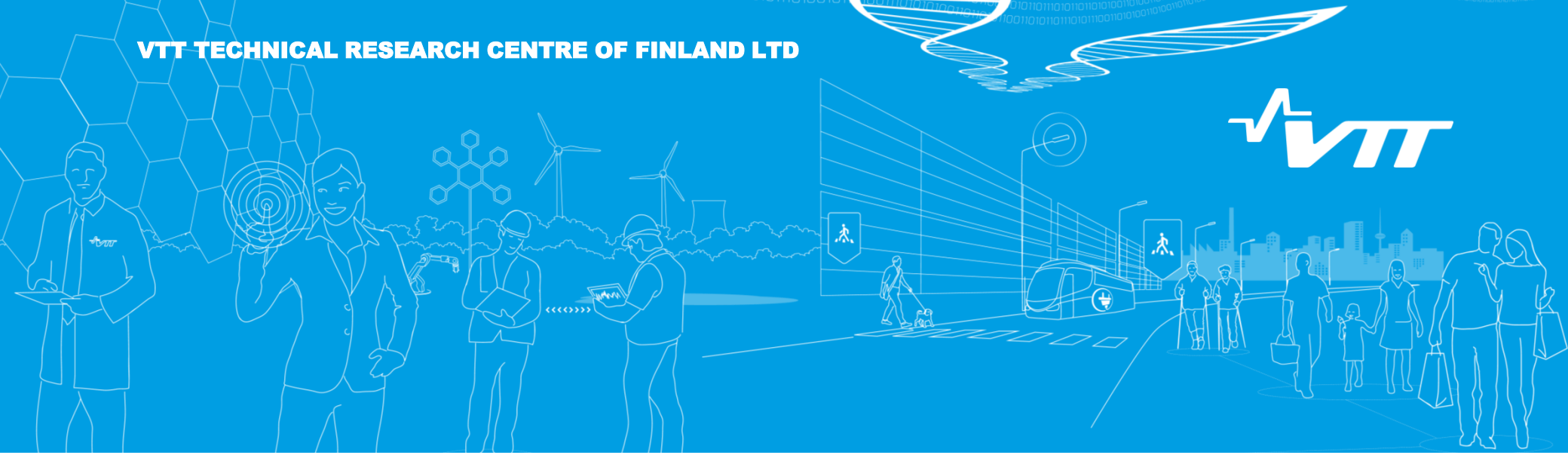

SQUIDs with sub-micron Josephson junctions for ultra-low-field magnetic resonance imaging

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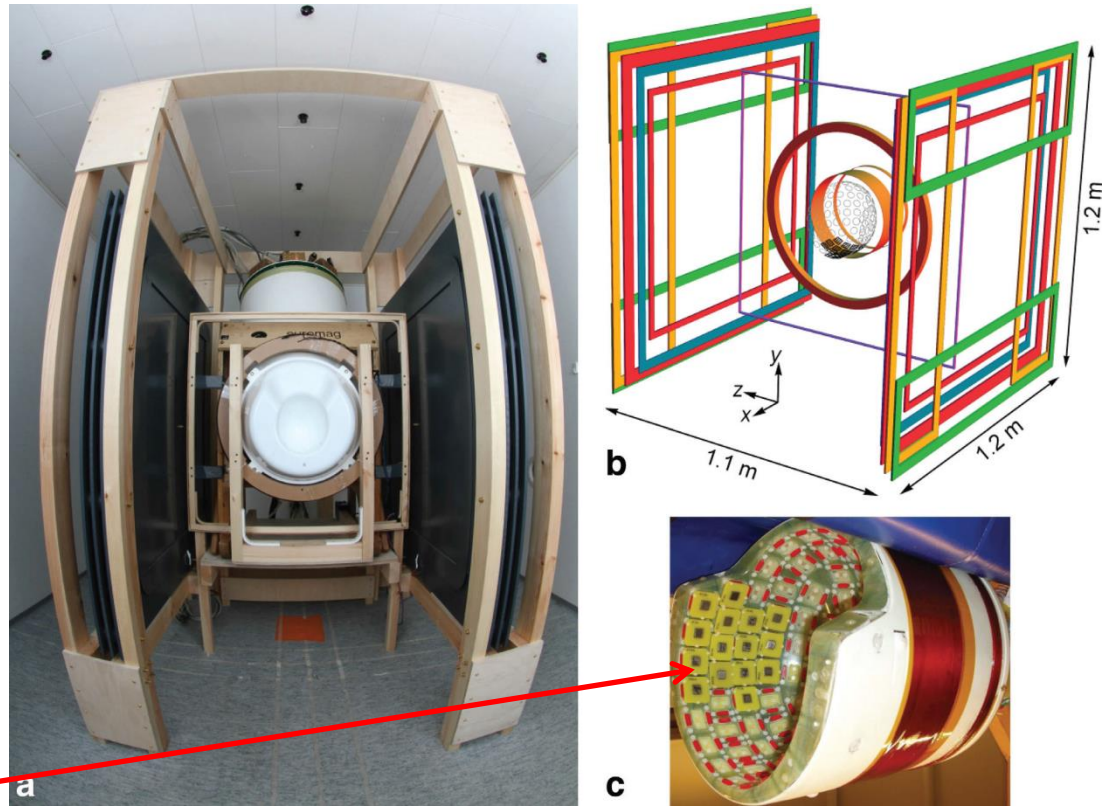
Combined magnetoencephalography (MEG) and magnetic resonance imaging (MRI)

