Dc SQUID-SQIF sensor with high transfer function based on sub-micrometer cross-type Josephson tunnel junctions

T. Schönau, M. Schmelz, V. Zakosarenko, R. Stolz, S. Anders, L. Fritzsch and H.–G. Meyer

Department of Quantum Detection,
Institute of Photonic Technology, A.-Einstein-Str. 9,
D-07745 Jena, Germany

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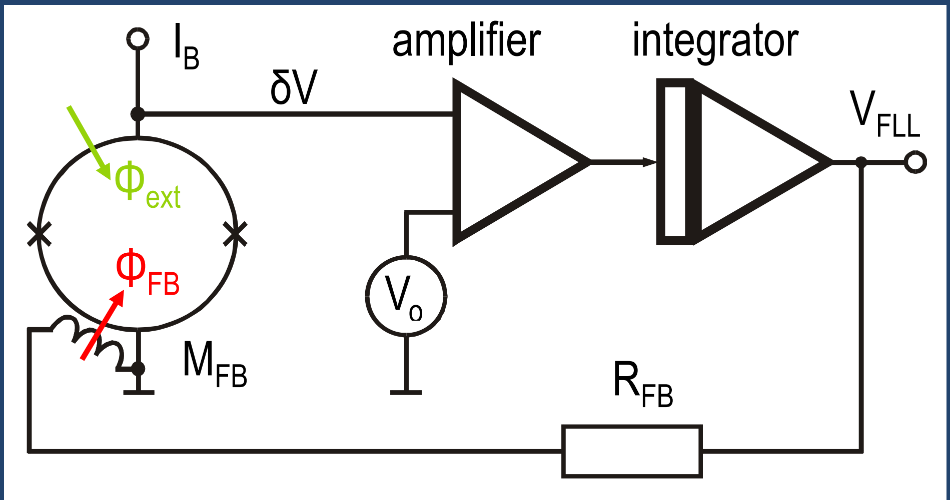
Outline

- Motivation
- What is a SQIF?
- Modes of operation of the SQUID-SQIF system
- Advantages of sub-micron Josephson junctions
- Post processing of the raw data
- Application of the setup
- Conclusions

Conventional SQUID read-out by a directly coupled flux locked loop (FLL)



$\Phi_{FB} = V_{FLL} M_{FB} / R_{FB}$

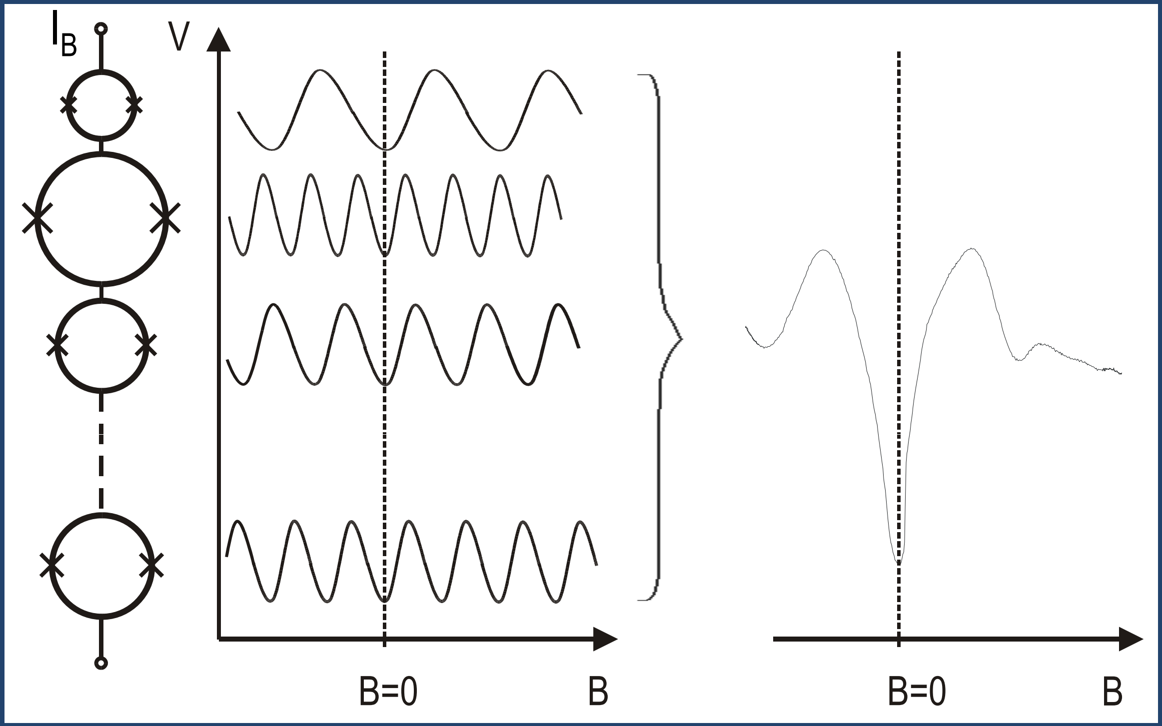
Slew rate is proportional to SQUID voltage swing and unity gain bandwidth of the amplifier.

Dynamic range is practically limited by the current noise contribution of R_{FB}.
→ $\Phi_{FB,max} < 1000\ \Phi_0$

Distance of 1 m between SQUID and FLL electronics limits the bandwith to 20 MHz
Drung D and Mück M 2004 "SQUID electronics" SQUID Handbook, ed Clarke J and Braginski A I (Weinheim: WILEY-VCH)

Cryogenic low noise amplification of the SQUID signal by a SQIF.

