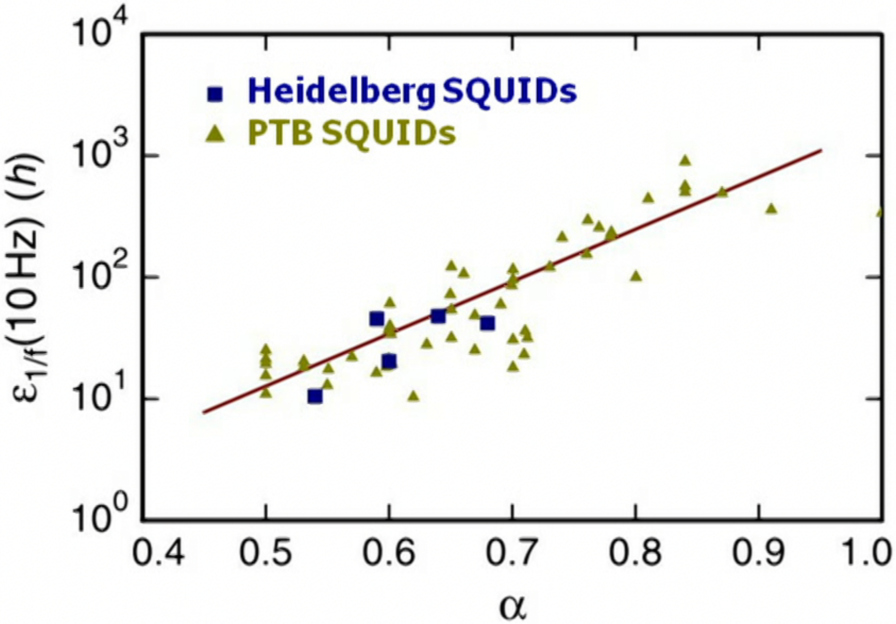
Supercond. Sci. Technol. **28** (2015) 045008 S. Kempf et al. U Heidelberg



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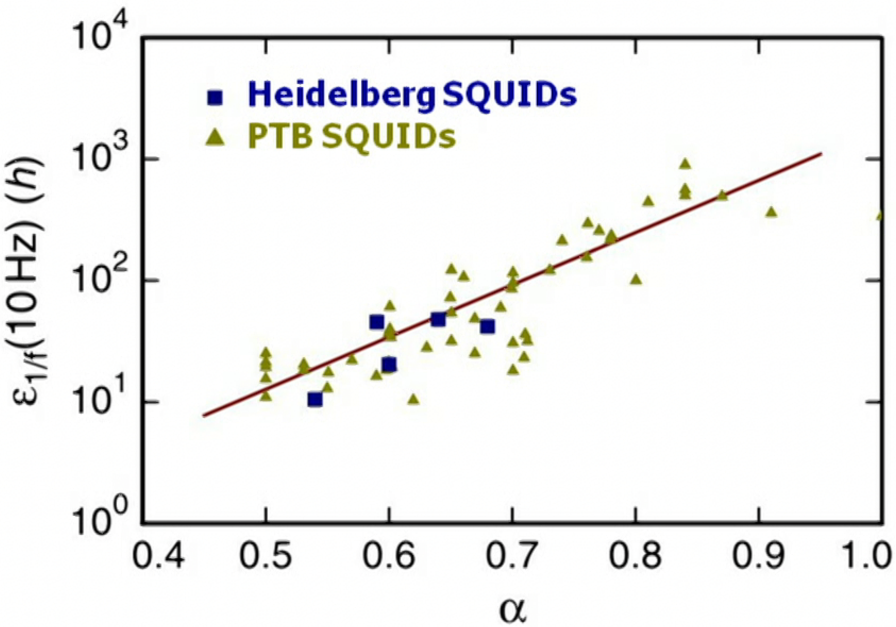

- random reversal of surface spin impurities: ? *danglings bonds, adsorbed O_2, nuclear spins, metal-induced gap states, ...*

Magnetic flux noise

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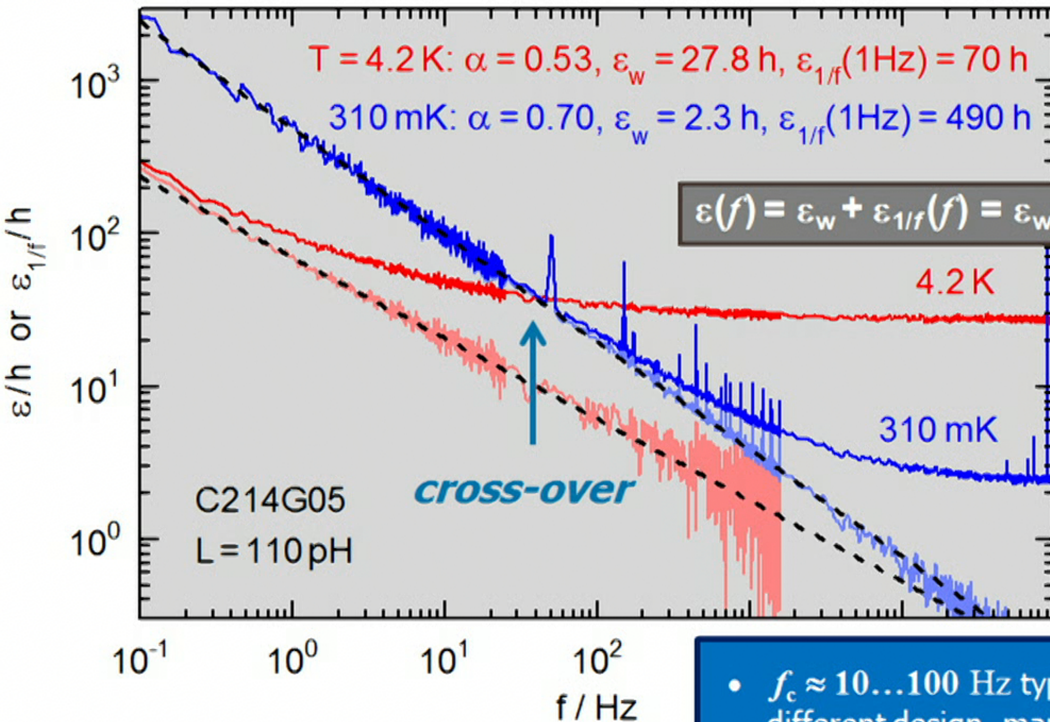


$$\varepsilon(f) = \varepsilon_w + \varepsilon_{1/f}(f) = \varepsilon_w + \varepsilon_{1/f}(1\,\text{Hz}) \times (f/\text{Hz})^{-\alpha}$$

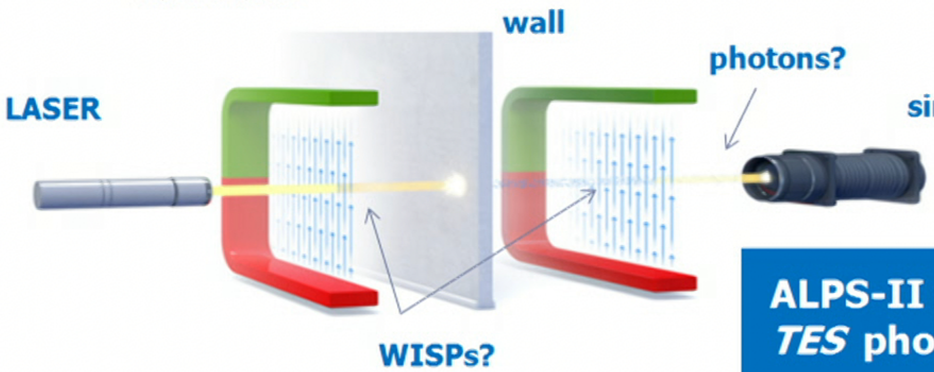
- $f_c \approx 10\ldots100$ Hz typical for sensors of very different design, manufacturer, materials
- higher T_{op} better for low frequency signals

SQUID sensor examples

SQUID sensors for TES readout

ALPS
Any Light Particle Search
alps.desy.de

Light-shining-through-a-wall experiment



ALPS-II :
TES **photon counter @ 1064nm**

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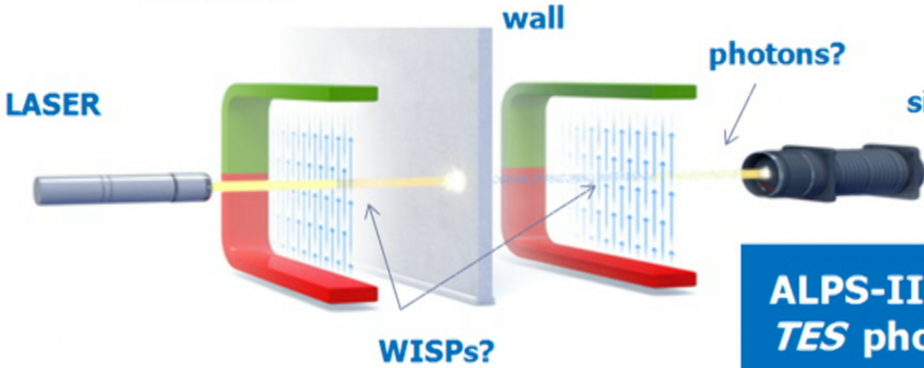

