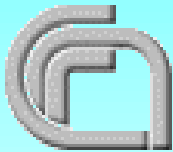


3D nanoSQUID with an energy sensitivity of $1.3 \hbar$ at 4.2 K

Carmin Granata



CNR-Institute of Applied Physics
and Intelligent Systems, Pozzuoli
(Napoli), Italy



Geneva, 17-21 September

RESEARCH GROUPS

C. Granata, A. Vettoliere

*CNR-Institute of Applied Physics and Intelligent Systems (ISASI),
Pozzuoli (Napoli), Italy*

M. Schemelz, V. Zakosarenko, R. Stolz

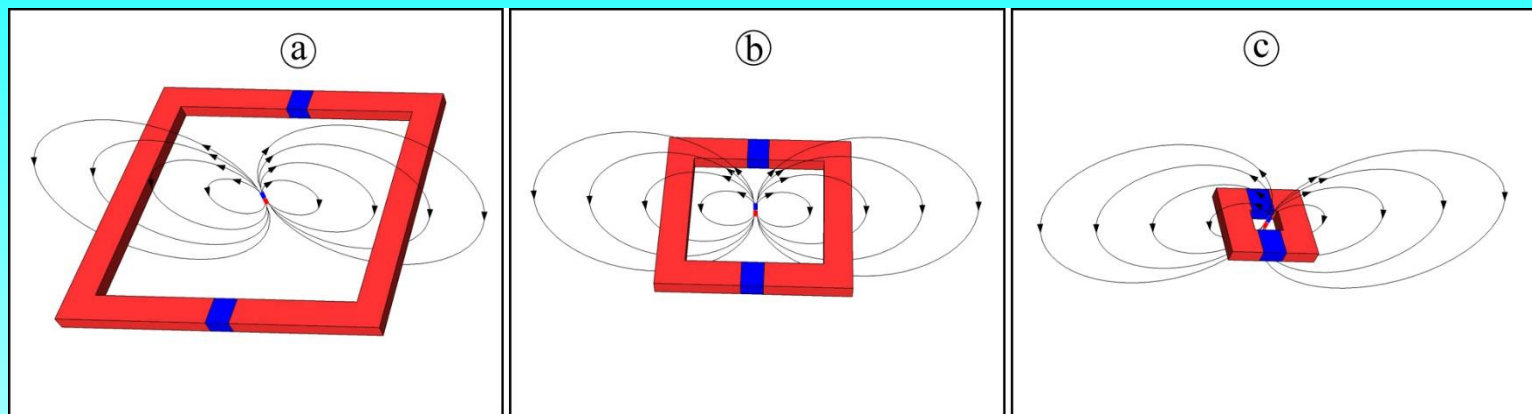
Leibniz Institute of Photonic Technology, Jena, Germany

M. Fretto, N. De Leo, *National Institute of Metrological Research
(INRiM), Torino, Italy*

Outline:

- Why a nanoSQUIDs?
- NanoSQUID based on sandwich Josephson nano-junctions
- Design, fabrication
- Characterization
- Spin sensitivity computation
- Conclusions

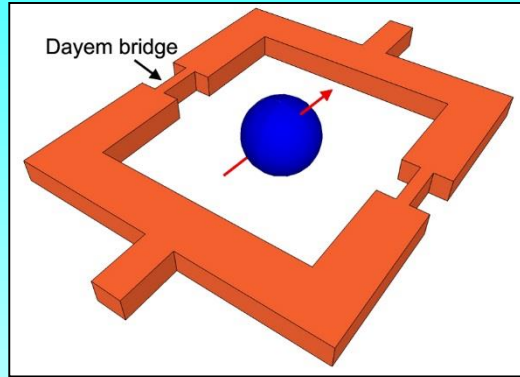
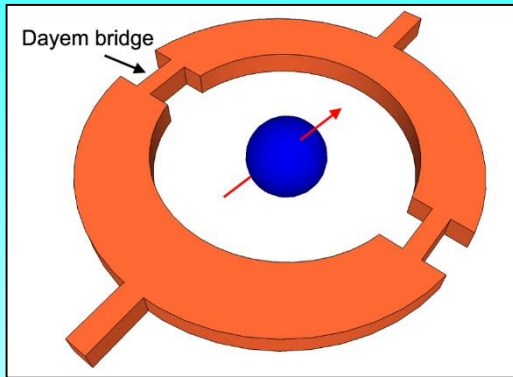
Why nanoSQUIDs?



By decreasing the detection coil size, the number of flux lines which return within the loop decreases and the net magnetic flux increases.

By using the current technique of nanofabrication (EBL and FIB), it is possible to fabricate SQUID having a loop radius less than 50 nm, obtaining an adequate sensitivity to detect the magnetic response of small spin populations.

Spin sensitivity



Hole:

$$S_n^{1/2} = 2a S_\Phi^{1/2} / (\mu_0 \mu_B)$$

Ketchen et al. IEEE Supercond. 1989

Square:

$$S_n^{1/2} = 4\pi a S_\Phi^{1/2} / (8\sqrt{2}\mu_0 \mu_B)$$

Granata et al. J Appl. Phys. 2009

a = SQUID loop radius or side length; μ_0 = vacuum permeability; μ_B = Bohr magneton

The magnetic flux produced by a magnetization variation M of the sample located in the SQUID loop is:

$$\Delta\Phi = \alpha \Delta M$$

where α is the magnetic flux coupling factor depending by the geometry of the device and the sample.