What is a SQIF (Superconducting Quantum Interference Filter)?



N: number of SQUIDs in the SQIF connected in series:

voltage swing: ~ N

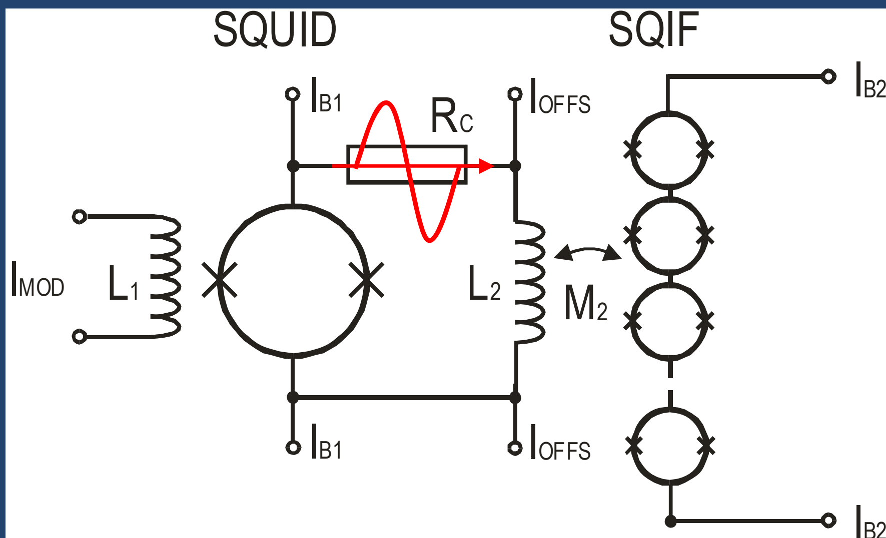
voltage noise: ~√N

→flux noise: ~ 1/√N

→low noise amplifier

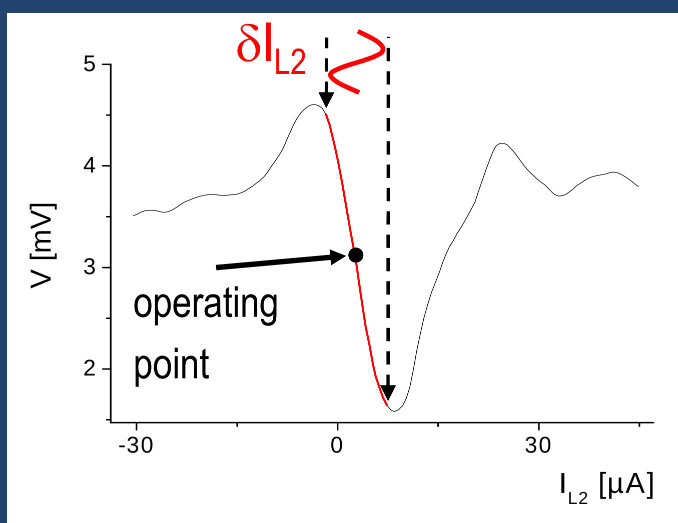
distribution of SQUID inductivities: 50..200 pH → unique major Peak @ B=0

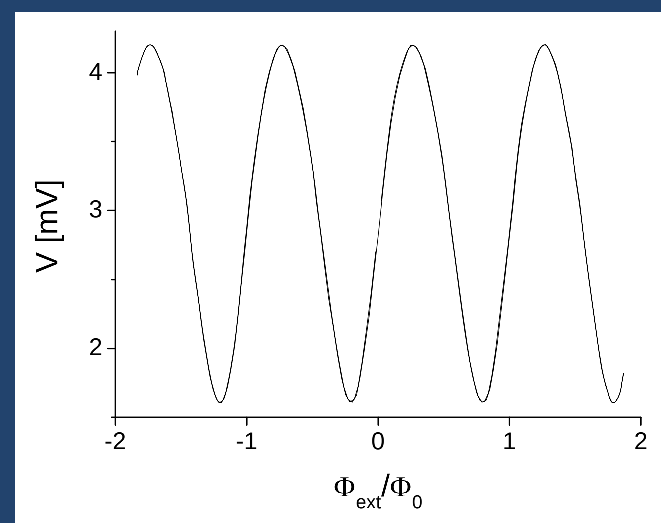
Dc SQUID-SQIF system for use with FLL electronics



Idea:
Low-noise amplification of the SQUID signal at the slope of the SQIF.