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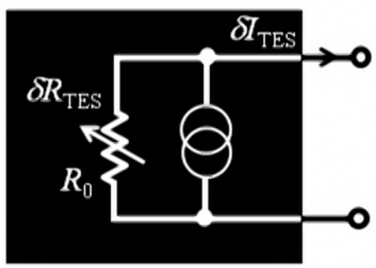
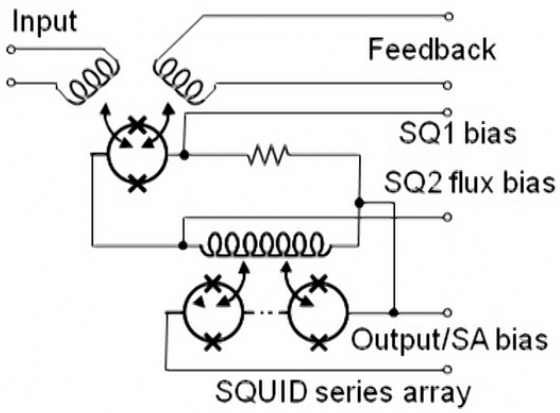


R_0	$\approx 1\ \Omega$
I_0	$\approx 100\ \mu\mathrm{A}$
δI_{TES}	$\approx 100\ \mathrm{nA}$
τ	$\approx 0.1 \ldots 1\ \mu\mathrm{s}$
T_{Bath}	$\approx 100\ \mathrm{mK}$
$\sqrt{S_{\mathrm{I,TES}}}$	$\approx 5\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$

SQUID sensors for TES readout



• 2-stage SQUID current sensor

- front-end SQ1 read out by 14-SQUID series array
- single-SQUID-like flux-response
- mK operation ok , magnetically robust
- integrated TES bias resistors & rf-filtered connections
- $L_{\mathrm{In}} \approx$ 2nH , input/feedback inductively decoupled

$\sqrt{S_I} < 2\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$ @ 0.1 K , $P_{\mathrm{Diss}} \approx$ **3 nW**

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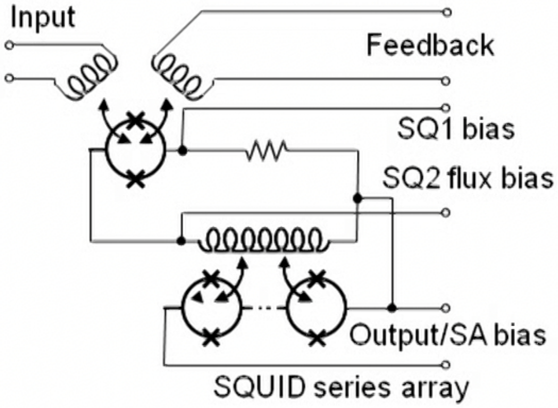

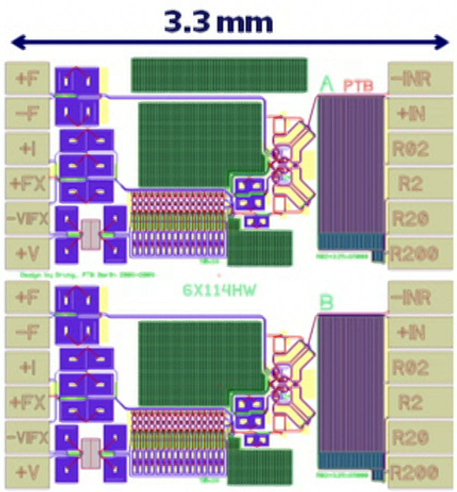

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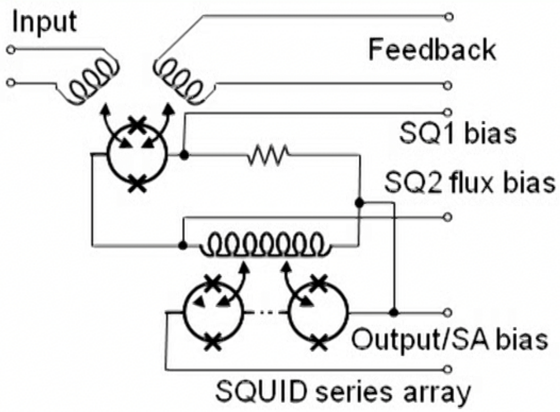
SQUID sensors for TES readout

PTB



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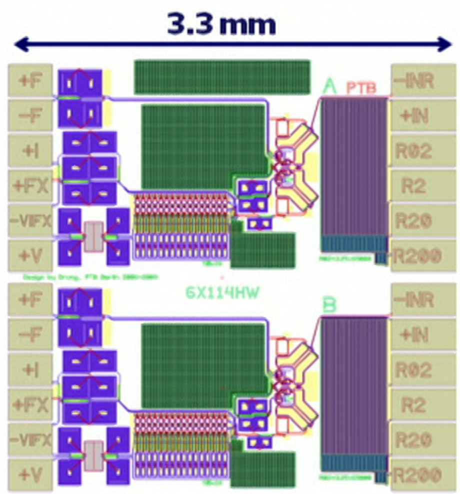
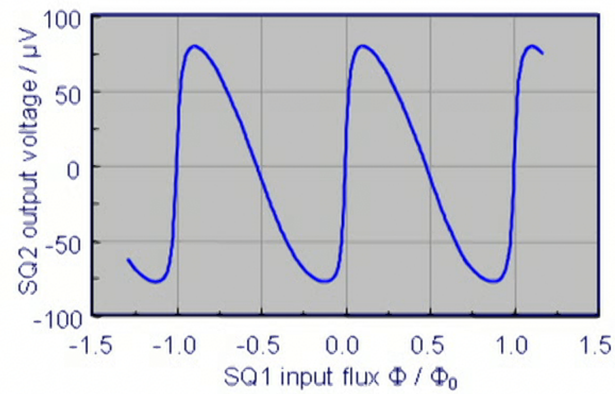
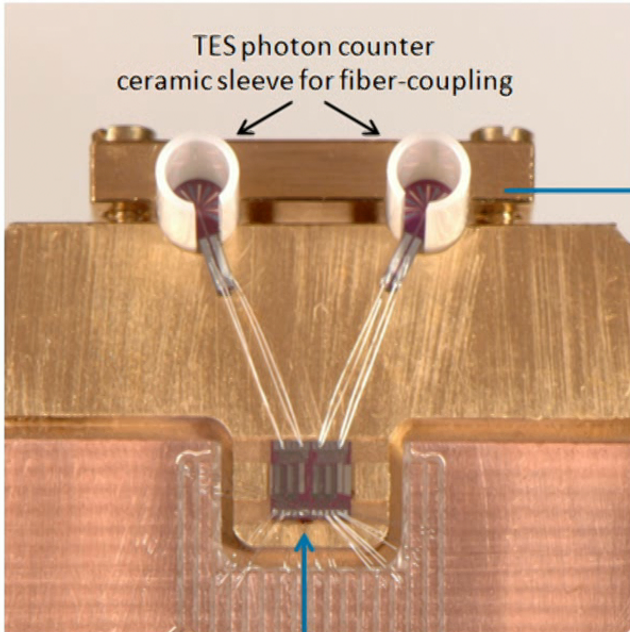
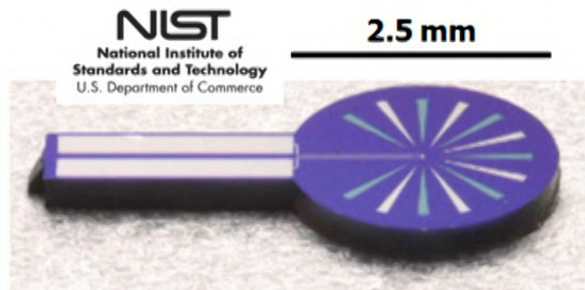