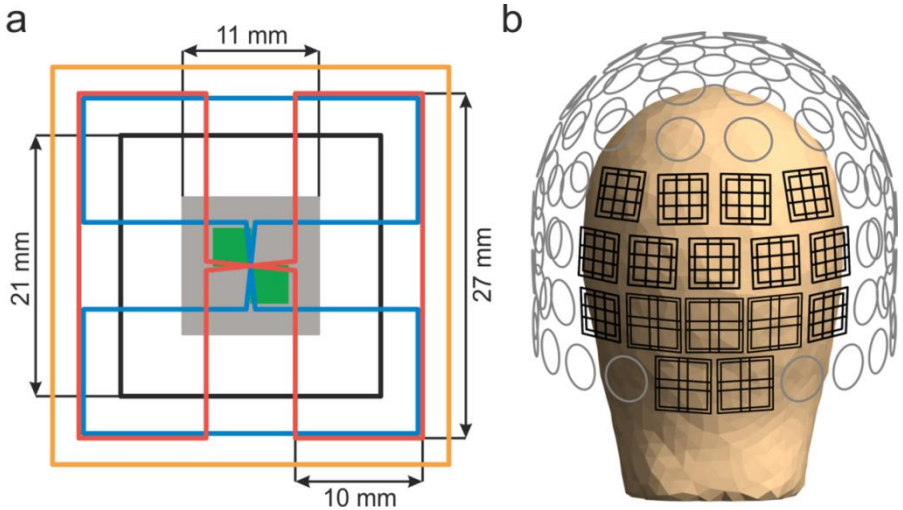
- The analysis of MEG data requires comparison with structural images
  - MR images taken with a separate device
  - Increased work load and inaccuracies between two coordinate systems
- Combined imaging technology developed in two EU-funded projects
  - Ultra-low-field MRI
- Sensor technology based on superconducting quantum interference devices (SQUIDs) developed by VTT



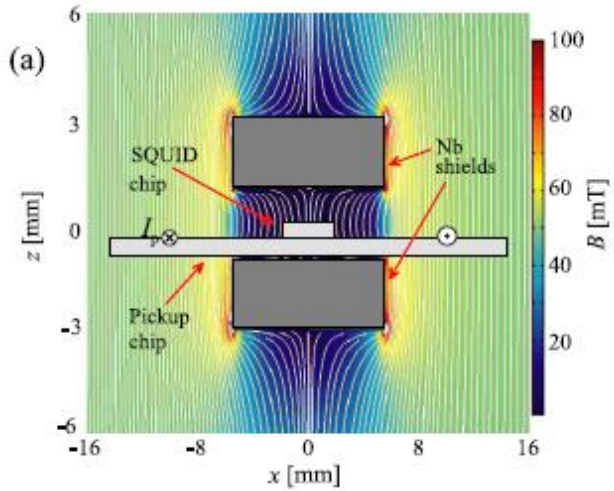
P.T. Vesanen et al., *Magn. Reson. Med.* **69**, 1795 (2012).

