Operation of a high-T_C SQUID gradiometer with a two-stage Joule-Thomson micro-cooler

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Swedish Foundation for Strategic Research

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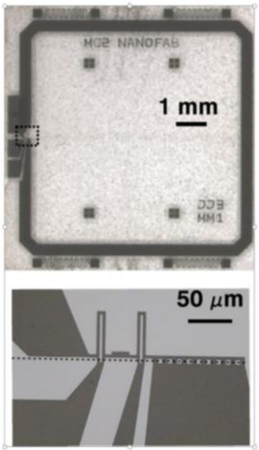
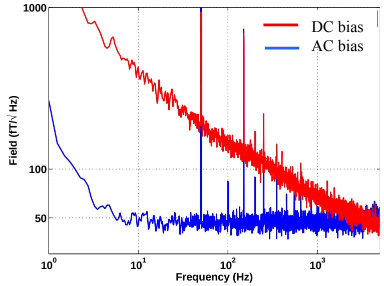
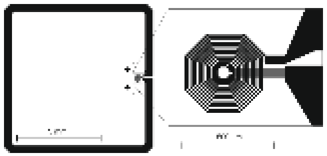
High-T_C SQUIDs at Chalmers:

Technology:

- Bicrystal grain boundary SQUIDs, 50 fT/Hz$^{1/2}$
- Multilayer flux transformers, 8 fT/Hz$^{1/2}$
- YBCO nano-wire SQUIDs

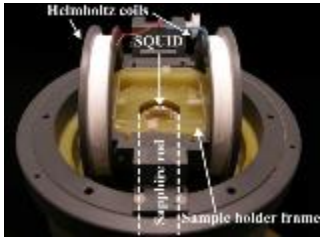






System integration:

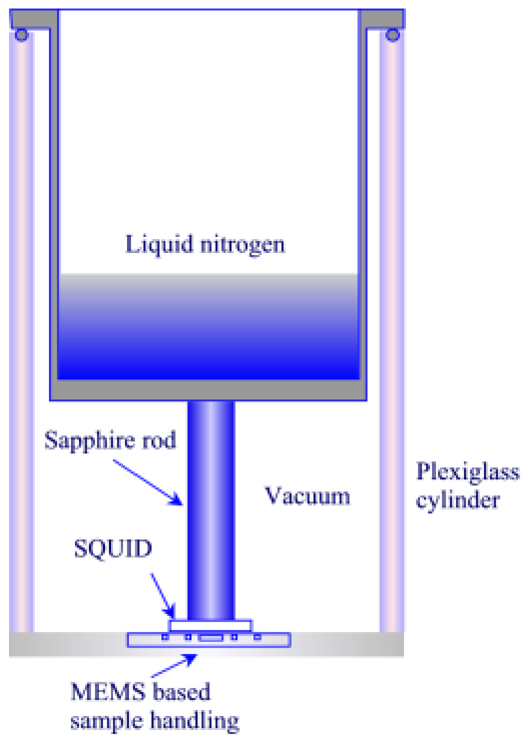
- Multichannel MEG systems (next talk C. Pfeiffer)
- Low-field MRI
- AC magnetic susceptibility, bio-diagnostics using magnetic nanoparticles

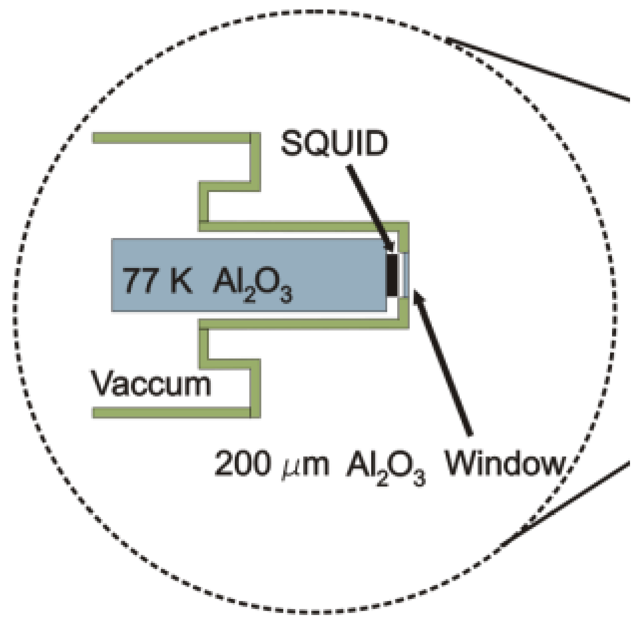


Öisjöen et al., *Supercond. Sci. Technol.* **21** (2008) 034004
Öisjöen et al., *Appl. Phys. Lett.* **100** (2012) 132601
Öisjöen et al., *Biosensors and Bioelectronics* **25** (2010) 1008–1013
Chukharkin et al., *Appl. Phys. Lett.* **101** (2012) 042602
Xie et al., *IEEE Trans. Appl. Supercond.* **25** (2015) 1601905
Ruffieux et al., *Supercond. Sci. Technol.* 30 (2017) 054006