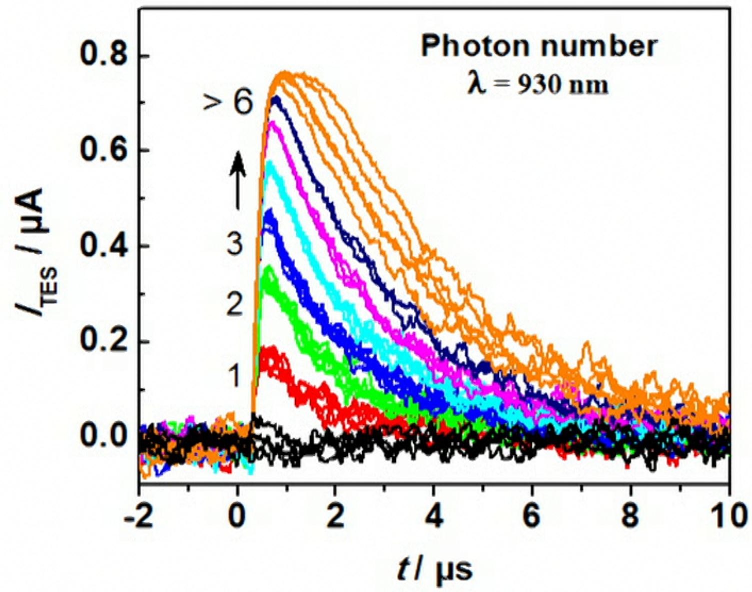


SQUID sensors for TES readout



**X114HW current sensor
chip size 3 mm × 3 mm**





SQUID sensors for pick-up coils

- **common configuration: superconducting wire-wound pick-up coil**
  - e. g. biomagnetism, susceptometry, NMR/NQR
  - $L_p \approx 0.1 \ldots 1\ \mu H$

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PTB

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PHYSICAL REVIEW X **4**, 021030 (2014)

Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)

Dmitry Budker,[1,5] Peter W. Graham,[2] Micah Ledbetter,[3] Surjeet Rajendran,[2] and Alexander O. Sushkov[4]

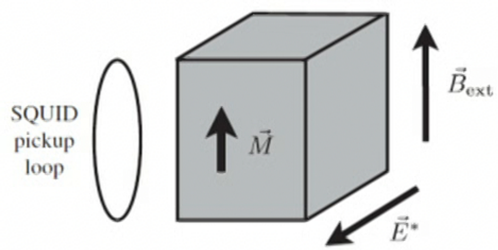

FIG. 1. Geometry of the experiment. The applied magnetic field $\vec{B}_{\text{ext}}$ is colinear with the sample magnetization $\vec{M}$. The effective electric field in the crystal $\vec{E}^*$ is perpendicular to $\vec{B}_{\text{ext}}$. The SQUID pickup loop is arranged to measure the transverse magnetization of the sample.

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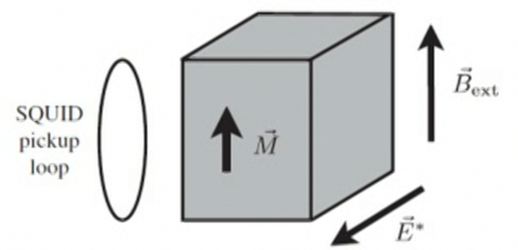

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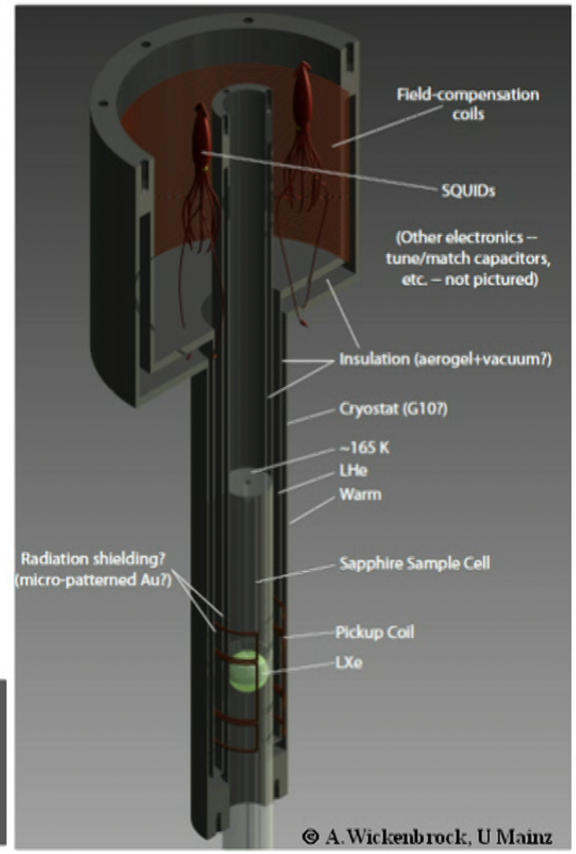
Xe-129:

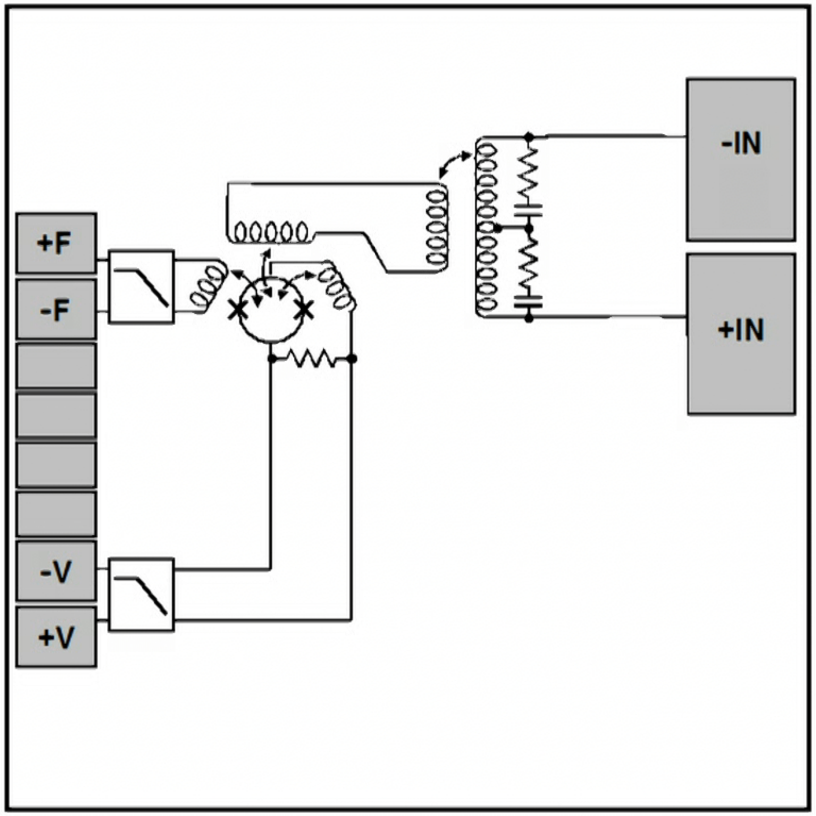
$B_{ext,max} = 10\,T \ldots 20\,T$

$f_{sig,max} = 118\,MHz \ldots 236\,MHz$



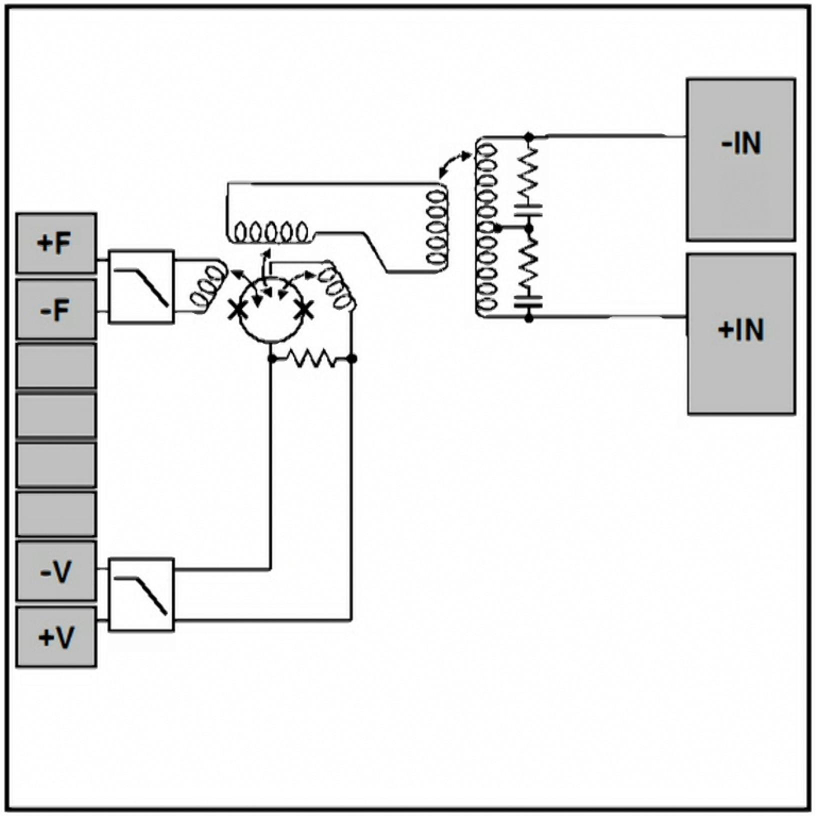
SQUID sensors for $L_p \approx 0.1 \ldots 1\ \mu H$