Sensors in MEGMRI -project

- Concept: to develop (commercial) MEG SQUIDs further to meet the additional requirements demanded by ULF MRI
  - Recovery from large prepolarization pulses => flux trapping
  - Large sensor arrays in demand
  - All-thin-film sensors easy to mass produce
- ~ 60 planar sensors with one magnetometer and two 1st order gradiometers packaged in 20 modules
- Sensor noise levels ~2-4 fT/Hz$^{1/2}$ / ~1-3 fT/(cmHz$^{1/2}$) and field tolerance up to 50 mT implemented with partial magnetic shielding



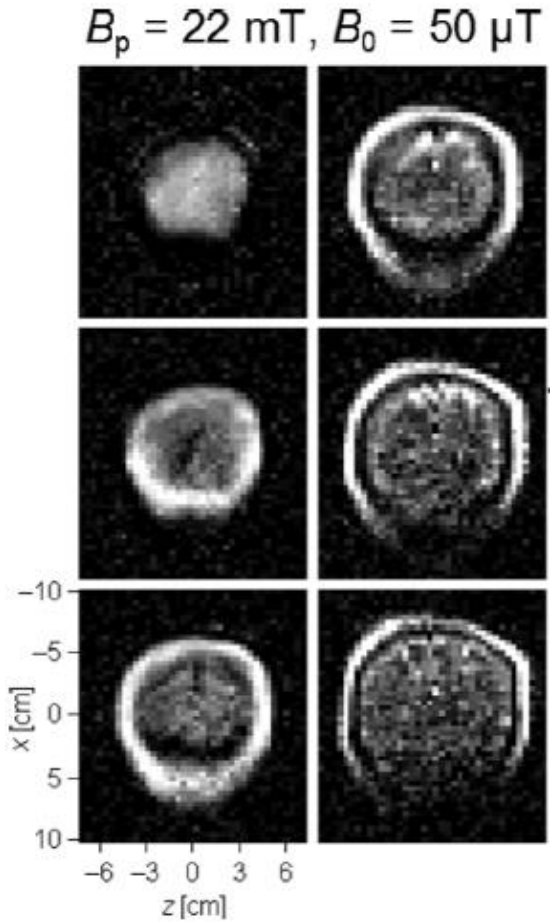
P.T. Vesanen et al., *Magn. Reson. Med.* **69**, 1795 (2012).



J. Luomahaara et al., *Superond. Sci. Tech.* 24, 075020 (2011).

Sensors in BREAKBEN -project

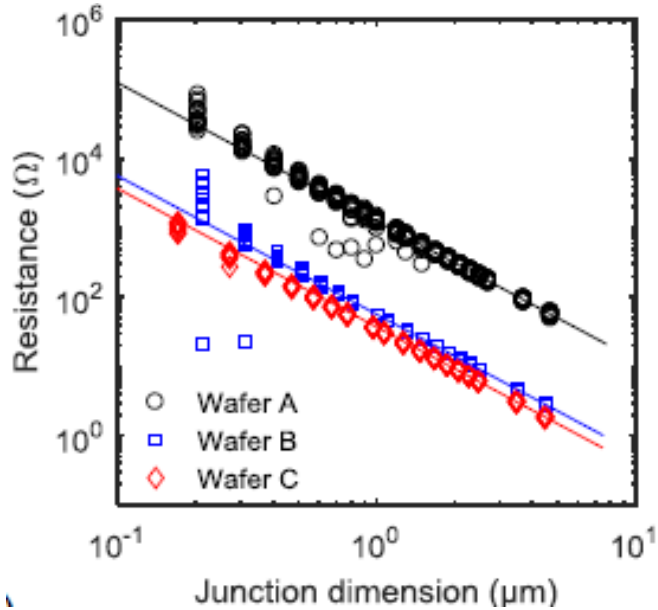
- Improvement of *SNR* for enhancing the image quality
- Specifications
  - High field tolerance required (Target: 150 – 200 mT)
  - Reduction of the noise level (Target: < 0.5 fT/rtHz)
  - Full head coverage (> 100 channels)
  - Removal of Nb shields
- Alternative approaches to reach the targets
  - Tight shielding for SQUIDs placed far away from the imaging volume
  - **Improved junction technology**
  - **Heating sensors**
  - Defluxing/degaussing sensors