Use SQIF as current sensor:
V-Φ characteristic should not be disturbed by homogeneous external magnetic fields up to 50 µT.
→ Gradiometric design with high symmetry





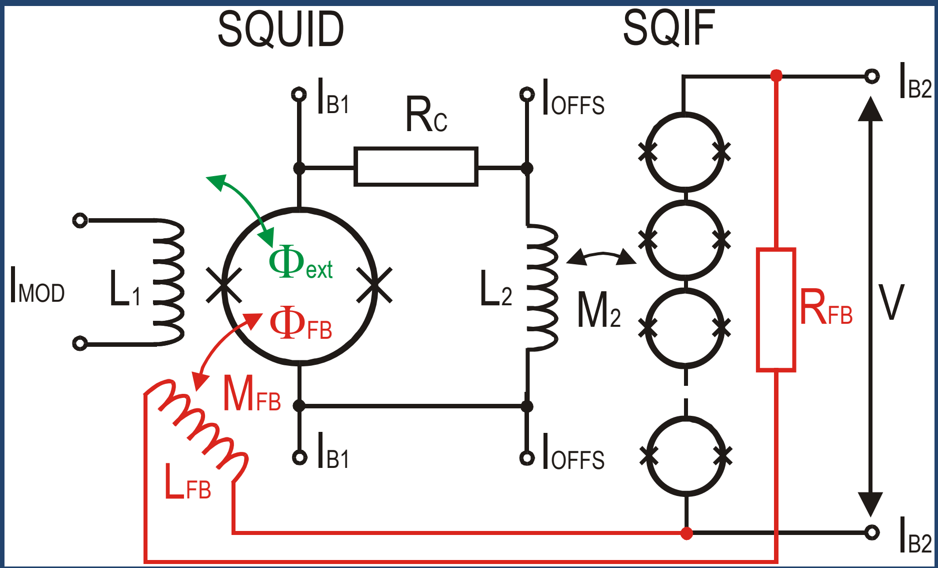
Dc SQUID-SQIF system with on-chip feedback

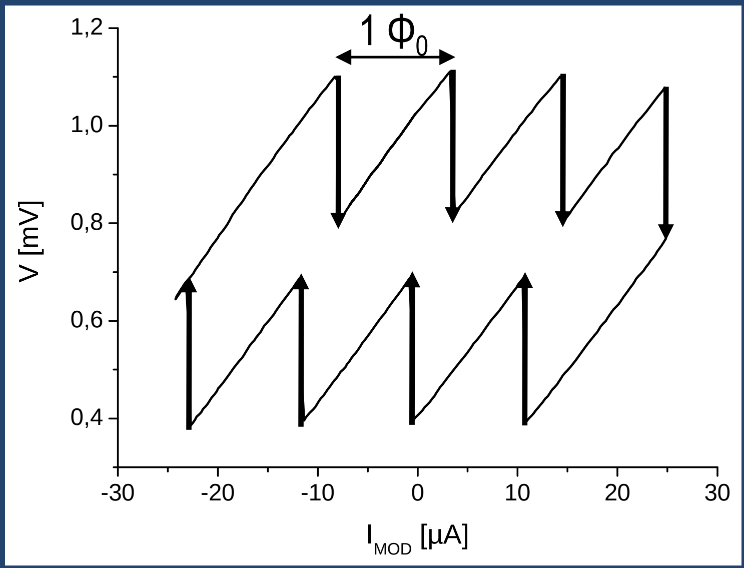
Feedback circuit is included on-chip:

→ Linearised hysteretic V-Φ characteristic with jumps and Φ_0-periodicity

Advantages:

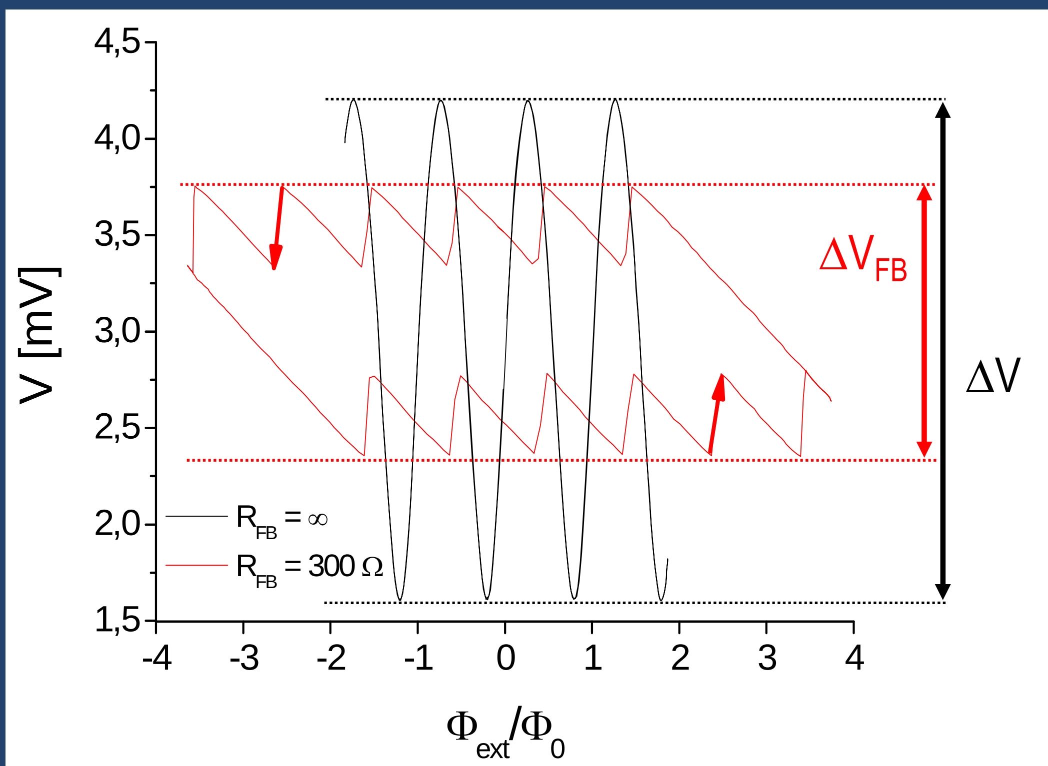
- No FLL electronics needed
- Short feedback path reduces signal propagation delay → enhanced bandwidth
- Fast intrinsic "reset" → practically unlimited dynamic range