The main results about nanoSQUIDs and their applications can be found in the recent extended review:

Physics Reports 614 (2016) 1–69



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Nano Superconducting Quantum Interference device: A powerful tool for nanoscale investigations

Carmine Granata*, Antonio Vettoliere

Institute of Applied Sciences and Intelligent Systems "E. Caianiello" del Consiglio Nazionale delle Ricerche, I-80078 Pozzuoli (Napoli), Italy



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Superconductor Science and Technology

Focus on NanoSQUIDs and their applications

Guest Editors

Ling Hao NPL, UK
Carmine Granata CNR, Italy

Scope

This special issue of SUST highlights recent development across the field of nanoSQUIDs and their application. Since the realization of the first nanoSQUID in 2003, the fabrication, the design and the performance of these nanosensors has been appreciably improved reaching a sensitivity that approaches to one electron spin per unit bandwidth. It is due to the progress, during the last ten years, in nanofabrication techniques, low noise readout circuits and performance simulations. Even if the nanoSQUID remains an object of dedicated research, the recent results are very encouraging in view of a wide employment of this nanodevice for several nanoscale applications. This special issue highlights advances in nano SQUID design, fabrication, performance and their applications including nanomagnetism, ultra high spatial resolution magnetic microscopy and other intriguing topics of material science and condensed matter.

More information about *Superconductor Science and Technology* can be found on our website: www.iopscience.org/sust.

Preface

Recent trends and perspectives of nanoSQUIDs: introduction to 'Focus on nanoSQUIDs and their applications'

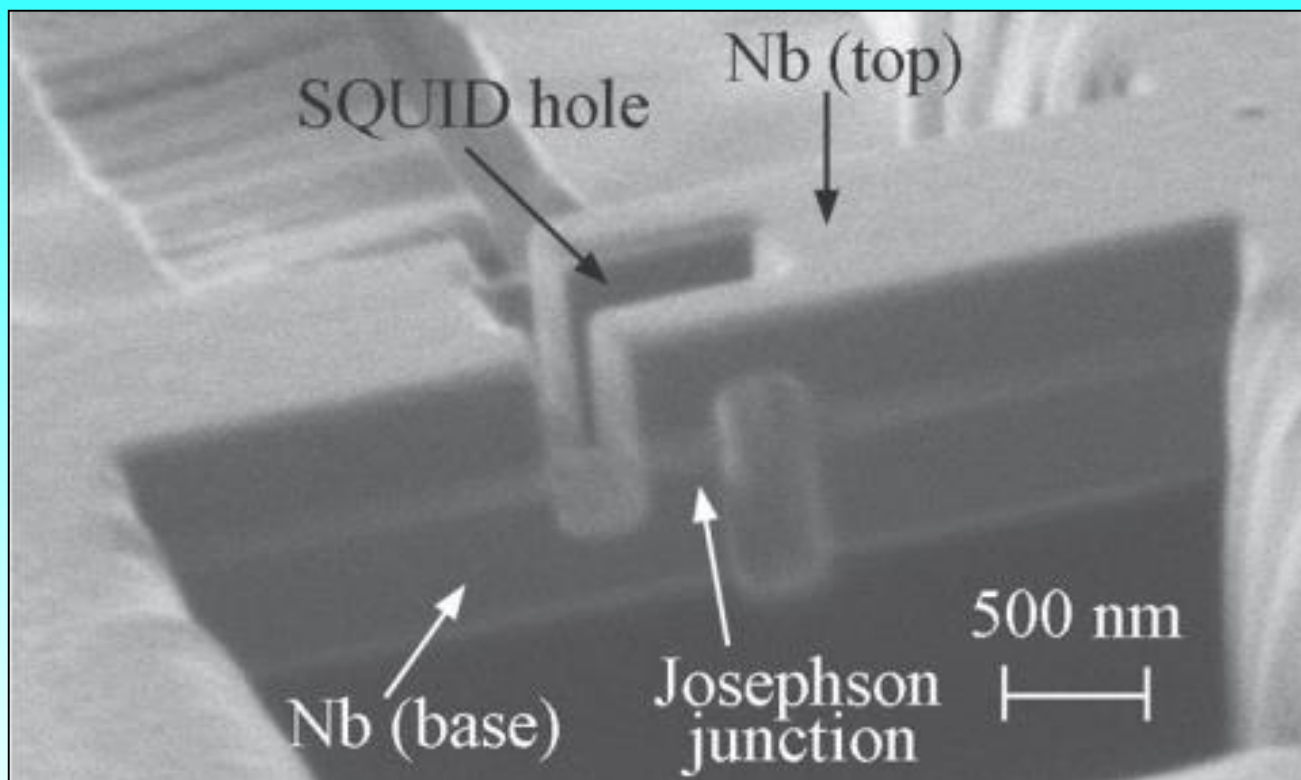
Ling Hao and Carmine Granata 2017 *Supercond. Sci. Technol.* **30** 050301

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ADVANTAGES OF NANOSQUIDS BASED ON TUNNEL NANOJUNCTIONS:

- High critical current modulation depths
- Non-hysteretic characteristic at $T=4.2$ K
 - Reliability
 - Robustness

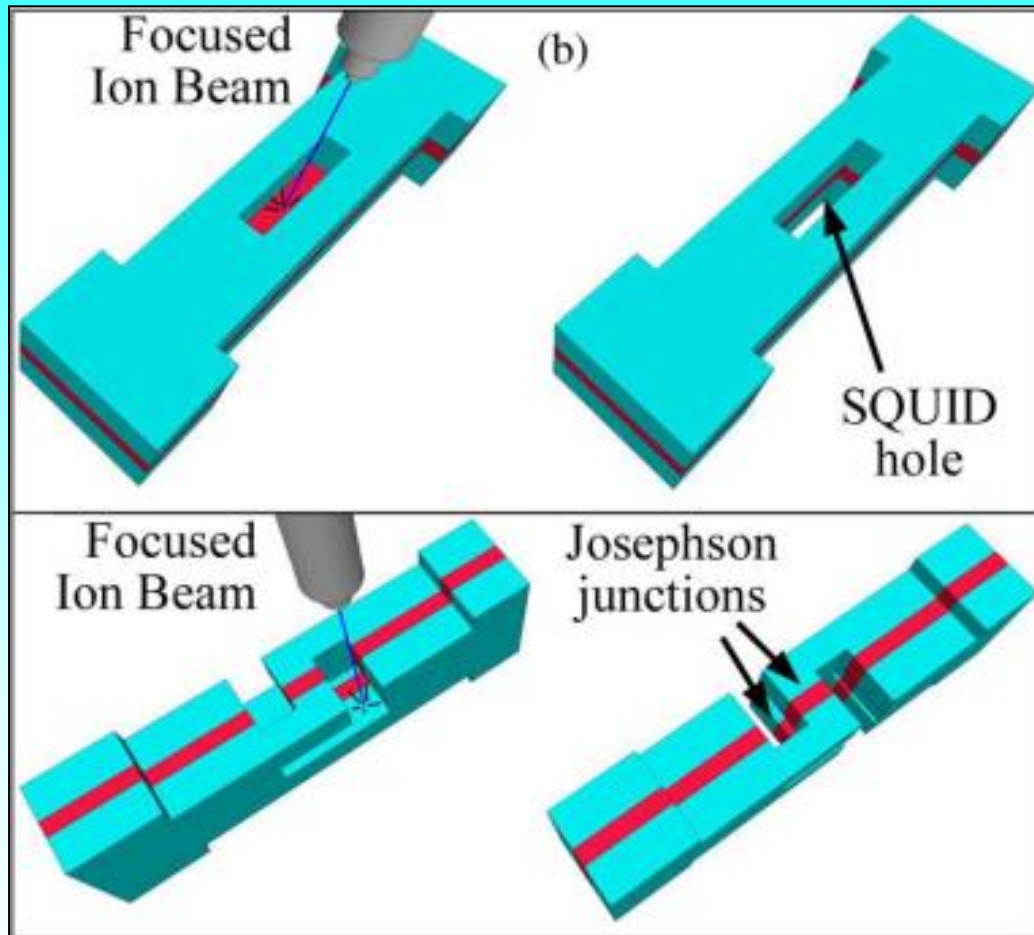
Niobium nanoSQUID based on nanojunctions



SEM images of a nanoSQUID fabricated by using the Focused Ion Beam (FIB) sculpting and the fully niobium technology. The flux capture area of the nanosensor is $(1 \times 0.2) \text{ mm}^2$ and the two Josephson tunnel junctions have an area of about $(0.3 \times 0.3) \text{ mm}^2$.