Cryocooling: liquid nitrogen, 77 K

- Epoxy re-enforced fiberglass cryostat, ~ 1 L of LN2, 24 h holding time
- Sensor is placed on sapphire ”cold finger” to avoid Eddy currents in Cu vessel
- Distance from 77 K to room temperature < 0.5 mm

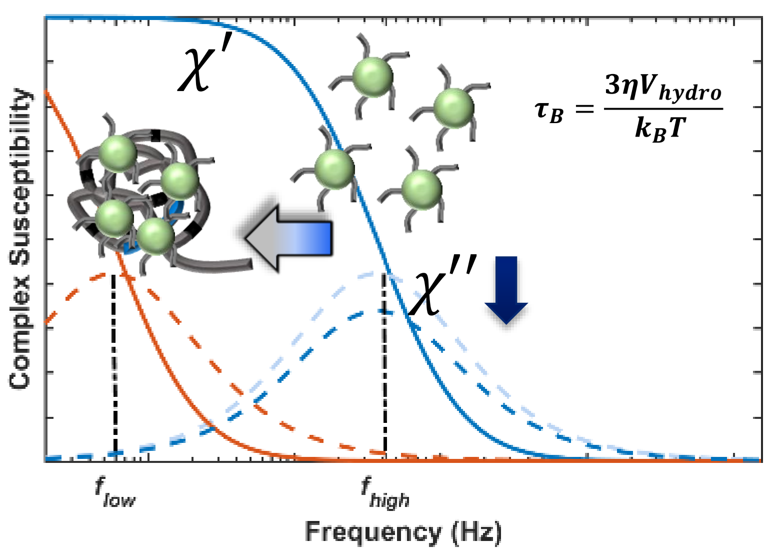




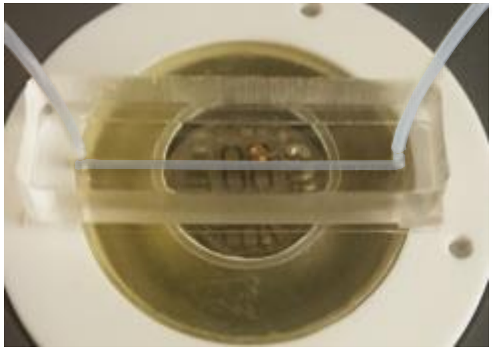
FLU-ID project

- 5-years national project (SSF), 32 MSEK in total, 6 teams
- Project goal: development of a portable diagnostics unit for detection of influenza
- Colloidal magnetic nano-particles as bio-labels, detection of hydrodynamic volume using AC magnetic susceptibility (ACS)
- High-T_C SQUID gradiometer ACS integrated with microfluidic chip

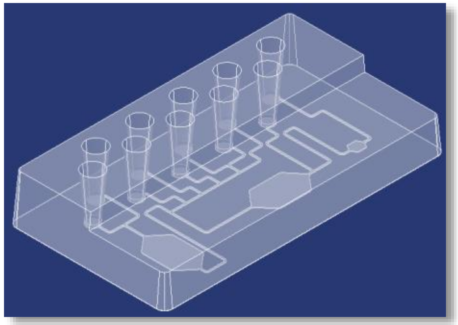
Detection principle:



Top view of the cryostat with microfluidic chip:

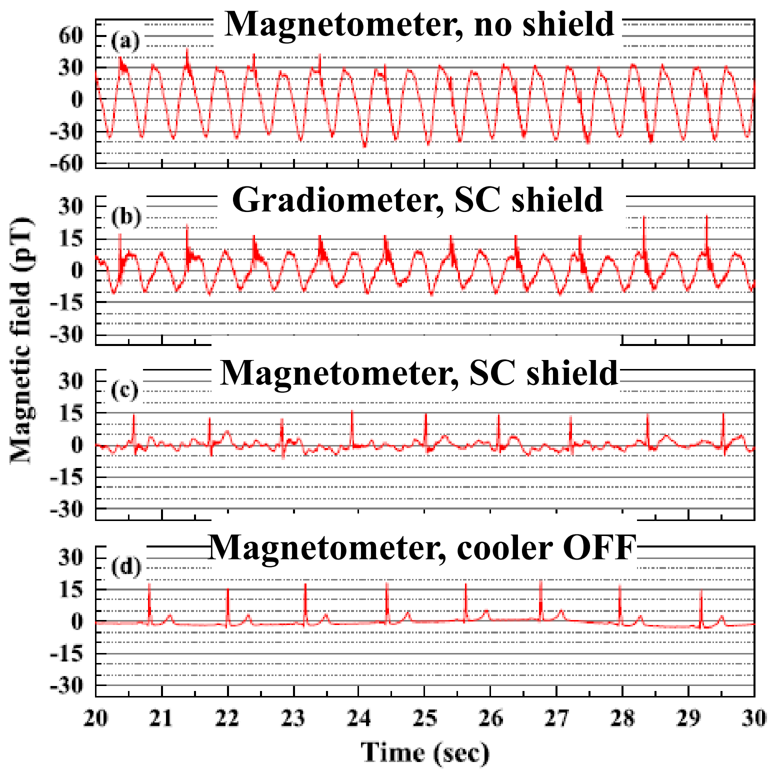


Microfluidic chip reactor prototype:



Cryo-cooling: mechanical coolers

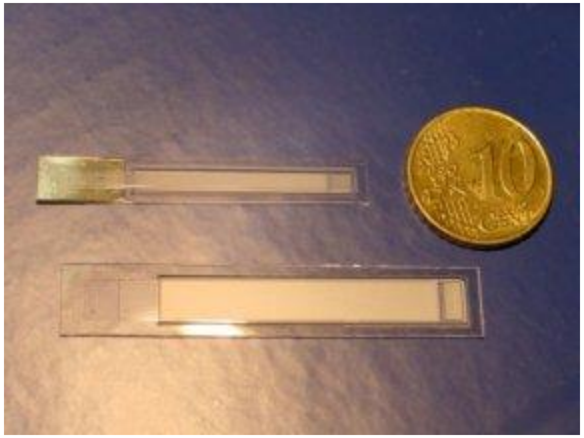
- **Joule-Thomson, Stirling, Gifford-McMahon**
  - Cheap, fast, T ~ 40-60 K
  - Moving metallic parts, vibrations
- **Pulsed tube coolers**
  - Less vibrations, T ~ 4 – 80 K
  - Expensive, orientation dependent
- **SQUID operation**
  - Mechanical and electromagnetic noise
  - Cyclic noise can be reduced by moving SQUID away from cold head and superconducting shielding

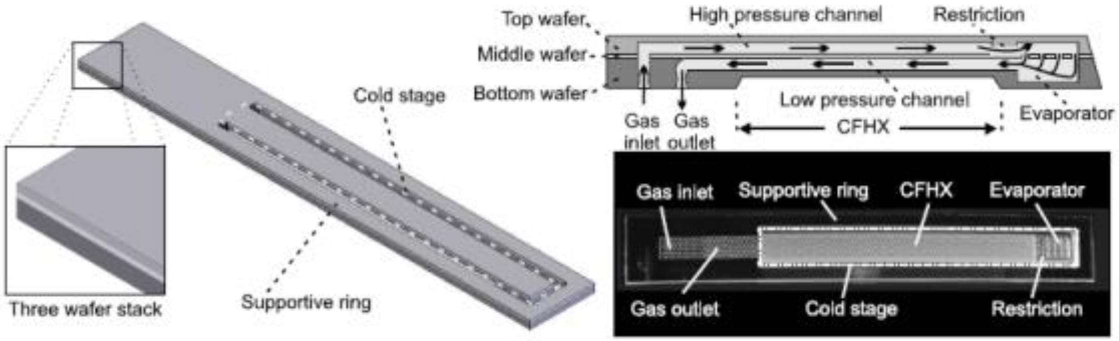


Yu *et al.*, *Supercond. Sci. Technol.* **27** (2014) 105007

Joule-Thomson micro-coolers

- MEMS-micromachined systems
- No moving parts – vibration free and long lifetime
- Can be scaled to small sizes – optimal for SQUIDs!
- No cryo-coolant is needed (“dry” coolers)





http://www.utwente.nl/tnw/ems/Research/JTmicrocooling/Microcooling/
“*Micromachined Joule-Thomson cryocooler*” P.P.P.M Lerou, PhD thesis, University of Twente (2007)

Joule-Thomson microcoolers

Demcon | Kryoz spin-off company from the University of Twente, the Netherlands

Commercial refrigerators based on MEMS Joule-Thomson micro-coolers, table-top systems

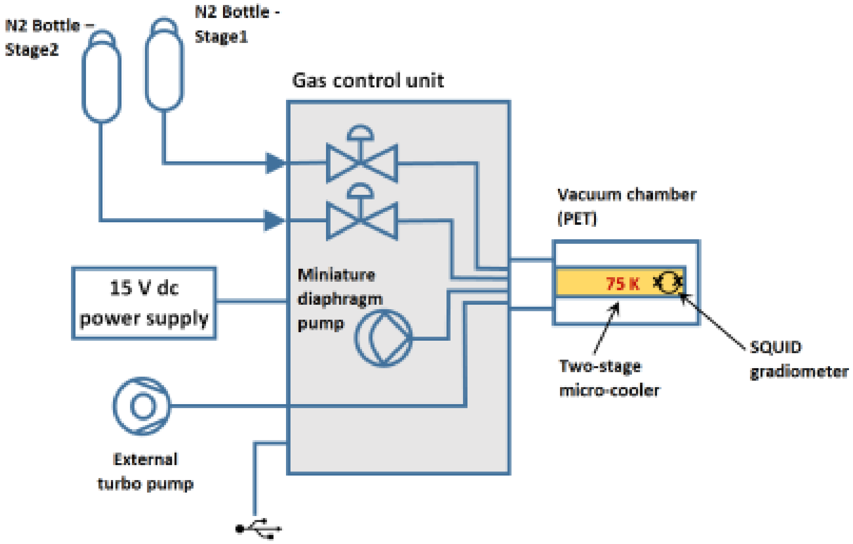
Open-loop Joule-Thomson cycle with high-pressure nitrogen gas (95 bar; ultra-high purity grade, 99.999%) from a commercial gas cylinder