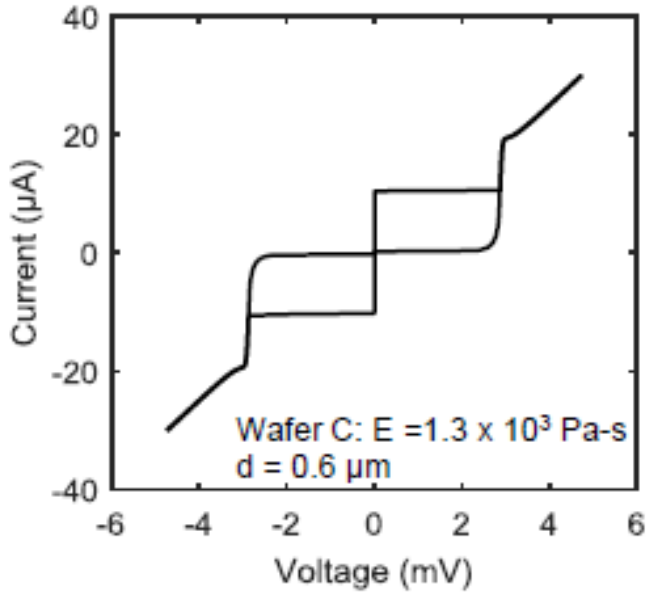


P.T. Vesanen et al., *Magn. Reson. Med.* **69**, 1795 (2012).

New fabrication process for small, cross-type Josephson junctions

- Succesful fabrication of JJs down to a realized junction size of 0.2 x 0.2 μm^2
- Critical current density range 0.1-3 kA/cm^2
- Narrow junctions less sensitive to flux trapping