C. Granata et al., J. Magn. Magn. Mat. 2015, M. Schemelz et al. Appl. Phys. Lett. 2017, N. De Leo et al., SUST 2017

Fabrication process

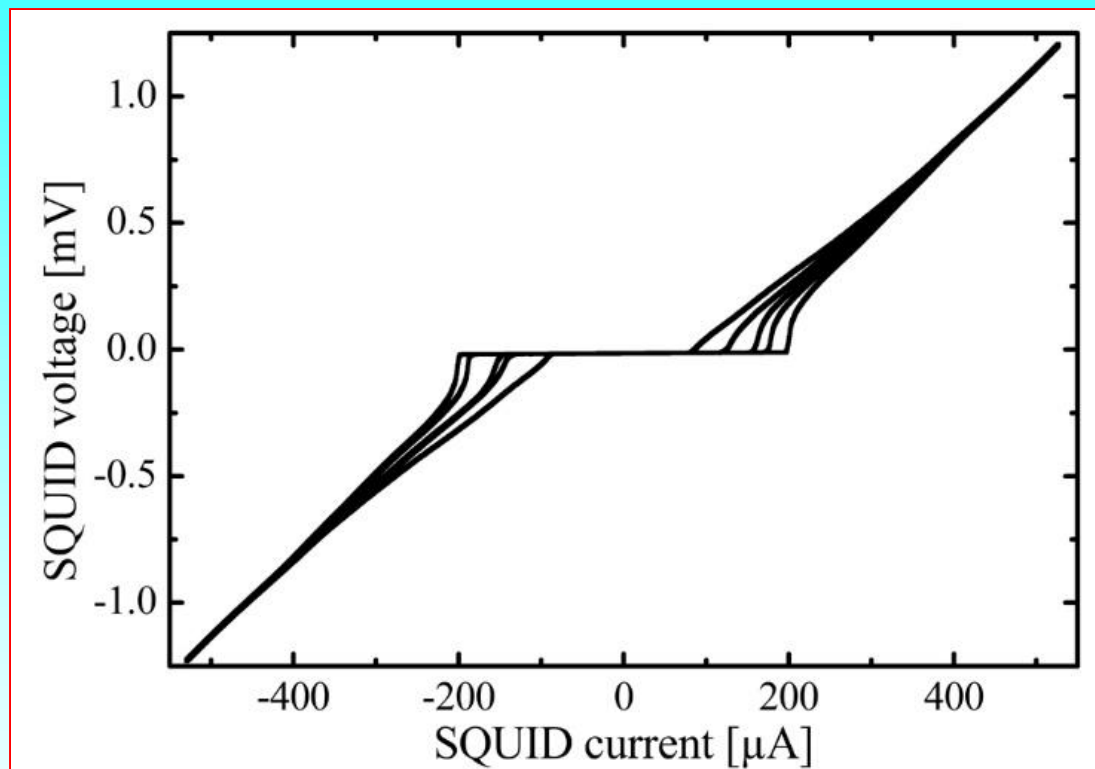


A rectangular hole is realized in the centre of the strip, resulting in two parallel lamellae and defining both the Josephson junction's width and the loop of the nanoSQUID device.

Afterwards, the sample is oriented parallel to the beam trajectory and two side cuts through the two lamellae were performed defining the length of the junctions.

C. Granata et al. IEEE TAS 2015; J. Supercond. Nov. Magn. 2014; N. De Leo et al. SUST 2017

Temperature dependence: V vs I



Set of current-voltage characteristics measured at 4.2 K for different magnetic flux threading the SQUID loop, ranging from 0 to $0.5 \Phi_0$ in steps of $0.1 \Phi_0$

M. Schemelz et al. Appl. Phys. Lett. 2017

High Critical current modulation depth ($118 \mu\text{A}$)

$\Delta I_0/I_0=0.6$ $\beta_L=0.63$ $L=6.5 \text{ pH}$

Supposing that at $T=4.2 \text{ K}$:

$$\beta_C = 2\pi R_N 2I_0 C / \Phi_0 = 1$$

with

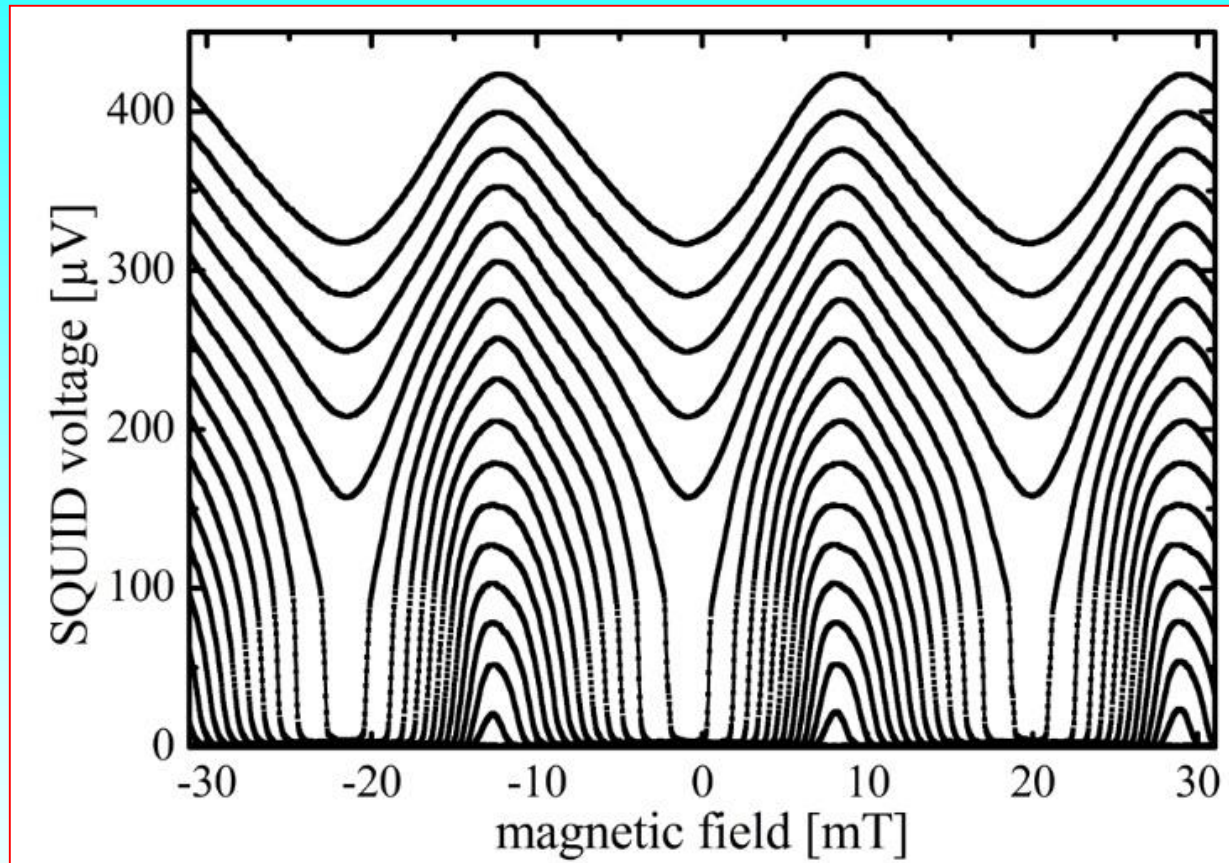
$$R_N = 2R_{N,S} = 4.9 \Omega, I_0 = I_c/2 = 101 \mu\text{A}$$