PTB



- single-SQUID current sensors with double transformer input
- different input inductances L_i
- developed for LHe operation

SQUID sensors for $L_\mathrm{p} \approx 0.1 \ldots 1\ \mu\mathrm{H}$



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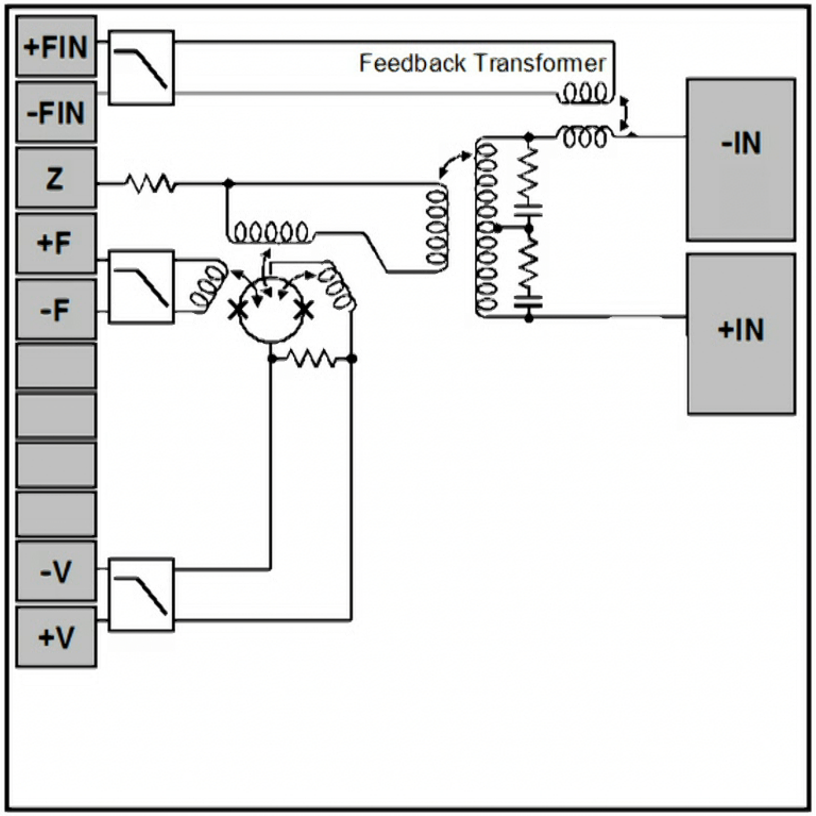
- additional features integrated:
  - rf-filters (~ 80 MHz)

SQUID sensors for $L_p \approx 0.1 \ldots 1\ \mu\mathrm{H}$

PTB



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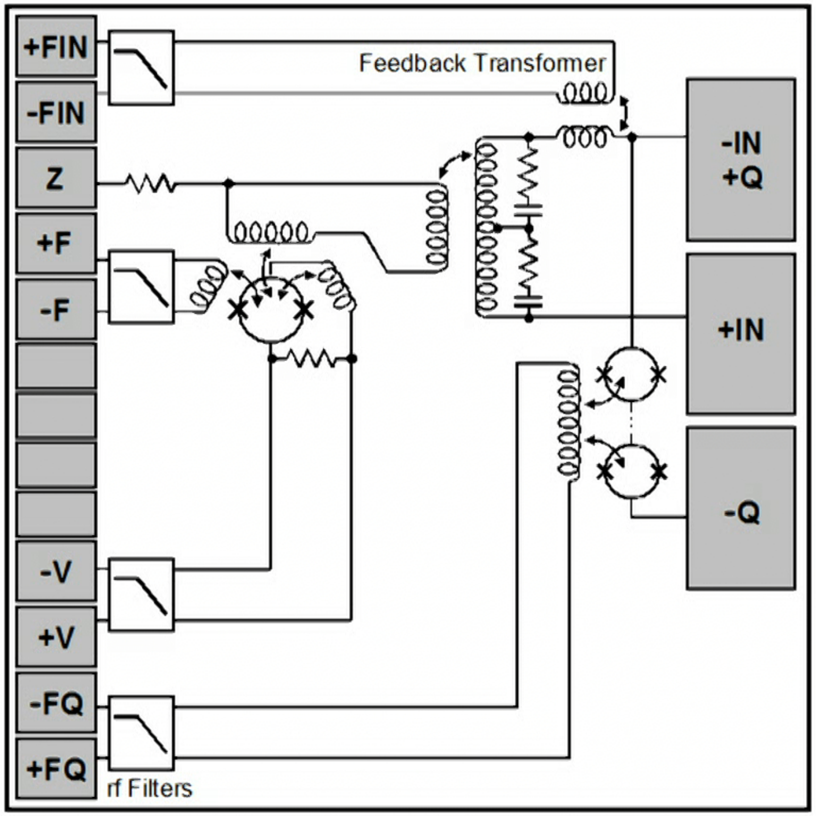

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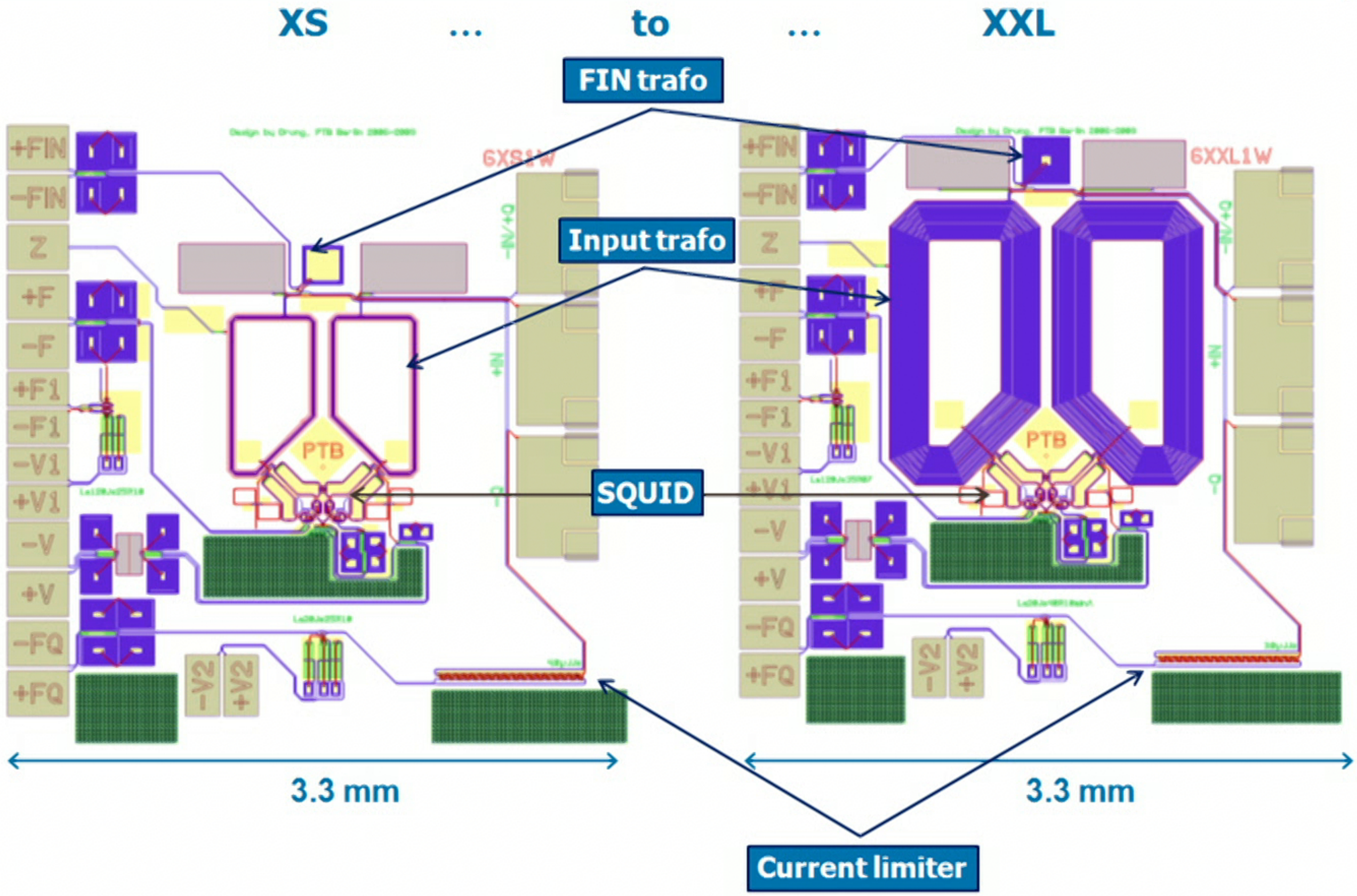
  - „feedback-into-input"
  - input current limiter