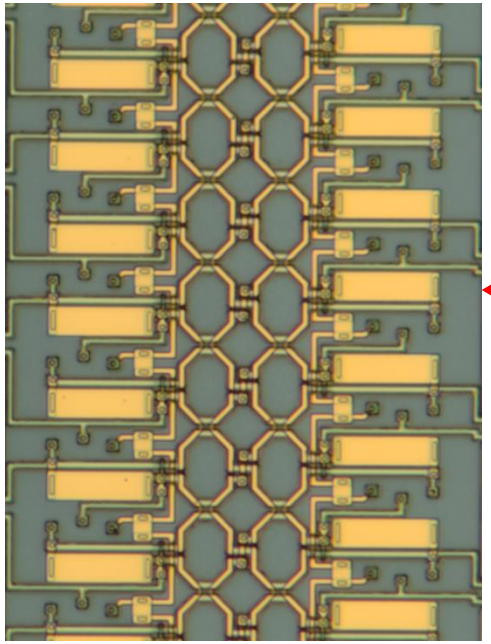


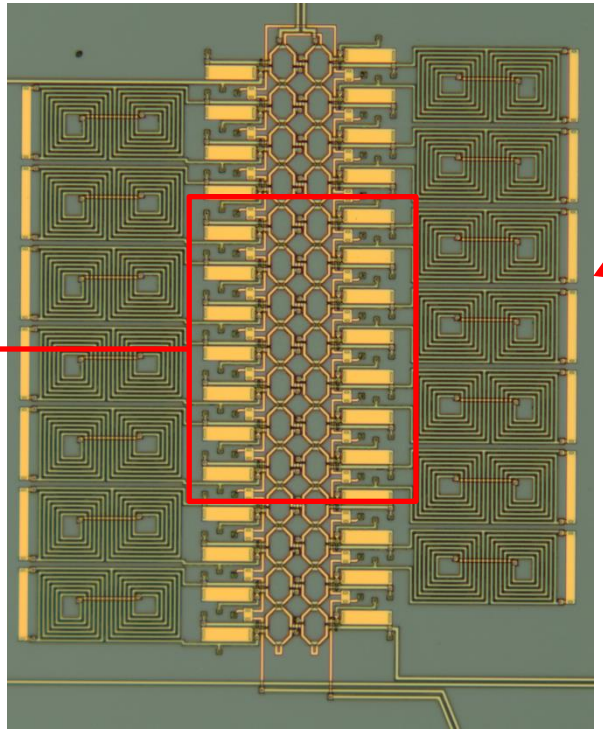


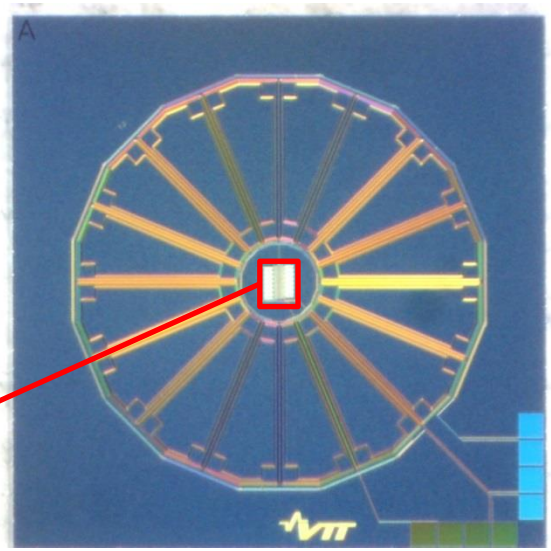
L. Grönberg, et al., "Side-wall spacer passivated sub-μm Josephson junction fabrication process," submitted for publication.

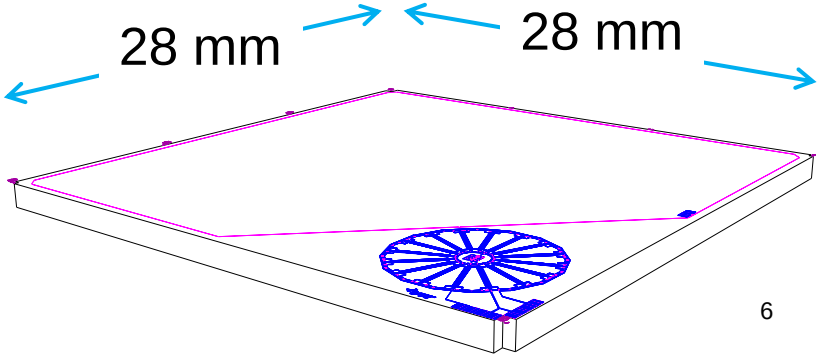
SQUID designs for the test fab round

- An array of 15 gradiometric SQUIDs with a realized junction size of 0.6 x 0.6 μm^2 coupled to a multiloop flux transformer
- Integrated magnetometers
  - Bugs in design, measurements performed without the pickup coil