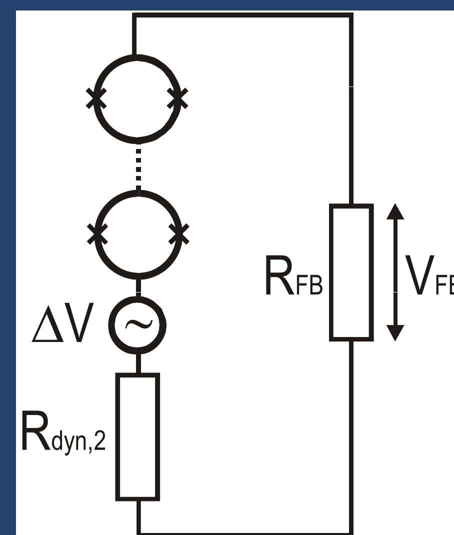




On-chip feedback decreases the transfer function $V_\Phi = \partial V / \partial \Phi$

The output voltage swing is reduced by shunting the SQIF with $R_{FB.}$





$$\frac{\Delta V_{FB}}{\Delta V} = \frac{R_{FB}}{R_{dyn,2} + R_{FB}}$$

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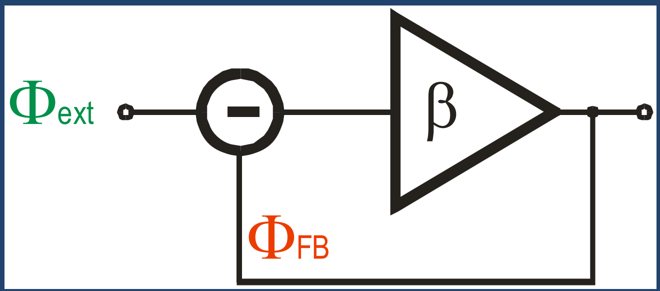


Two-stage system can be schematically reduced to a flux amplifier with open loop gain β:

$$\beta = \frac{\pi \cdot \Delta U \cdot M_{FB}}{R_{dyn,2} + R_{FB}}$$ here: $\beta \approx 10$

Open loop case: $\Phi_{FB} = \beta \cdot \Phi_{ext}$

Closed loop case: $\Phi_{FB} = \beta/(1+\beta) \cdot \Phi_{ext}$

$$\frac{V_{\Phi,FB}}{V_\Phi} = \frac{1}{1+\beta} \cdot \frac{R_{FB}}{R_{dyn,2} + R_{FB}}$$

< 1

Conclusions:

- General compromise between feedback strength β (linearisation) and transfer function $V_{\Phi,FB}$
- Contribution of amplifier voltage noise increases with decreasing transfer function

→ V_Φ (and thus the voltage swing of the SQIF) should be maximized

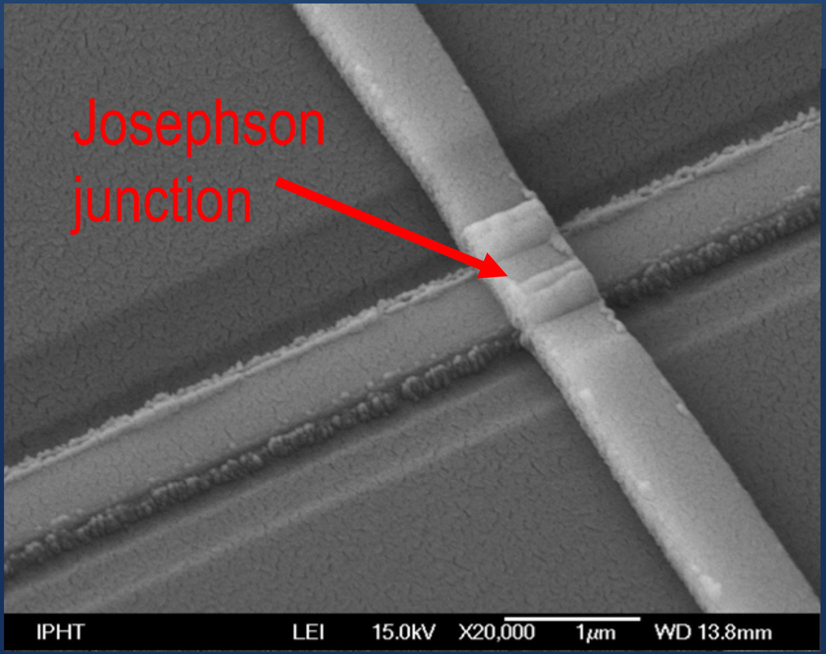
How to increase the voltage swing of the SQIF?

SQUID parameters with $\beta_C = \beta_L = 1$:

$2\delta U = \frac{\Phi_0}{\sqrt{2\pi L_{SQ} C}}$	usable voltage swing
$\varepsilon = 16 k_B T \sqrt{L_{SQ} C}$	energy resolution
$\sqrt{S_\Phi} = 4 L_{SQ}^{3/4} C^{1/4} \sqrt{2 k_B T}$	intrinsic flux noise

Sub-micron cross-type Josephon tunnel junctions exhibit a significant lower (parasitic) junction capacitance C.