SQUID sensors for $L_p \approx 0.1 \ldots 1\ \mu H$



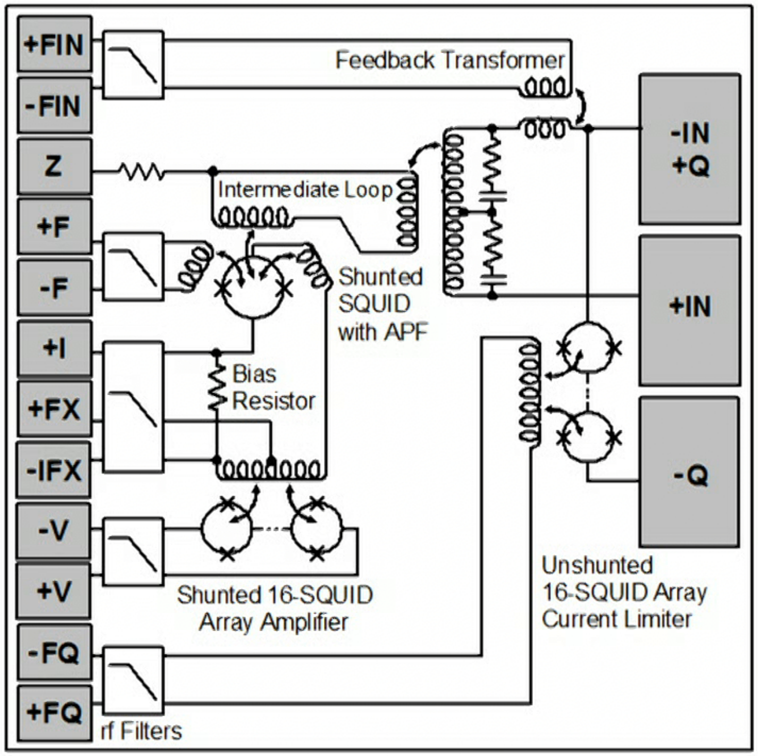
SQUID sensors for $L_p \approx 0.1 \ldots 1\ \mu H$ PTB

size	L_i / nH	$\delta I / \delta\Phi$ / $\mu A/\Phi_0$	$\sqrt{S_I}$ / pA/√Hz	$\varepsilon_c / \hbar$	$\sqrt{S_B}$ / fT√Hz
XS	27	2.3	2.8	900	6.6
S	65	1.3	1.6		1.9
M	150	0.8	1	700	0.6
L	400	0.5	0.6		0.6
XL	1000	0.3	0.4		0.06
XXL	1800	0.23	0.3		0.03

typical white noise at 4.2K

↑ ideally matched magnetometer ($N_P = 1$, $L_P = L_i$, $L_{para} = 0$)

SQUID sensors for <1K



Integrated 2-stage SQUID cascade

- **Sensor:** single SQUID, 2nd order grad
- **Amplifier:** SQUID series array, $N = 16$

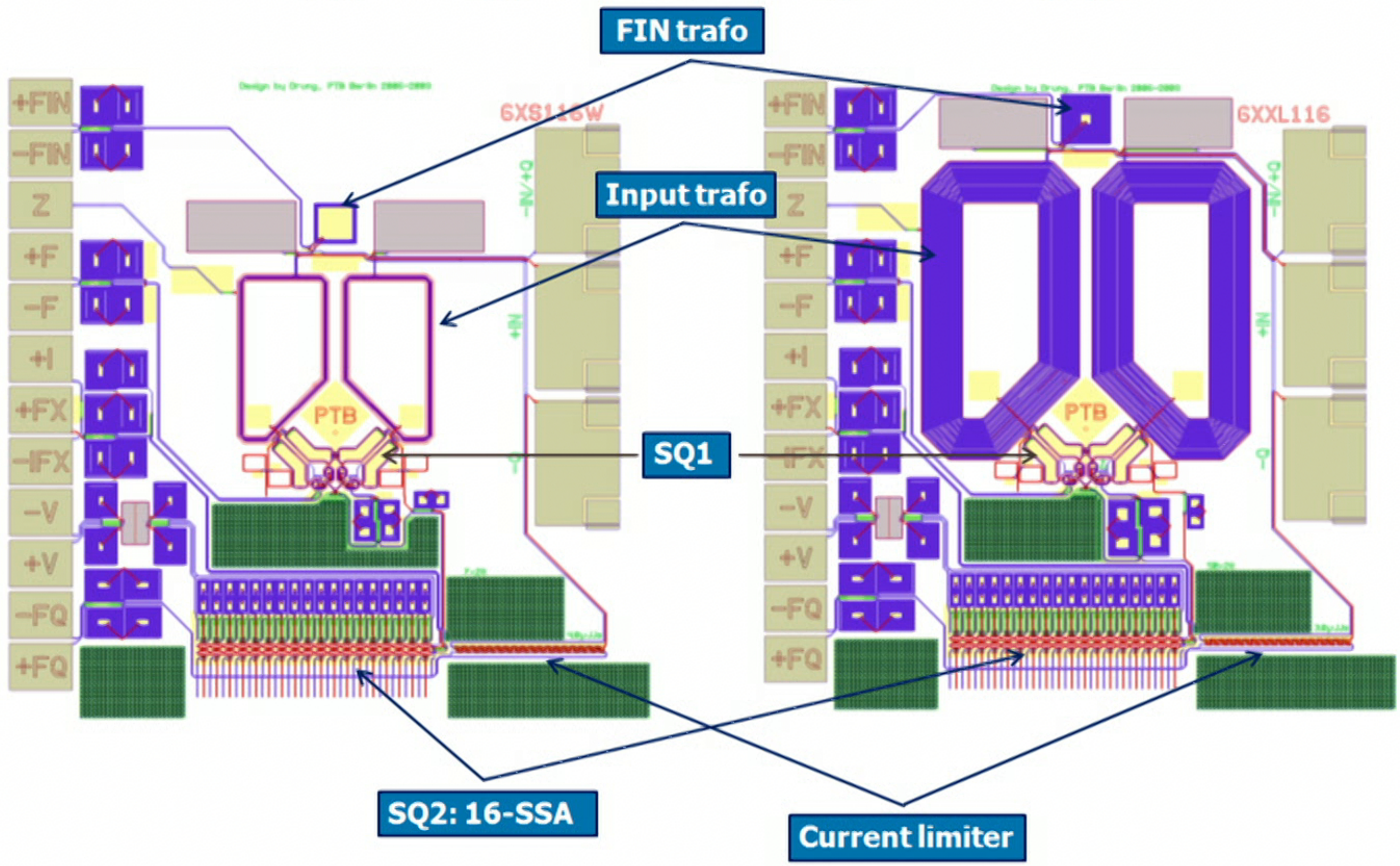
Why?

- **1-stage: - RT electronics noise contribution**
  - does not scale w/ T

- **Input and additional features same as for their 1-stage cousins**

SQUID sensors for <1K

XS ... to ... XXL



Physikalisch-Technische Bundesanstalt ■ Braunschweig und Berlin

Nationales Metrologieinstitut

SQUID sensors for <1K

size	L_i / nH	$\delta I/\delta\Phi$ / $\mu A/\Phi_0$	$\sqrt{S_I}$ / fA/$\sqrt{Hz}$	ε_c / $\hbar$
XS	27	2.3	620	50
S	65	1.3	400	
M	150	0.8	240	40
L	400	0.5	150	
XL	1000	0.3	100	
XXL	1800	0.23	70	

typical white noise at 0.3K

SQUID sensors for <1K

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$\approx 3 \times \varepsilon_{theor}$

typical white noise at 0.3K

SQUID sensors for <1K

PTB

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$\approx 3 \times \varepsilon_{theor}$

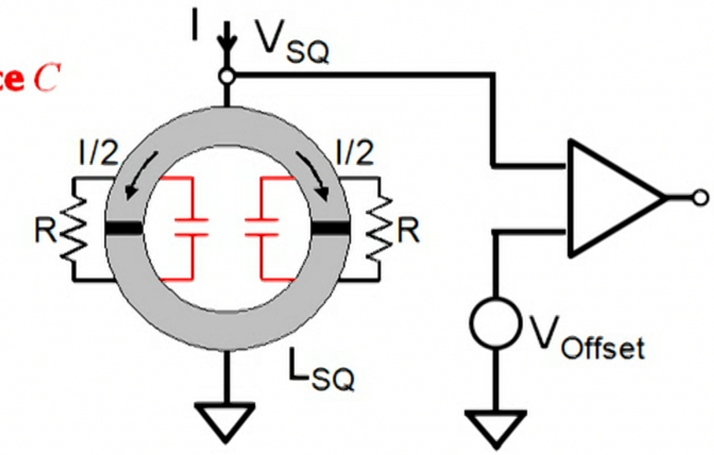
typical white noise at 0.3K

How to get to the theroretical limit ?