$C=60 \text{ fF}$

It is compatible with the nanojunction capacitance and the parasitic capacitance of the leads.

Voltage vs magnetic field characteristics



Transfer function
as high as:
 $V_{\Phi} = 5 \text{ mV}/\Phi_0$



Considering the input voltage
of a low noise amplifier:

$$S^{1/2}_V = 0.33 \text{ nV/Hz}^{1/2}$$

The noise contribution of the
room electronics is:

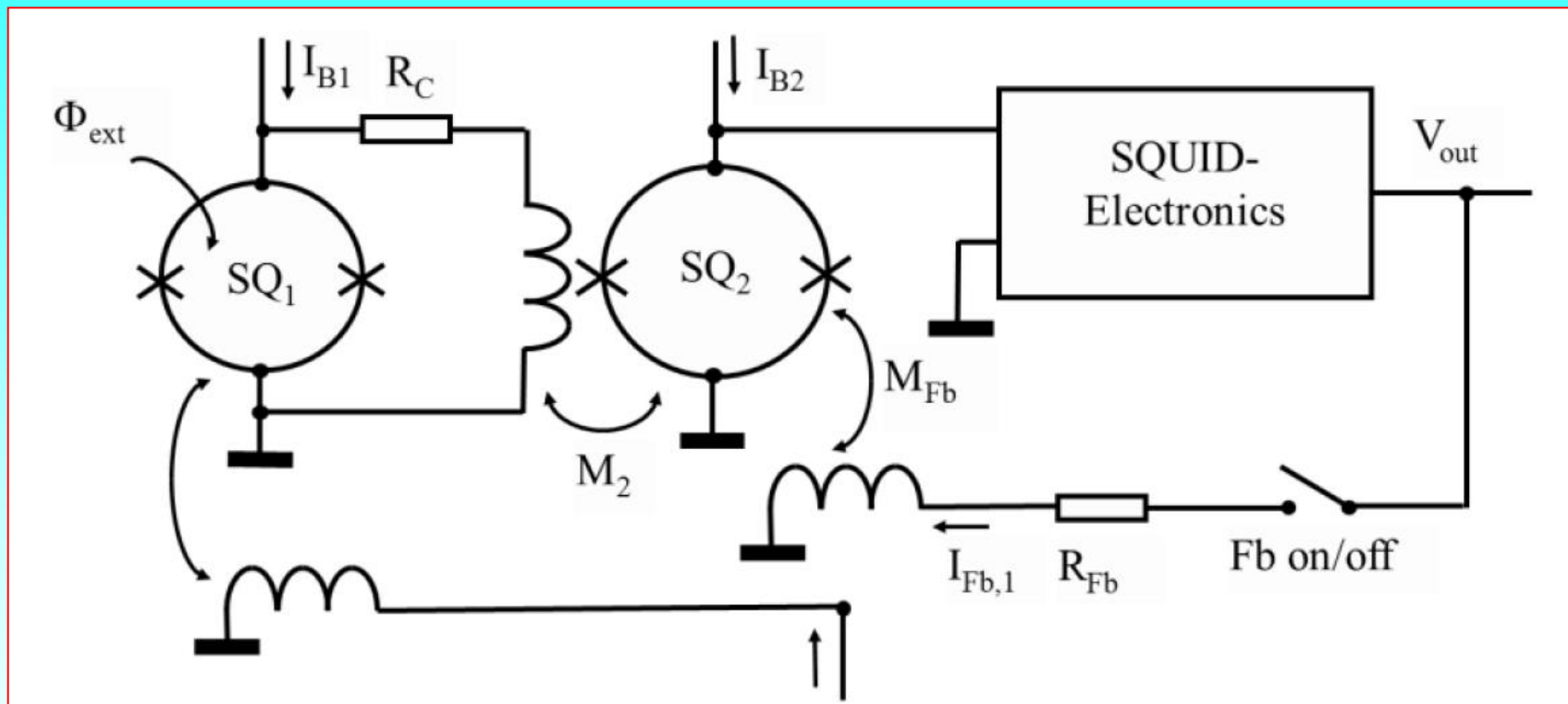
$$S^{1/2}_{\Phi} = S^{1/2}_V / V_{\Phi} = 66 \text{ n}\Phi_0/\text{Hz}^{1/2}$$

Set of flux-voltage characteristics with stepwise increasing bias
current, ranging from 80 to 250 μA in steps of 10 μA ($T=4.2 \text{ K}$)

The shape of the curve is a clear signature of a sinusoidal current-phase relationship.