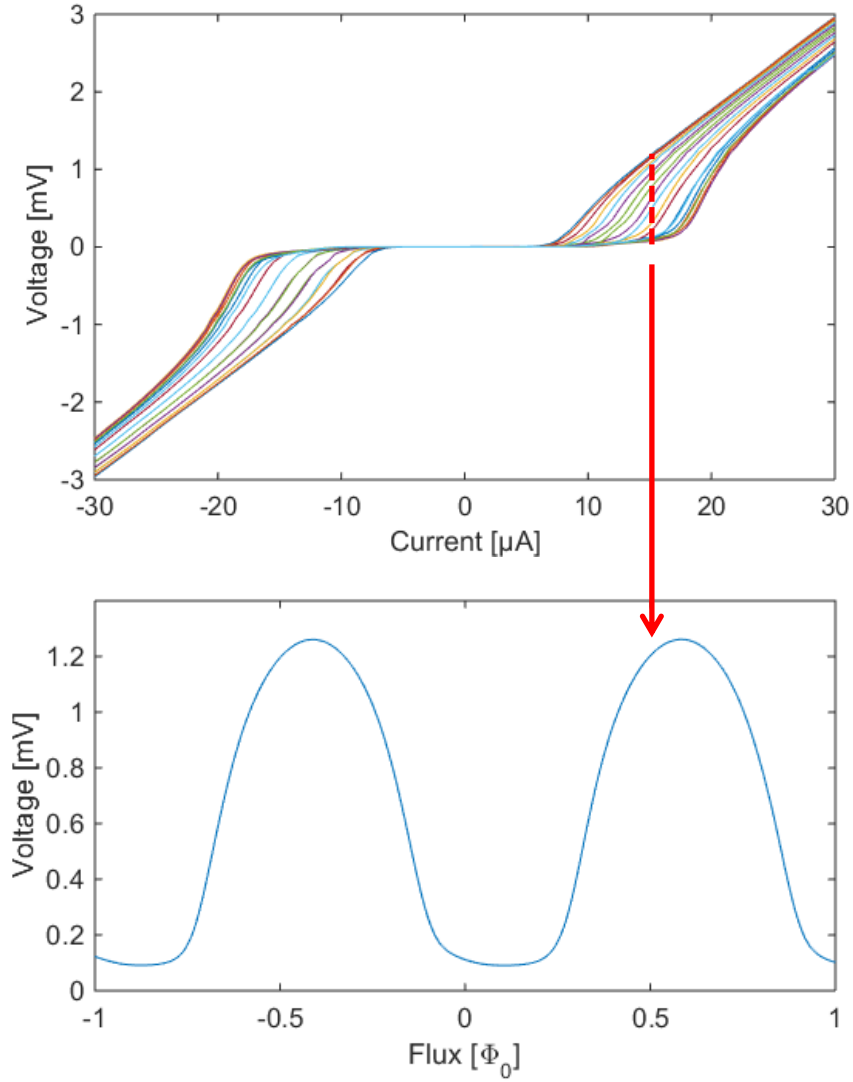






SQUID characterization

- SQUID operation with smooth characteristics verified
- Measured device parameters
  - Junction size 0.6 µm
  - Junction critical current 8 µA
  - Dynamic resistance 130 Ω
  - Input inductance ~ 420 nH
  - Mutual inductance Φ_0/7.8 µA (feedback)
  - Mutual inductance Φ_0/5.6 µA (input)