Magnetic flux noise

- sensor of magnetic flux Φ through the SQUID ring

parasitic JJ capacitance C



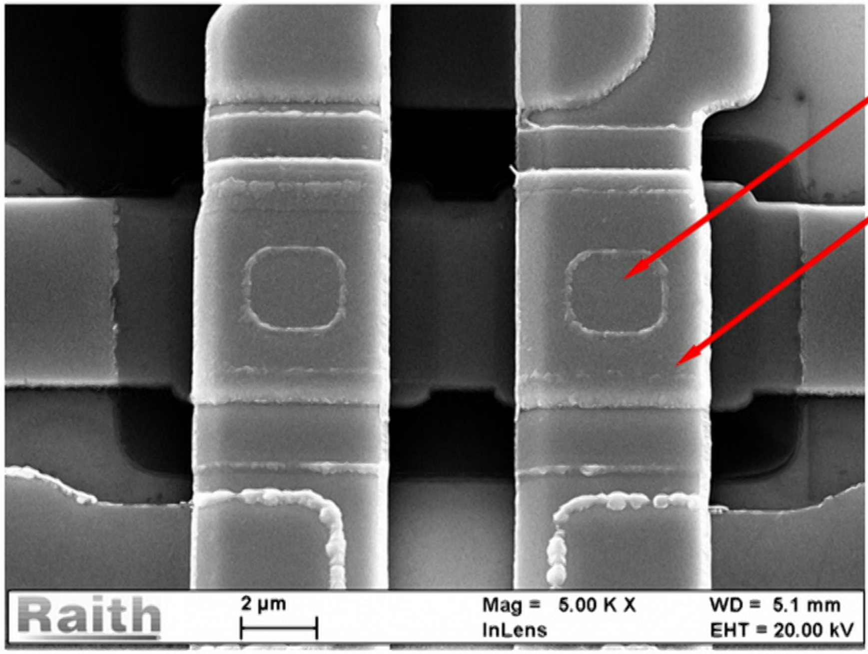
$$\Rightarrow \varepsilon_{theor} \equiv \frac{S_\Phi}{2L_{SQ}} \approx \frac{2(1+\beta_L)\,\Phi_0\,k_B T}{I_C R}$$

$$\beta_L = 2I_C L_{SQ} / \Phi_0 \approx 1$$

for optimum LTS-SQUID noise

LTS dc-SQUID sensors

- **Example: PTB SQUID fab process, UV contact lithography, minimum feature size 2μm**



JJ area:
ca. 5…6 μm²

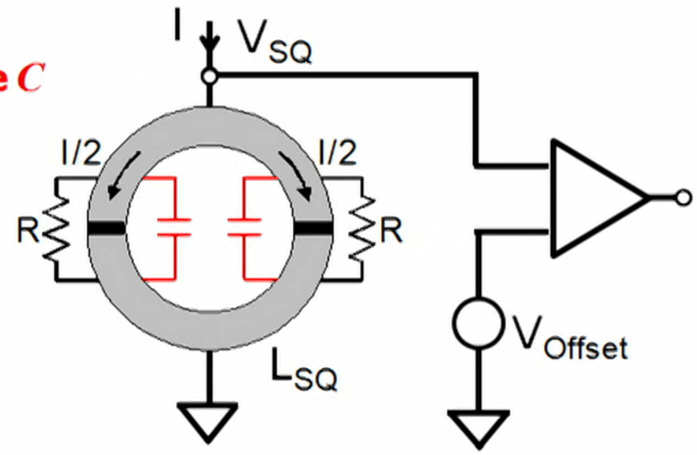
overlap area:
ca. 25…30 μm²

$$C_{JJ*} = C_{JJ} + C_{overlap}$$
$$\approx 0.2\text{pF} + 0.2\text{pF}$$

Magnetic flux noise

○ **sensor of magnetic flux Φ through the SQUID ring**

parasitic JJ capacitance C



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JJ damping requirement:

$$R^2 C < \Phi_0 / 2\pi I_C$$

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Magnetic flux noise

- **sensor of magnetic flux Φ through the SQUID ring**

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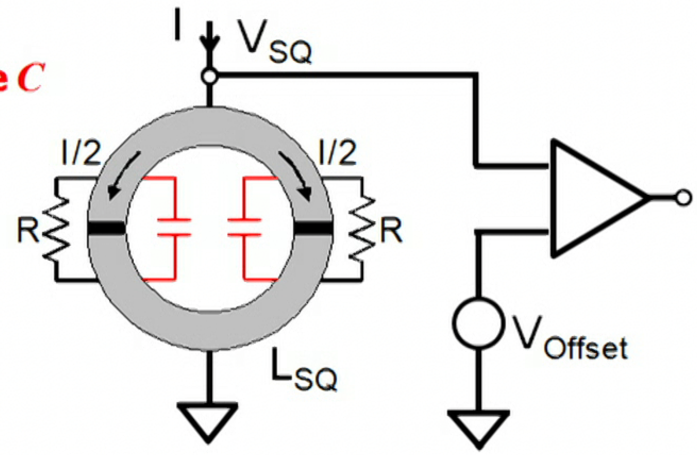

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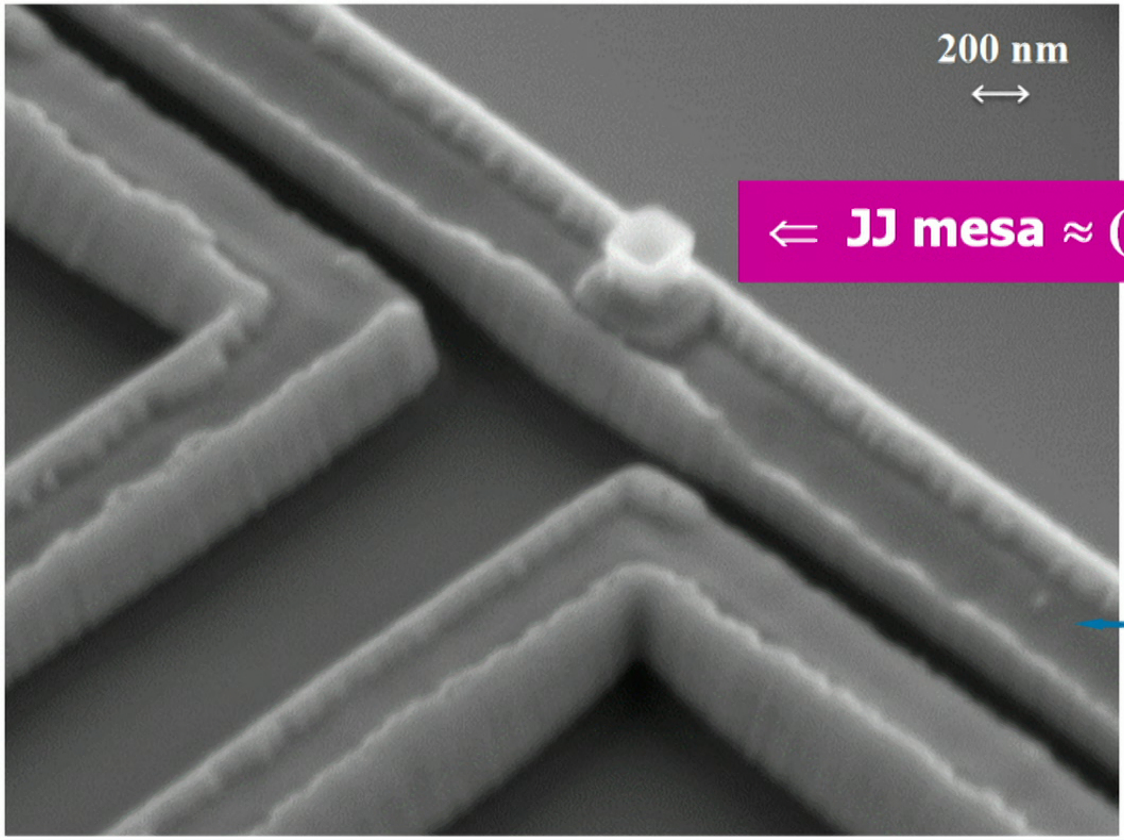
for optimum LTS-SQUID noise