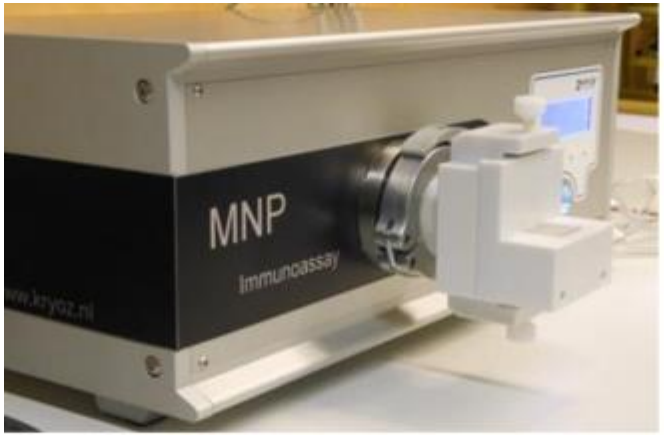
Specs: minimum T = 90 K, maximum cooling power 100 mW @ 95 K, temperature stability 50 mK

http://kryoz.nl/portfolio-item/cryolab-s-2/

Two-stage micro-cooler development

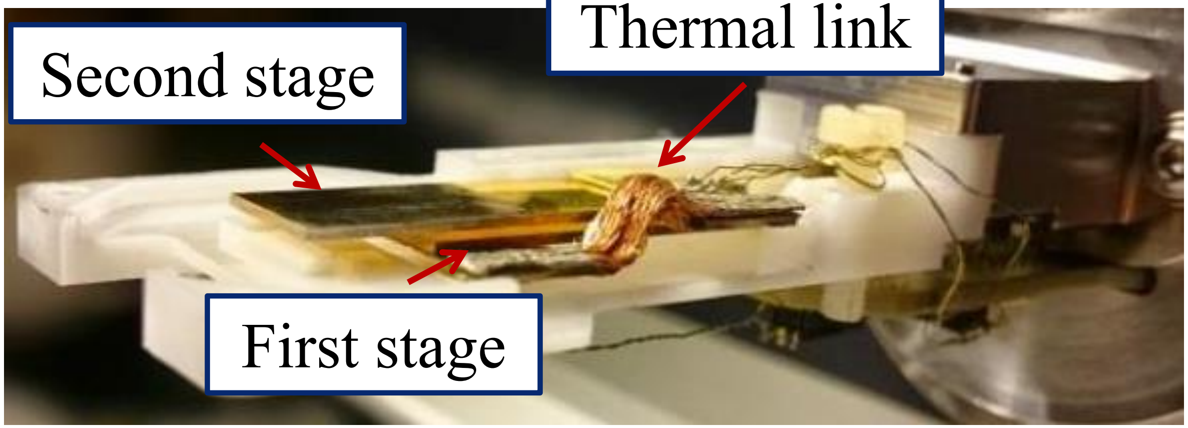
- Single stage micro-cooler is not sufficient to provide cooling power at 77 K
- Joint project between Chalmers and Kryoz to develop two-stage system
- Base temperature 75 K. Optimization of micro-cooler design, gas control system and interfacing between MC1&2 and micro-cooler with SQUID