Anders S, Schmelz M, Fritzsch L, Stolz R, Zakosarenko V, Schönau T and Meyer H-G 2009 Supercond. Sci. Technol. 22 064012



Scanning electron microscope image of a Josephson tunnel junction with an area of (0.6x0.6) µm².

Implement the dc SQUID-SQIF setup in this technology.

Overview of new class of magnetometer-SQUIDs

	ML2A	ML2B	ML4.5	ML7	ML12
Outer pickup coil dimension	2.0 mm	2.0 mm	4.5 mm	7.0 mm	12.2 mm
Loop number	8	4	8	10	12
$1 / A_{eff, meas}$	5.55 nT/Φ_0	3.03 nT/Φ_0	1.09 nT/Φ_0	0.57 nT/Φ_0	0.25 nT/Φ_0
β_C	0.44	0.37	0.38	0.31	0.36
ΔV	170 µV	145 µV	135 µV	110 µV	100 µV
Field resolution	3.5 fT/Hz$^{1/2}$	4.5 fT/Hz$^{1/2}$	1.6 fT/Hz$^{1/2}$	0.7 fT/Hz$^{1/2}$	0.33 fT/Hz$^{1/2}$
Flux noise	0.63 µΦ_0/Hz$^{1/2}$	1.5 µΦ_0/Hz$^{1/2}$	1.1 µΦ_0/Hz$^{1/2}$	1.23 µΦ_0/Hz$^{1/2}$	1.34 µΦ_0/Hz$^{1/2}$

Schmelz M, Stolz R, Zakosarenko V, Schönau T, Anders S, Fritzsch L, Mück M and Meyer H-G 2011 Supercond. Sci. Technol. 24 065009

Advantages over window-type technology:

- Decreased flux noise
- Increased voltage swing
- Better field stability during cooldown and operation

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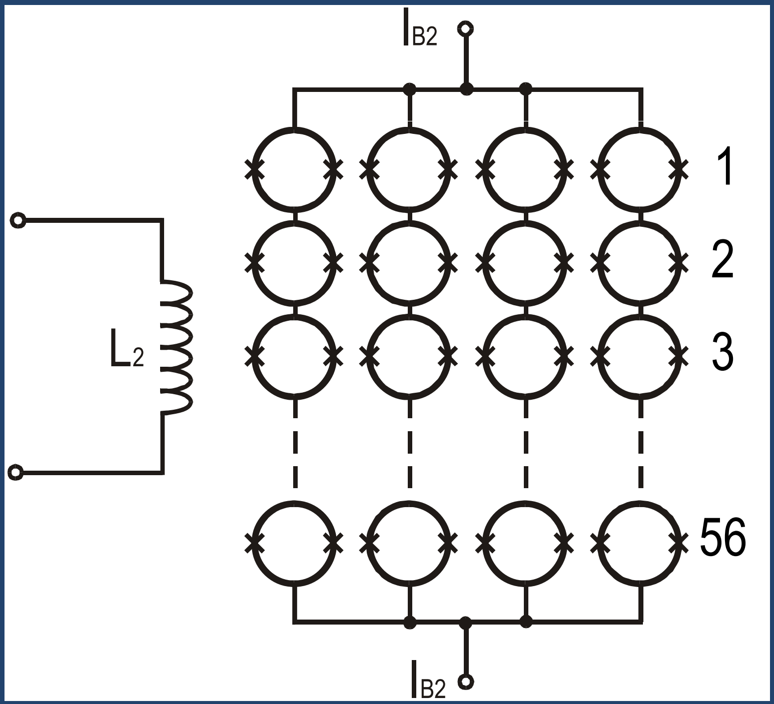
Magnetometer with the lowest flux noise is chosen to better see the noise contributions of the second stage and the room temperature electronics!

General design of the SQIF

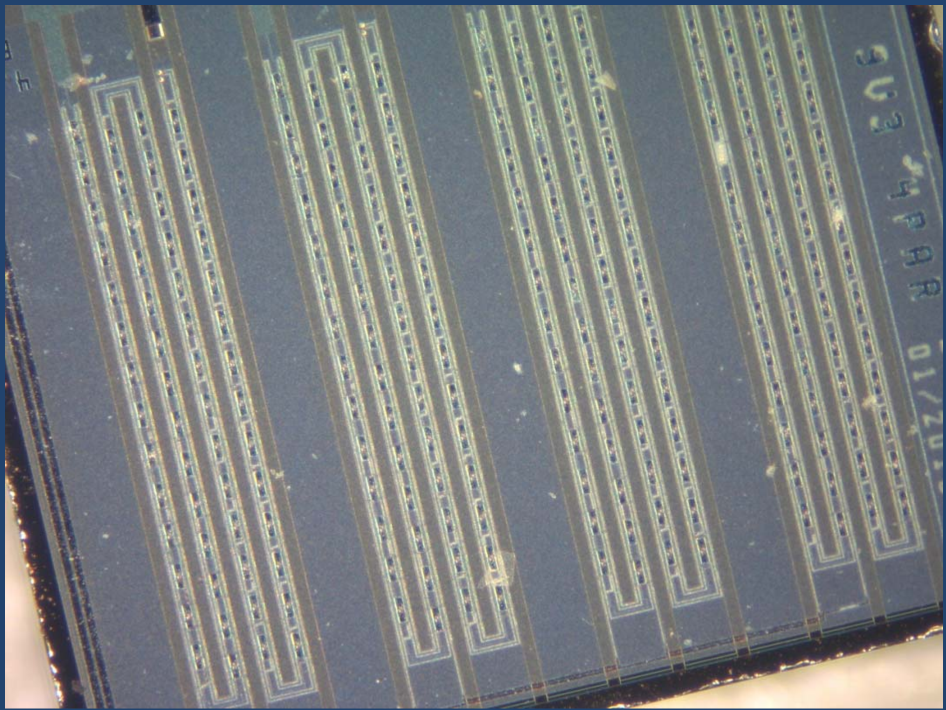
SQIF is realized as an on-chip parallel-series connection of 4x56 SQUIDs.