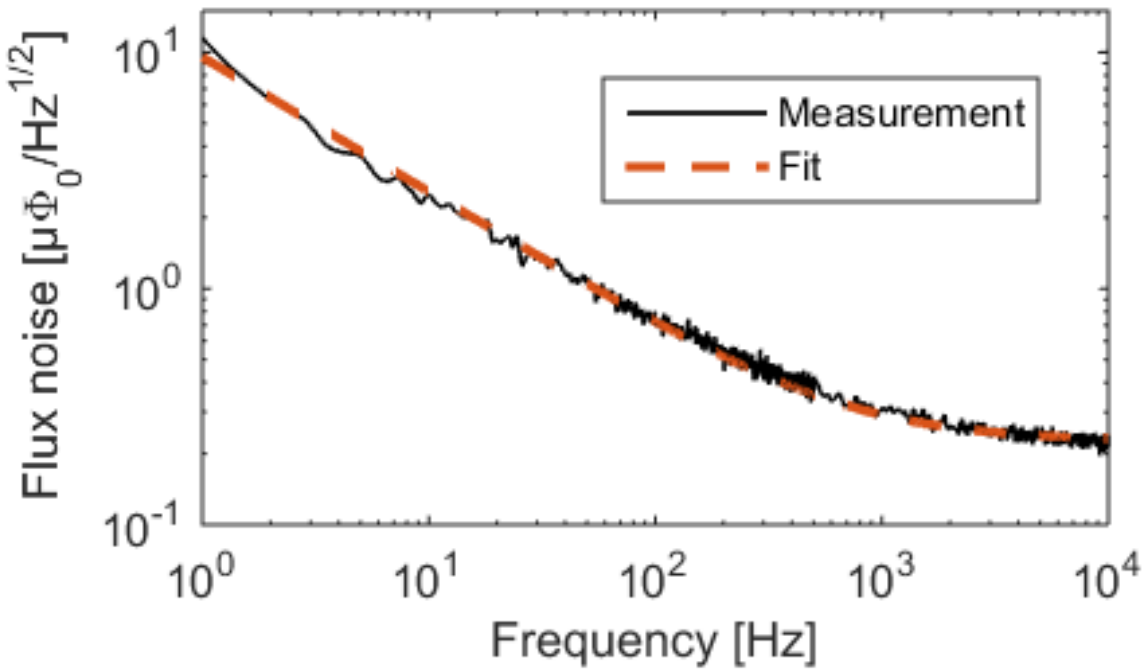


SQUID noise characterization

- A fit to the measured flux noise spectrum:

$$S_{\Phi}=(0.23\ \mu\Phi_0/\mathrm{Hz}^{1/2})^2+(9.5\ \mu\Phi_0)^2 f^{-1.14}$$

- Significant 1/*f* noise noise observed, corner frequency at 600 Hz
- In the white part of the spectrum, measurements still contained a noise contribution from the read-out electronics



Measurement setup for pulsing experiments

Test dewar designed and manufactured by Elekta

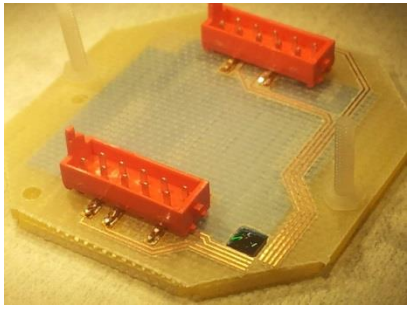
Magnetically shielded room at Aalto University

Helmholz coil

Coil system used for pulsing SQUIDs (~ 1.5 mT/A)

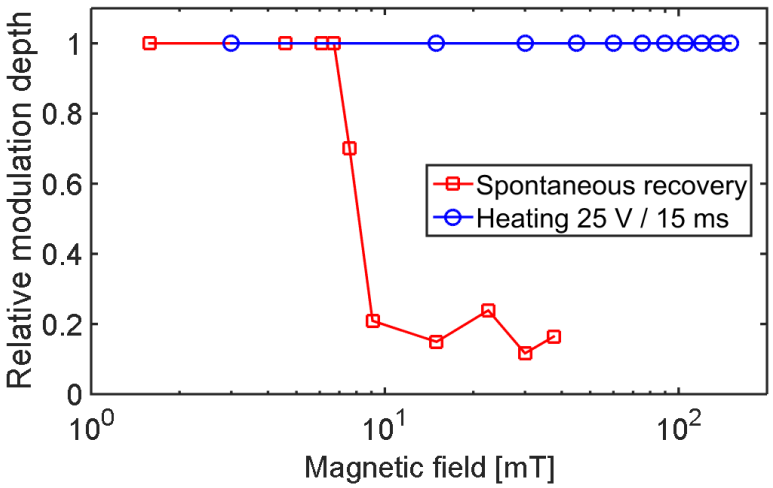
Biasing and readout electronics (with FLL) modified and adopted from previous projects

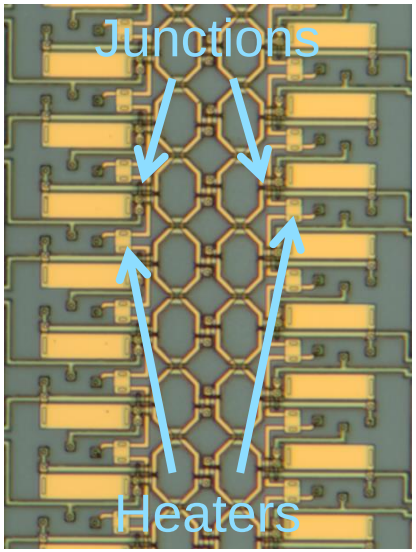
Glass fiber dipstick with 3D printed mechanical parts