$\Rightarrow$ reduce JJ size

Sub-μm JJs for SQUID sensors

- **electron beam lithography** + chemo-mechanical polishing, reactive ion etching



⇐ **JJ mesa** ≈ $(0.2 \times 0.2)\ \mu m^2$

Nb I

Sub-µm JJs for SQUID sensors

PTB

- **electron beam lithography** + chemo-mechanical polishing, reactive ion etching

- **EBL-JJ process currently in development: $(0.8 \times 0.8)\ \mu m^2$**

size	L_i / nH	$\delta I / \delta \Phi$ / $\mu A/\Phi_0$
XS	27	2.3
S	65	1.3
M	150	0.8
L	400	0.5
XL	1000	0.3
XXL	1800	0.23

$\varepsilon_c / \hbar$
<20
<15

expected at 0.3K

Electromagnetic Interference - EMI

PTB

- **common problem in SQUID setups: EMI**
- via SQUID sensor → magnetic shielding
- interference along readout wiring: optimal shielding may not be possible

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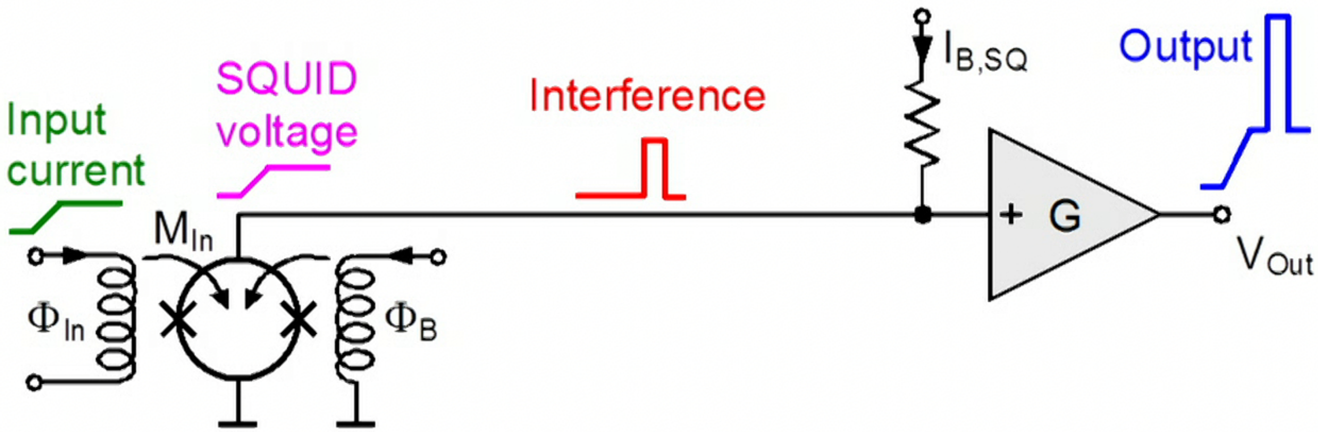
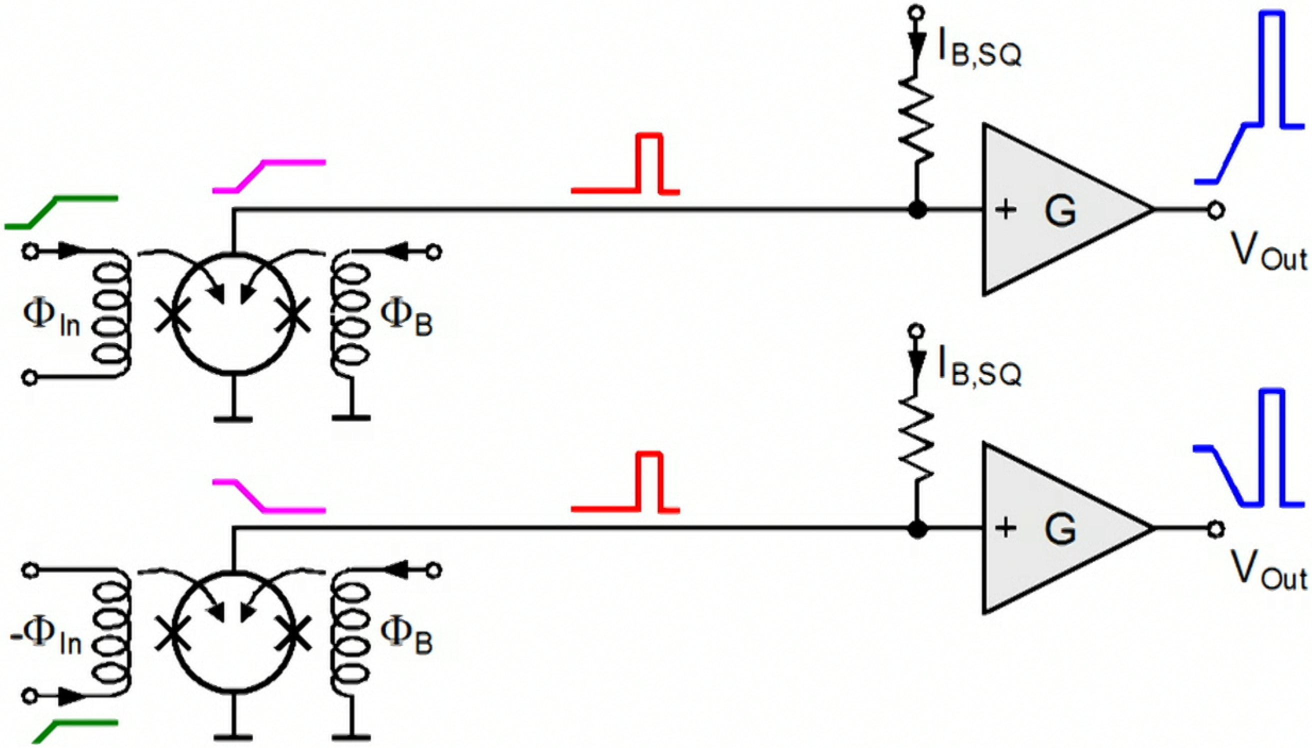


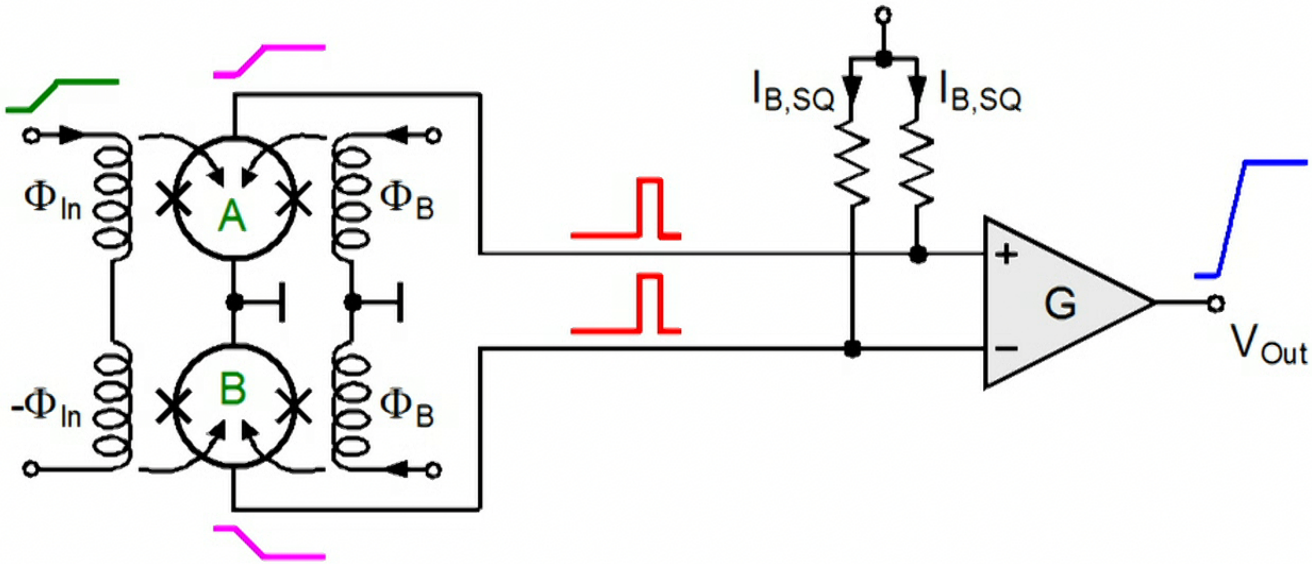
SQUID sensor w/ differential output

• two identical SQUID sensors, but inverted input polarity



SQUID sensor w/ differential output

- two identical SQUID sensors, but inverted input polarity
- combine both sensors, read out with differential amp