→ Increased bias current modulation

→ Feedback strength of $\beta \approx 10$

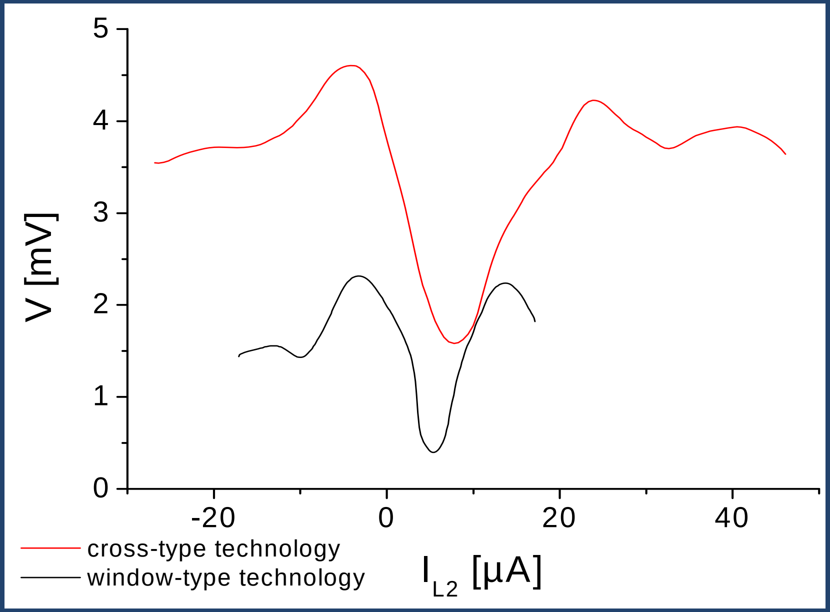


chipsize: 2.5 x 2.5 mm²

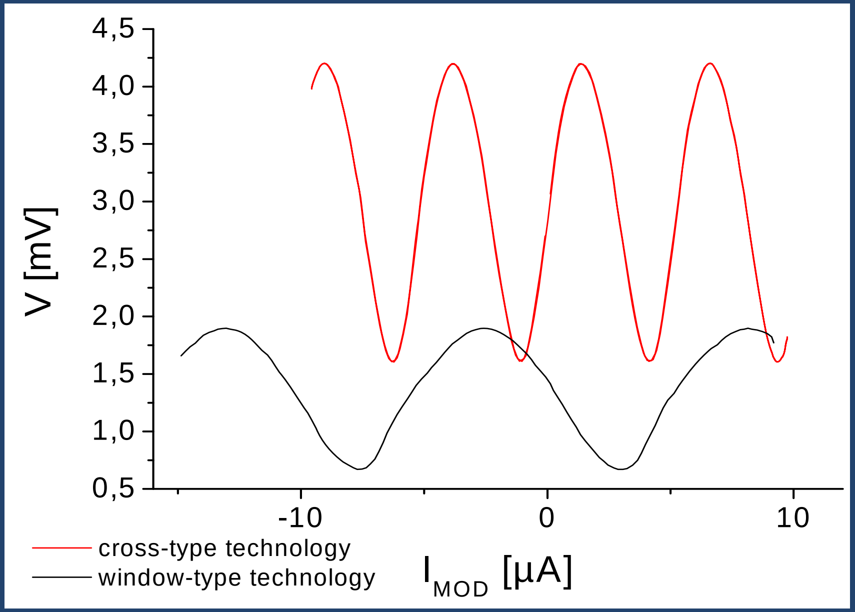


Comparison of cross-type and window-type technology

SQIF characteristic



Sensor characteristic without on-chip feedback



Noise considerations

Technology	Flux noise of the SQUID [$\mu\Phi_0/Hz^{1/2}$]	Flux noise of the two-stage setup with $\beta = 0$ [$\mu\Phi_0/Hz^{1/2}$]	Flux noise of the two-stage setup with $\beta \approx 10$ [$\mu\Phi_0/Hz^{1/2}$]
Window-type	3.5	3.54	≈ 8
Cross-type	0.63	3.5	to be done

value is too high!

Measured noise in window-type technology fits to theoretical estimations.