Field tolerance – response recovery

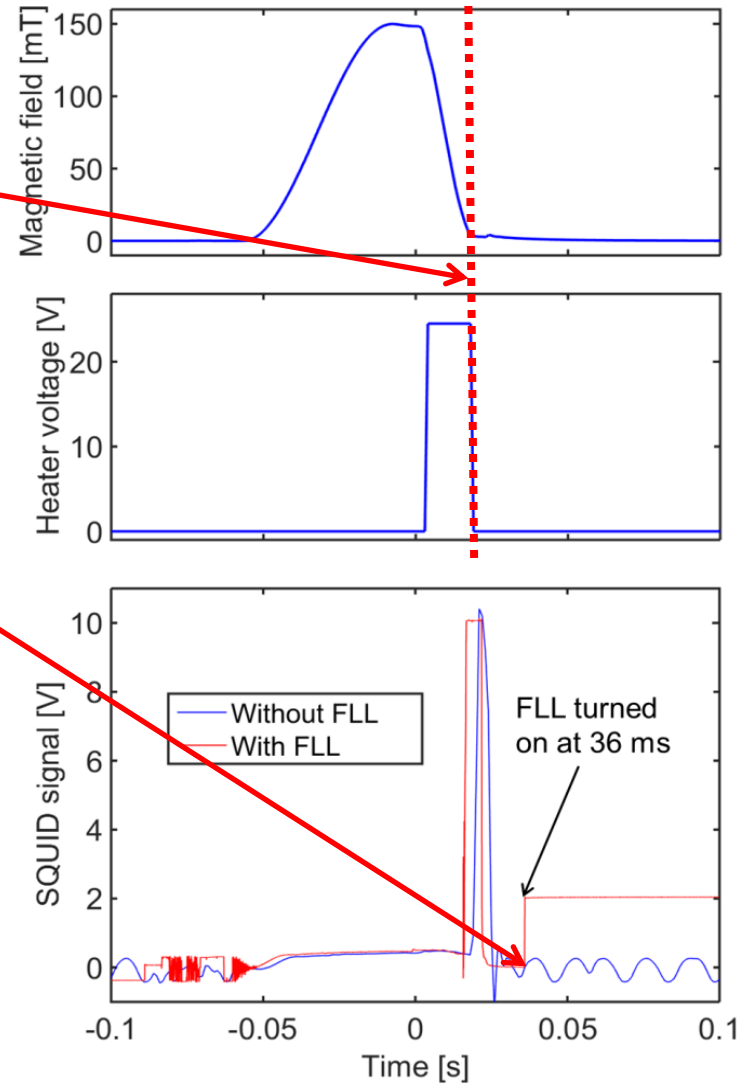
- Response recovery after perpendicular magnetic field pulsing measured
- Spontaneous recovery up to 7 mT
- Modulation curve maintained in the measurement field above 2 mT
- Assisted recovery
  - Heating elements placed close to junctions
  - SQUID operation recovered with a heating pulse of 25 V / 10 mA / 15 ms (independent of pulse magnitude)
  - Tested up to 150 mT without the pickup coil connected





Heating in an MRI sequence

- Magnetic field brought down ~ 20 ms after which the heating of the sensor is ended
- Modulation curve recovered at around 36 ms
  - Open loop mode
  - Flux sweep applied to feedback
- Transient-like noise **not** observed after magnetic pulsing
  - Flux locked loop (FLL) mode
  - No pickup coil
- Unshielded SQUID operation possible for ULF MRI



Summary

- A new, narrow line junction technology demonstrated
- New SQUIDs designed and characterized
  - Rather low white noise level but substantial 1/*f* noise
    - Bias reversal
    - Adjustment of SQUID parameters to their optimum
  - Spontaneous field tolerance of the sensors not very high but heating helps
    - SQUID array not the best choice from this perspective
    - Unshielded sensor realisation doable
- Final sensor performance evaluated with SQUID magnetic field sensors
  - Transient-like noise due to flux reorganisation in the pickup coil expected
    - Heating and/or defluxing
    - Choosing pickup coil
      - Technology: thin film vs. wire wound
      - Material: niobium vs. lead
      - Geometry: gradiometer vs. magnetometer

Thank you!