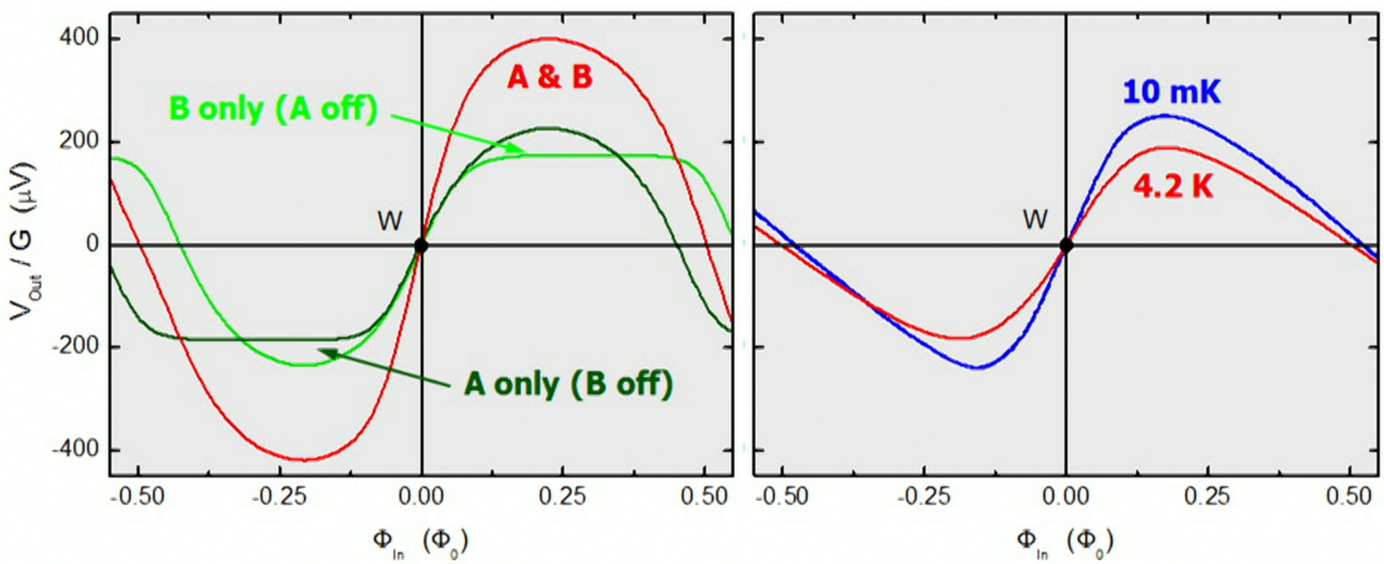


diffSQUID - demo

- two identical SQUID sensors, but inverted input polarity
- combine both sensors, read out with differential amp

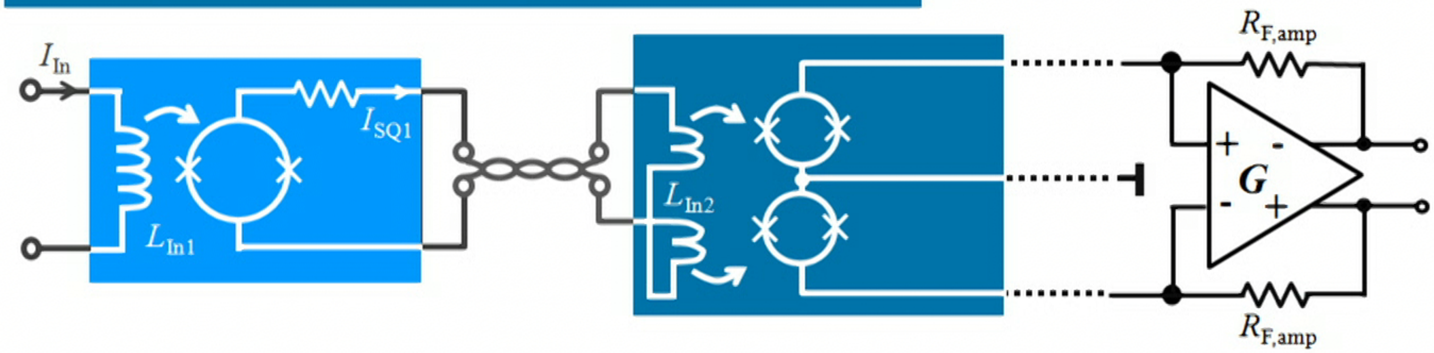
two 16-SQUID series arrays A and B unloaded, 4.2 K

two 16-SQUID series arrays wired as diffSQUID 2 x 50 Ω load



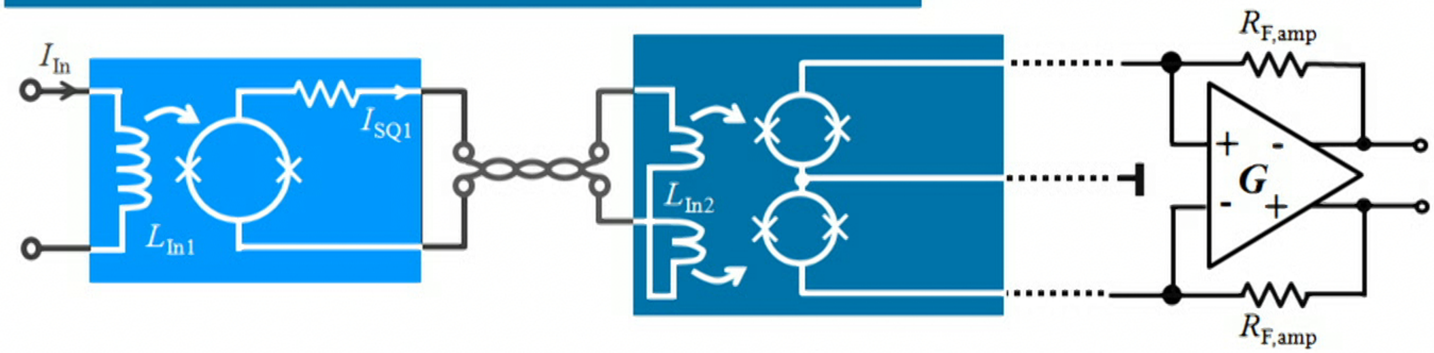
diffSQUID – signal booster

• diffSQUID for amplifier stage in SQUID cascades

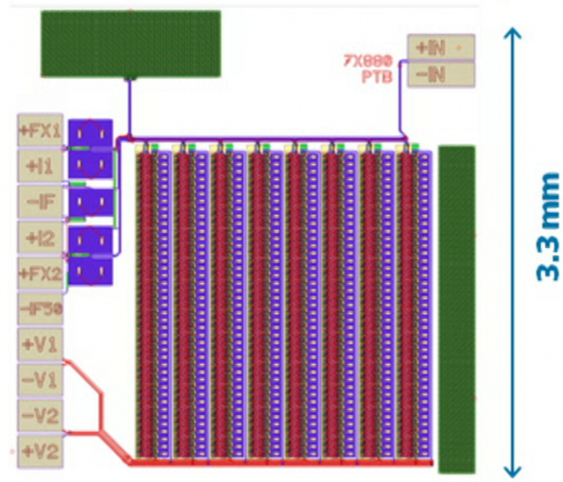


diffSQUID – signal booster

- **diffSQUID for amplifier stage in SQUID cascades**



- **serial-parallel SQUID array**
  two halves: 80-S × 4-P (1280 JJs)
- **total input inductance** $L_i = 40\ \mathrm{nH}$
- **dynamic resistance** $R_{dyn} \approx 120\ \Omega$
- **dissipation** $P_{diss} \approx 200\ \mathrm{nW}$
- **output: 3 mV$_{p\text{-}p}$** into 2×50 Ω load



Summary

PTB

- **LTS dc-SQUID sensors 50 years after their invention**
  - *reliable cryoelectronic circuits based on thin-film technology*
  - *very versatile and sensitive devices for various precision measurements*

- **PTB SQUID sensors**
  - *multi-purpose Nb-Al/AlO-Nb-based SQUID current sensors single SQUIDs and intergrated 2-stage SQUID cascades*
  - *for* 4.2 K *and below* ; $\varepsilon < 50\ \hbar$ @ 300mK
  - *highly sensitive magnetometers*