→ Negligible noise contribution for $\beta = 0$

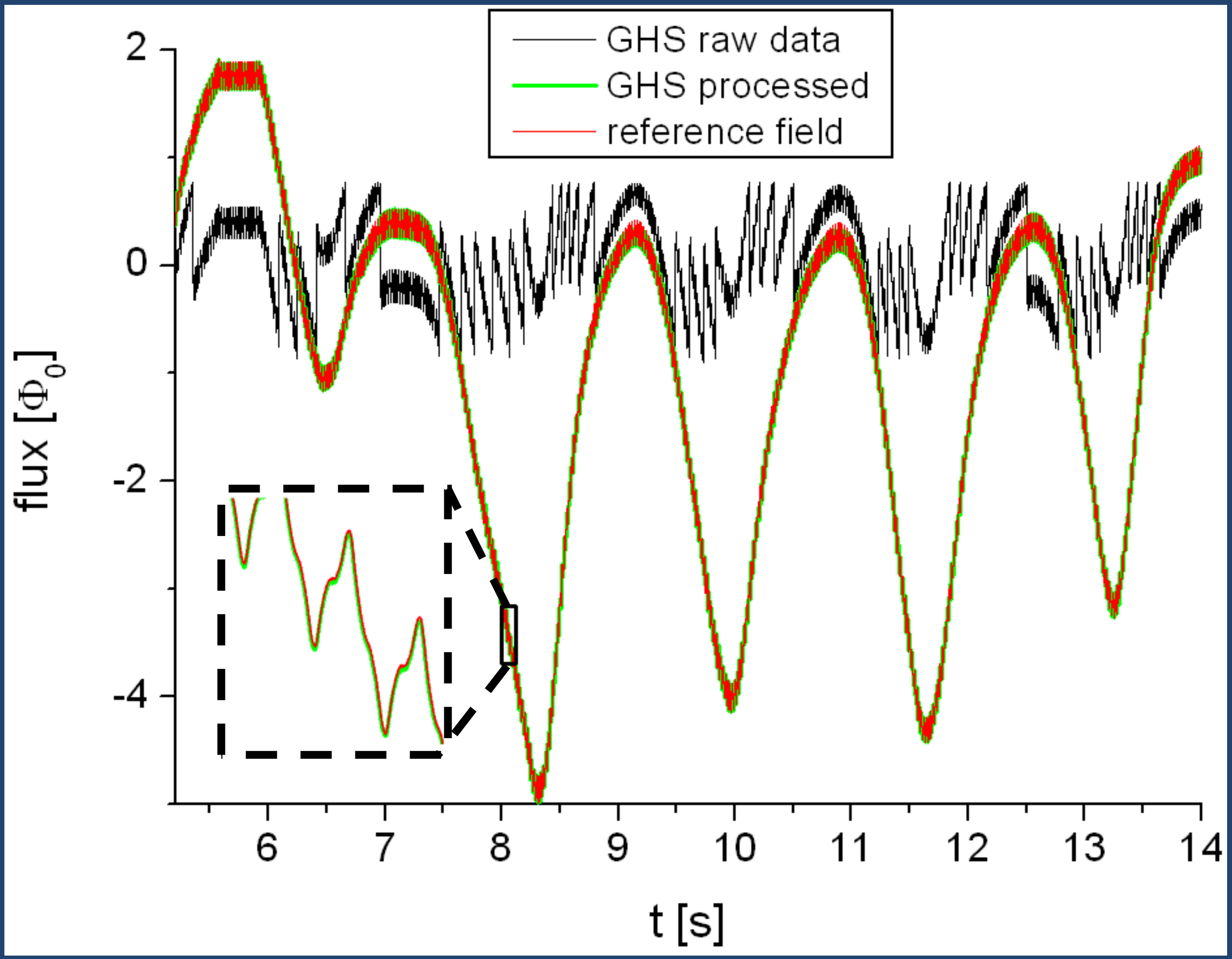
→ Voltage noise of amplifier dominates for $\beta \approx 10$ due to reduced transfer function

Unexpected high flux noise level for the two-stage setup with cross-type technology

→ SQIF, electronics?