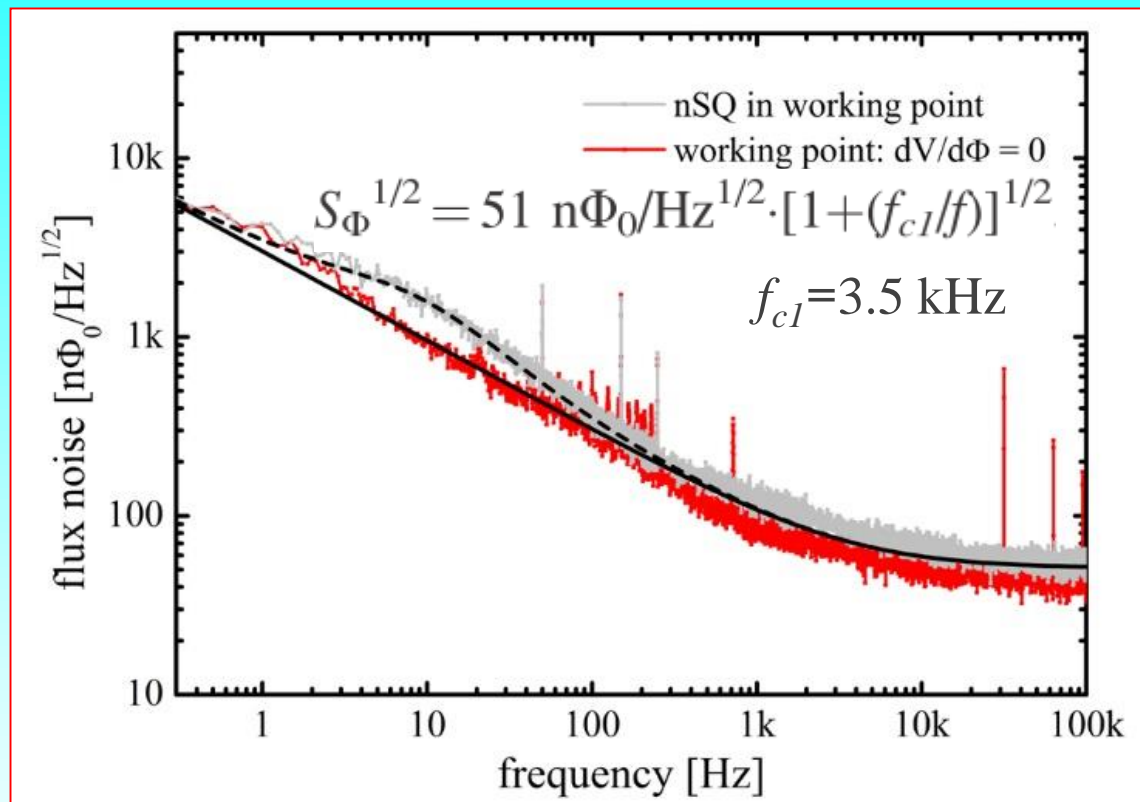
M. Schemelz et al. Appl. Phys. Lett. 2017

Two-stage SQUID readout



The nanoSQUID (SQ1) is voltage-biased with a parallel resistor $R=1.5 \, \Omega$. The critical current change of the nanoSQUIDS is sensed with the SQUID amplifier (SQ2-parallel double-washer). Feedback from a directly coupled SQUID electronics (Supracon) is applied to the amplifier SQUID ($S_I^{1/2} = 5 \, \text{pA}/\text{Hz}^{1/2}$).

Magnetic flux noise measurements



Flux noise spectral density measured at 4.2 K (gray line), and the corresponding fit is shown as a dashed black line. In magnetic insensitive working points, a behavior according to the red line has been observed, indicating critical current fluctuations as the main reason for the degraded low-frequency noise performance.

For β_L and β_C about 1:

$$S_{\Phi}^{1/2} = 4L_{SQ}^{3/4}C_{JJ}^{1/4}(2k_B T)^{1/2}$$



$$S_{\Phi}^{1/2} = 42 \text{ n}\Phi_0/\text{Hz}^{1/2}$$

Experimental value:
51 n Φ_0 /Hz^{1/2}

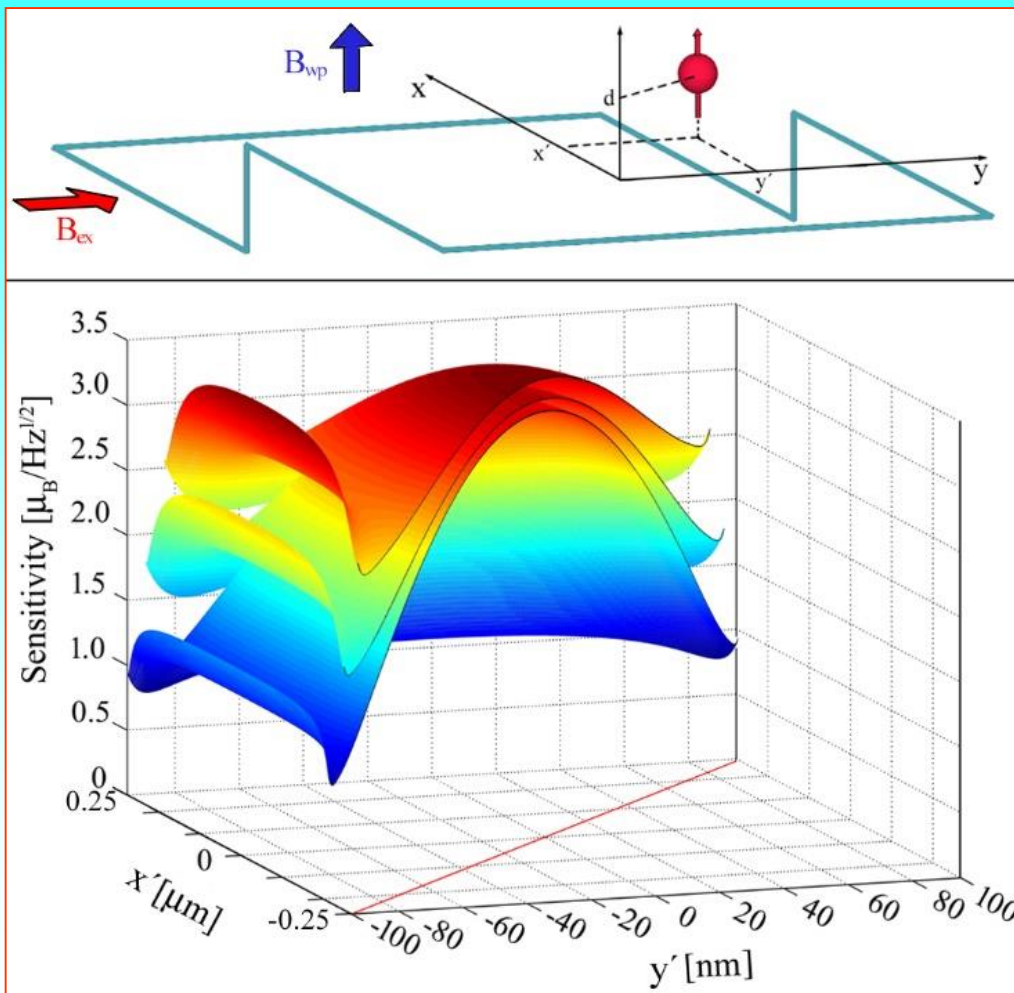
Excellent agreement!

Energy resolution in
white region:

$$\varepsilon = S_{\Phi}/(2L_{SQ}) \approx 1.3 \text{ h}$$

M. Schemelz et al. Appl. Phys. Lett. 2017

Spin sensitivity computation



The position and the distance with respect to the folded coil, as well as the excitation field (B_{ex}) and the field to adjust the SQUID working point (B_{wp}) are shown.

Simulated spin sensitivity as a function of the position within the half nanoSQUID loop for three different distances (10 nm, 20 nm, and 30 nm) of particle with the magnetic moment of Bohr magneton from the loop plane. In order to display the larger variations, the cut was made along the loop diagonal.

For a distance of 10 nm:

$S_N^{1/2} \approx 3 \mu_B/\text{Hz}^{1/2}$ in the central region

$S_N^{1/2} \approx 1 \mu_B/\text{Hz}^{1/2}$ close to the edges

Filamentary model, Granata et al J. Appl. Phys. 2009

M. Schemelz et al. Appl. Phys. Lett. 2017

Conclusions

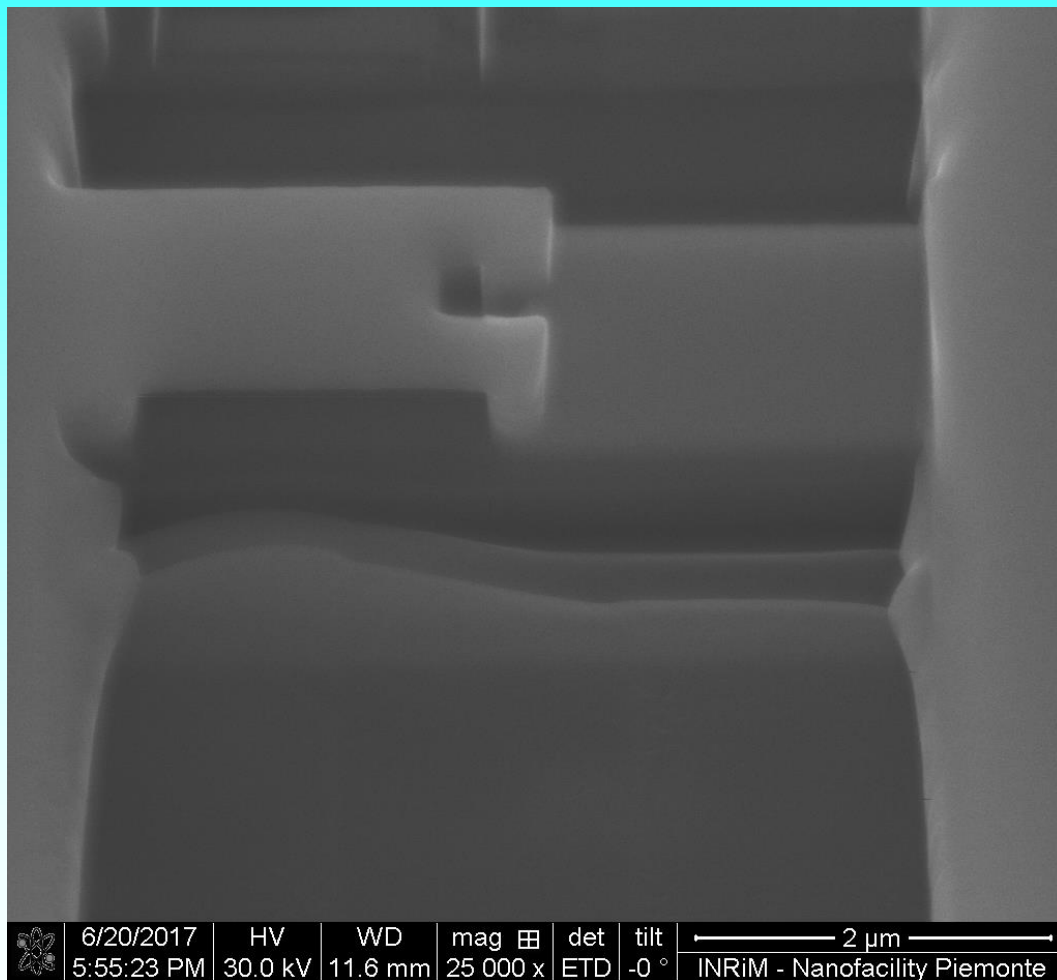
Niobium nano-SQUID based on tunnel Josephson nanojunctions with an energy sensitivity of $1.3 h$ at $T=4.2$ K has been presented.