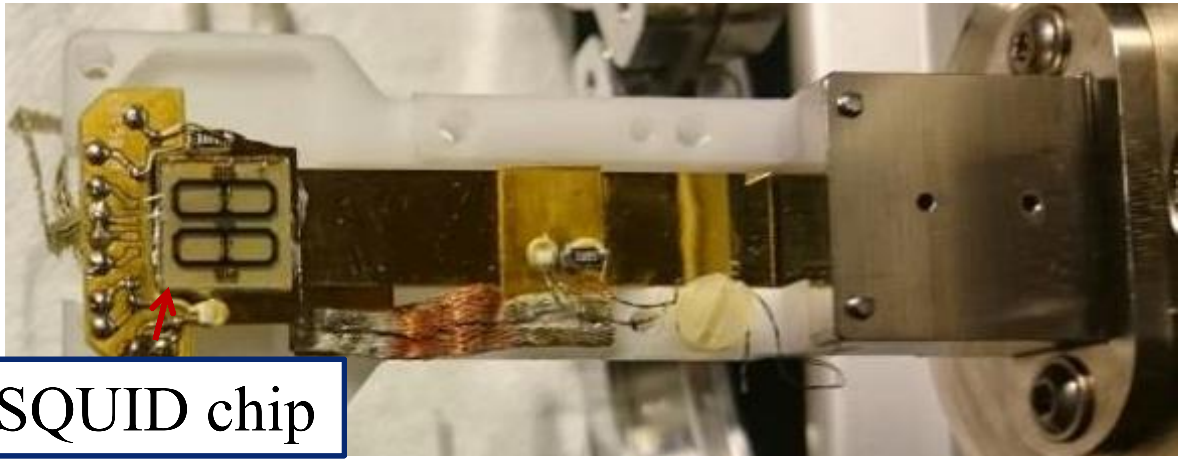


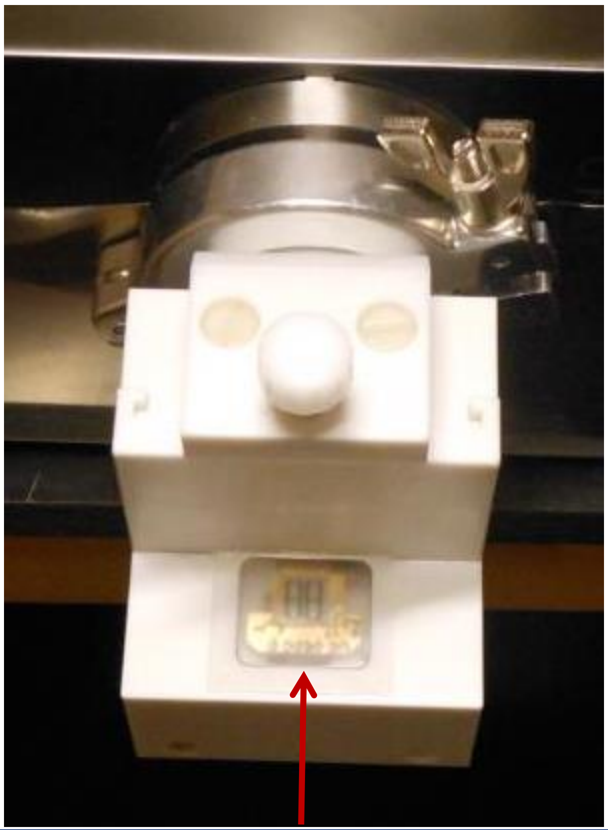


http://kryoz.nl/portfolio-item/cryolab-msg/

Micro-cooler cold stage

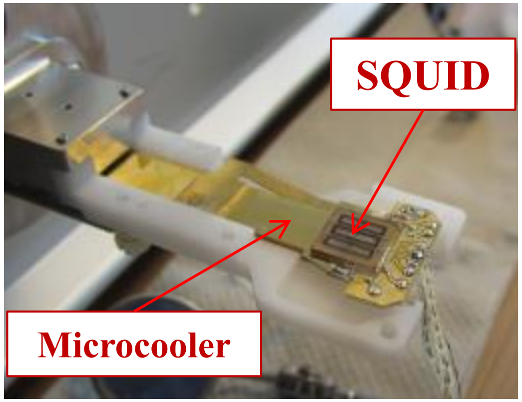




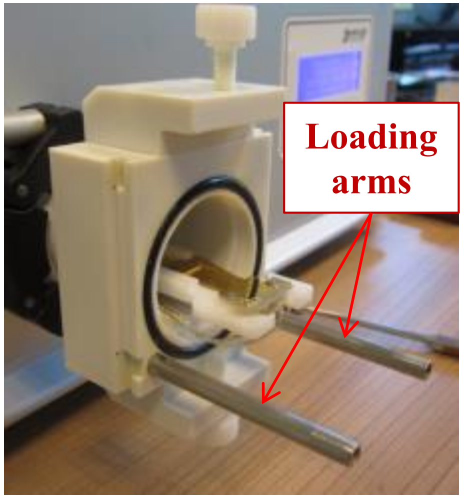


Micro-cooler cold stage

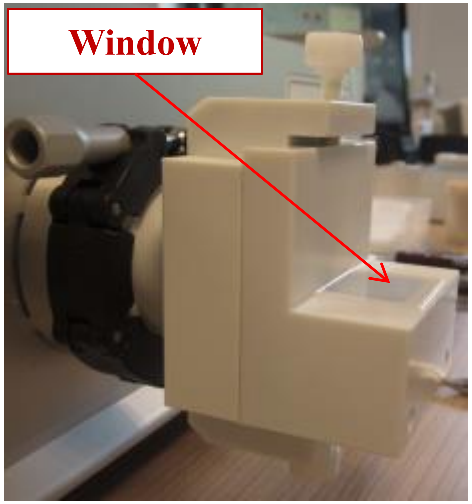
- Plastic vacuum chamber designed and fabricated at Chalmers; new MC-SQUID interface and MC gas control system at Kryoz.
- Vacuum and SQUID performance confirmed at Kryoz. Complete system has been delivered and tested at Chalmers in 2014.