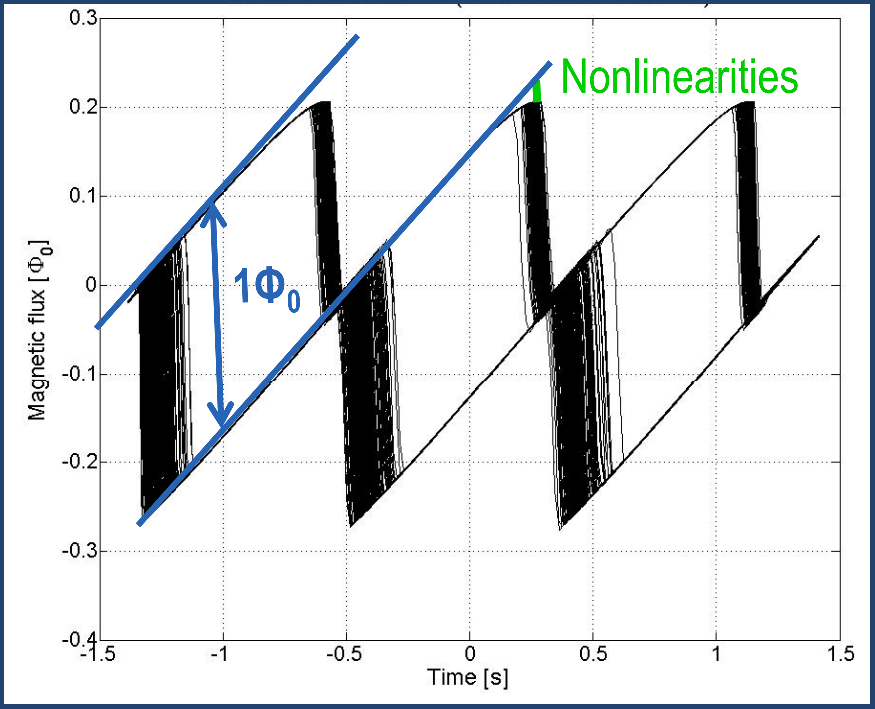
Post processing

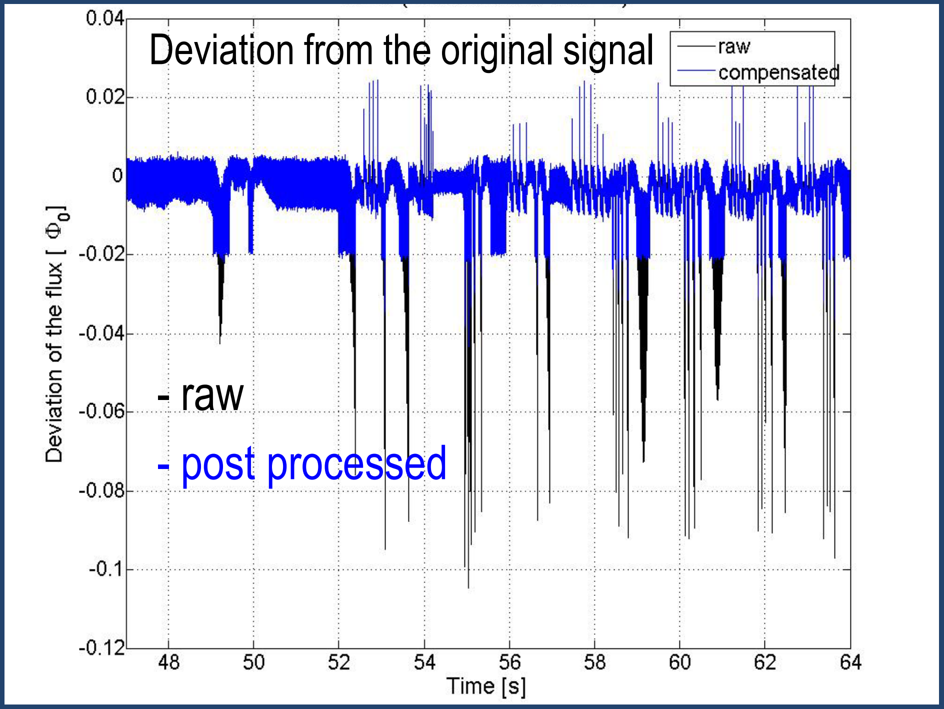
- Elimination of jumps by post processing (jump detection by soft- or hardware)



Post processing

- Linearization by on-chip feedback only up to a certain quality / accuracy
  → Reduction of nonlinearities by passing the data through a transfer function



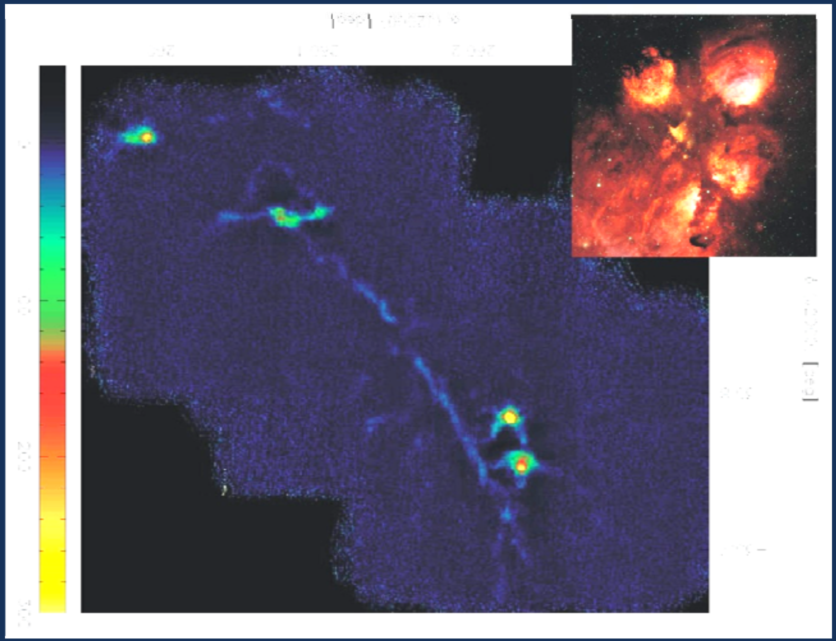


Application of the technique

- 2-stage system is used as small signal amplifier in a readout system for radiation detectors,

→ The Submillimeter APEX Bolometer Camera (SABOCA), consisting of a 39 pixel array of transition-edge sensors.

12m – APEX radio telescope at the altitude of 5100m at Chajnantor Atacama, Chile.



http://www.mpifr-bonn.mpg.de/staff/gsiringo/saboca/

Conclusions

- Dc SQUID-SQIF sensor with a voltage swing of about 3 mV developed
- on-chip feedback possible

  → avoids limitations (dynamic range, slew rate, bandwith) of a conventional FLL
- Noise can be theoretically estimated for the window-type technology but has to be further investigated for SQIFs based on cross-type junctions
- Application of the system as a small signal amplifier is demonstrated at Submillimeter APEX Bolometer Camera SABOCA

Outlook

- Develop electronics for two-stage read-out & hardware jump detection
- Use the setup as a magnetic field sensor for geophysical exploration

Thank you for your attention!