•The nano-SQUIDs based on Josephson nanojunction (Nb/Al-AlO_x/Nb) have exhibited:

- high critical current modulation depths**
- high responsivity**
- ultra-low magnetic flux noise**

THANK YOU FOR YOUR ATTENTION

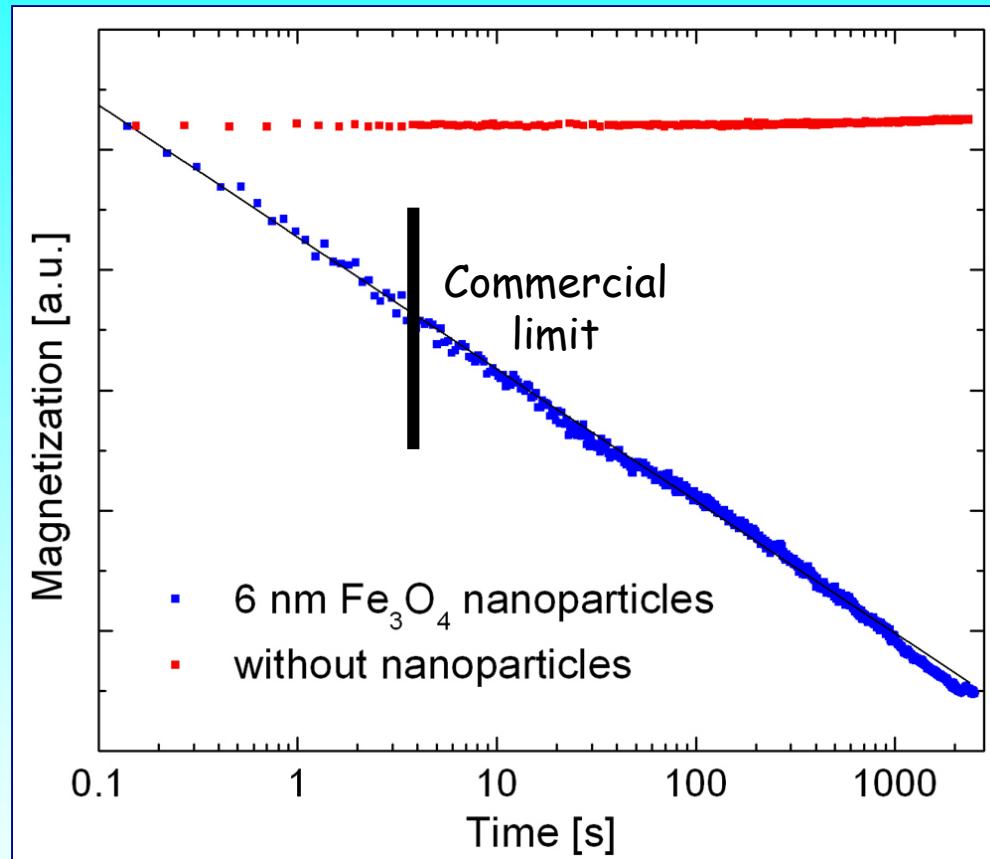
Work in progress



Reduction of parasitic capacitance

**Suspended 3D nanoSQUID
based on FIB sculpting
technique.**

Magnetic relaxation measurement



Magnetic relaxation measurement at $T = 4.2$ K of Fe_3O_4 nanoparticles having an average diameter of 6 nm and cooled in a magnetic field of 10 mT (blue dots). The black straight line is an exponential fit of the data. The same measurement was previously performed without the nanoparticles (red squares).