SQUID mounted on two-stage microcooler with new interface



Stationary part of vacuum chamber made from PET

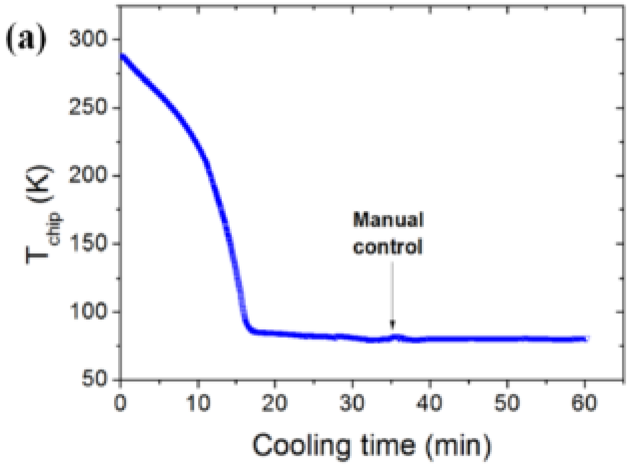


Adjustable part of vacuum chamber with 0.25 mm sapphire window

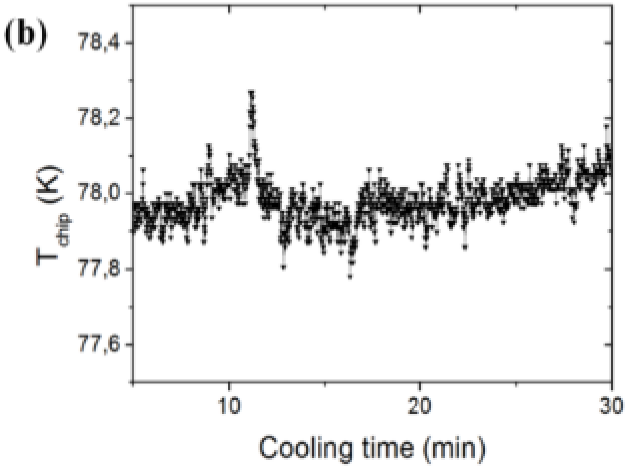
Cooling performance

- Fast cooling down time ~ 20 min.
- Manual control of the temperature using pressure regulator to minimize noise from solenoid valve actuation.
- Temperature stability about ±80 mK

Cooling cycle:



Temperature stability:



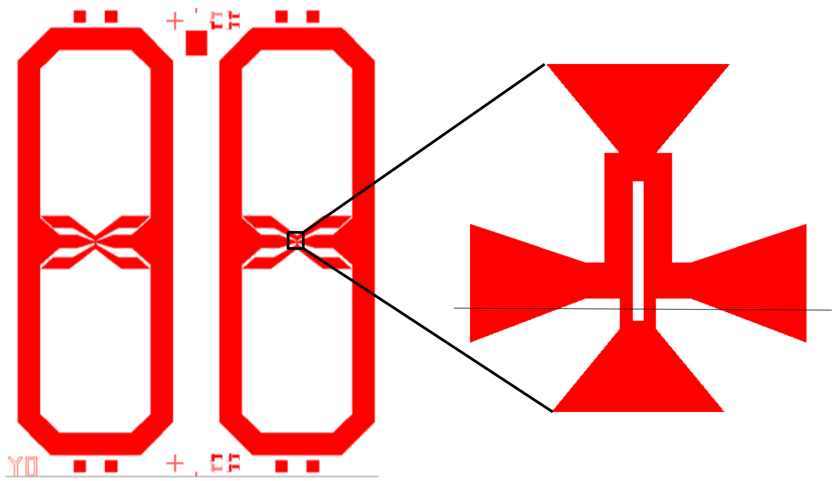
A. Kalaboukhov et al., *Supercond. Sci. Technol.* **29** (2016) 095014

SQUID gradiometer

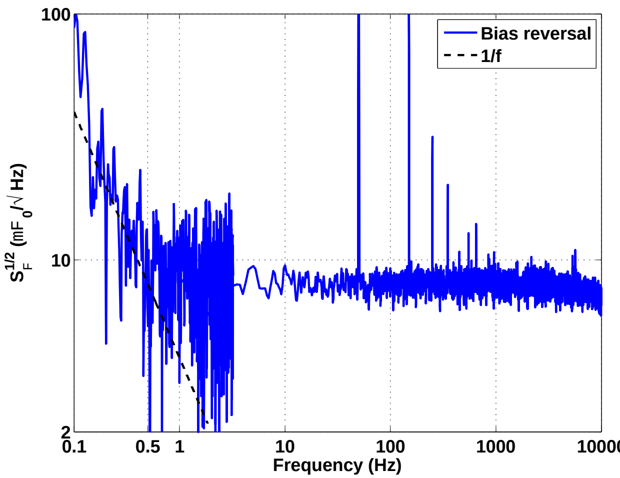
✓ First-order planar dc SQUID gradiometers fabricated from $YBa_2Cu_3O_{7-x}$ thin films on 10 mm × 10 mm $SrTiO_3$ bicrystal substrates with 24° misorientation angle.

✓ Optimized design to achieve very low *1/f* magnetic flux noise
[F. Öijsjön et al., *Supecond. Sci. Technol.* **21** (2008) 034004]

Gradiometer layout:

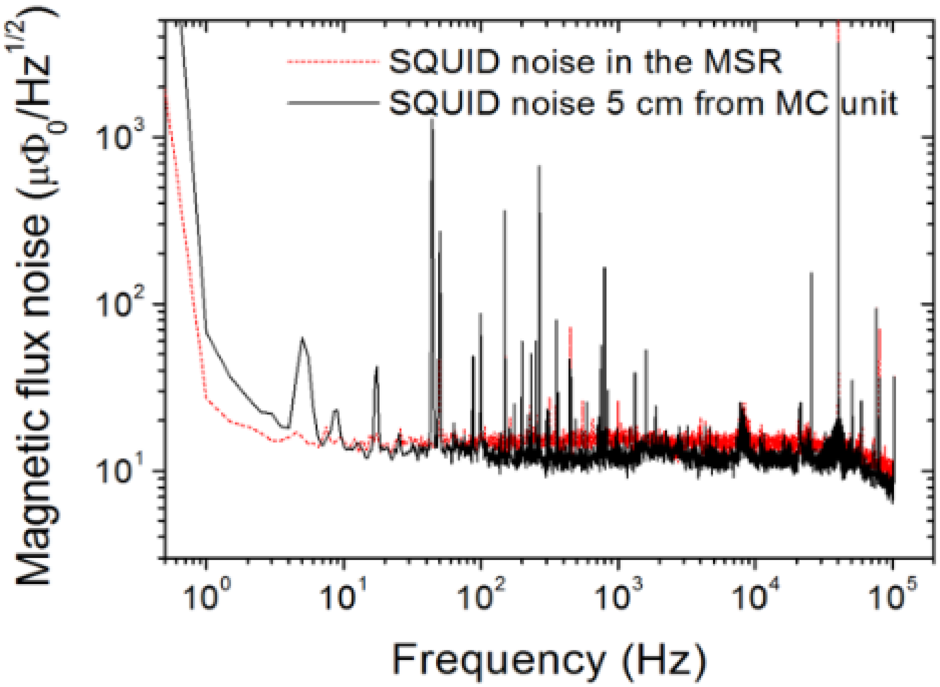


Magnetic flux noise:



White noise: 8 μΦ/√Hz (>0.5 Hz)
1/f-knee at 0.5 Hz

Magnetic noise from micro-cooler



- Magnetic flux noise was recorded using an external **SQUID placed in the LN_2 cryostat at a distance of 5 cm** from the micro-cooler cold head.
- The micro-cooler was operating at its base temperature during the measurements of magnetic noise. **Powered from 220 V line.**
- The white noise level of the SQUID is not affected by the presence of the micro-cooler.

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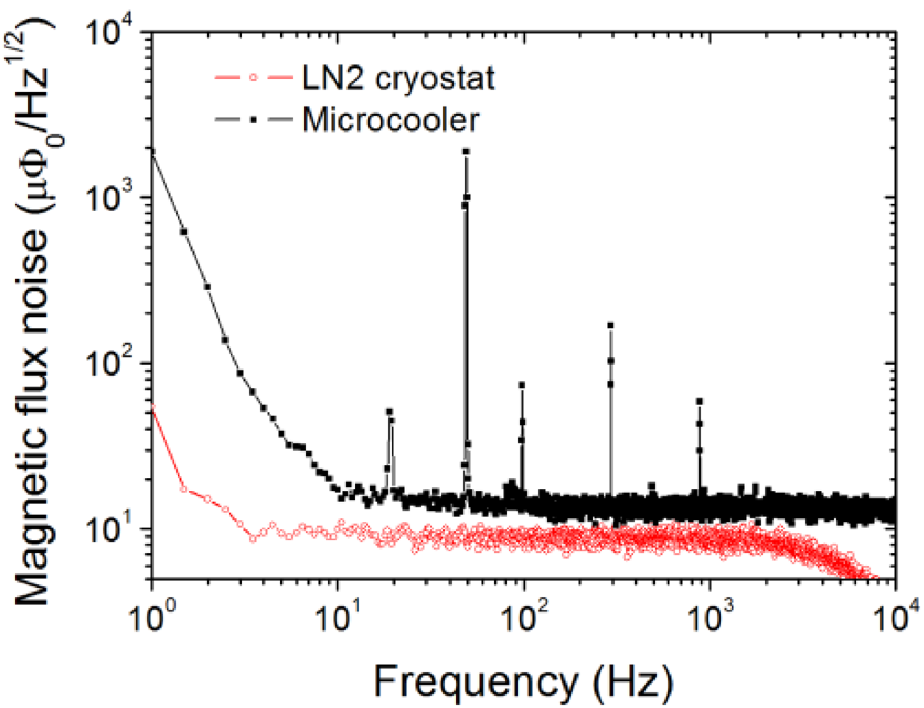
SQUID noise on the micro-cooler

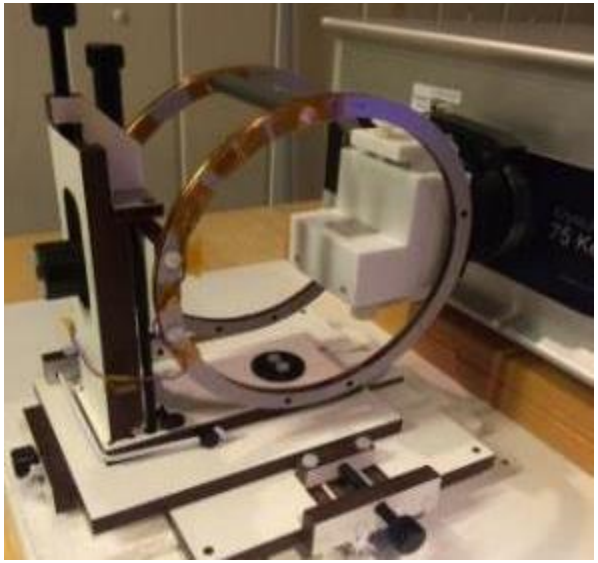


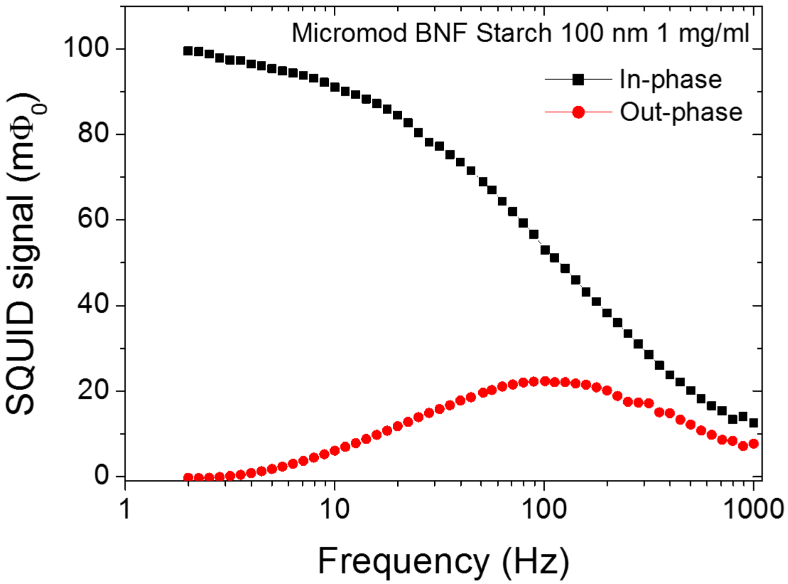
- All noise measurements were performed **in magnetically shielded room** (< 5 nT residual dc field).
- Micro-cooler was powered from filtered +15 V dc power supply
- The equivalent magnetic flux noise of the high-T_C SQUID gradiometer is **largely unaffected by the micro-cooler setup**.
- A small increase in white noise level is partially due to manganine wire resistance (6 Ω per wire).
- Higher *1/f* noise may be due to temperature instability of the micro-cooler .

A. Kalaboukhov et al., *Supercond. Sci. Technol.* **29** (2016) 095014

ACS based on micro-cooler unit

- ACS measurements were performed using our **high-T_C SQUID gradiometer placed on the micro-cooler.**
- MNPs with average diameter of 100 nm and corresponding relaxation frequency of 170 Hz were used.





Conclusions & Outlook

- **MEMS micro-cooler system has been successfully utilized for cooling of our high-T_C SQUID gradiometer**.
- Micro-cooler does not affect the magnetic flux noise of the SQUID.
- AC susceptibility measurements have been performed using high-T_C SQUID gradiometer placed on the micro-cooler.
- Only a SQUID gradiometer was tested: further optimization and shielding may be required in order to operate a magnetometer.
- Future developments: closed-loop system is required!

Thank you!