HTS SQUIDs and GRADIOMETERS: CURRENT STATUS and PERSPECTIVES

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Future Perspectives of Superconducting Josephson Devices

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Outline

1. Starting Point for HTS SQUIDs and Gradiometers
2. The 2-SQUID Gradiometer
3. Step-edge Junctions
4. Gradiometric SQUIDs
5. G-SQUID Gradiometers
6. Future Directions and Applications
7. Conclusions

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SQUIDs and Gradiometers - A Starting Point

What *can* be done

- ✓ Films (YBCO)
- ✓ Junctions — bicrystal or step-edge
- ✓ SQUIDs with narrow trackwidths OK unshielded in Earth's field

Design and operating constraints

- ∗ Usually single layer of YBCO
- ∗ Substrate size/film coverage (and cost if bicrystal substrate)
- ∗ Use of liquid N_2

Problems

- ☹ Small substrates (e.g. $10 \times 10\,\mathrm{mm}^2$) → poor gradient sensitivity (even although the intrinsic SQUID flux sensitivity is as good as possible)
- ☹ Single layer → first-order gradiometers
- ☹ SQUID → magnetometric response, resulting in a balance of only 1 part in 300 or worse.

Requirements for real applications

- As large a baseline as possible
- A high degree of balance
- Simple fabrication — e.g. with only one HTS layer
- Portability — cooling needs, immunity to Earth's field

Our Solutions

A. Two-SQUID single layer gradiometers

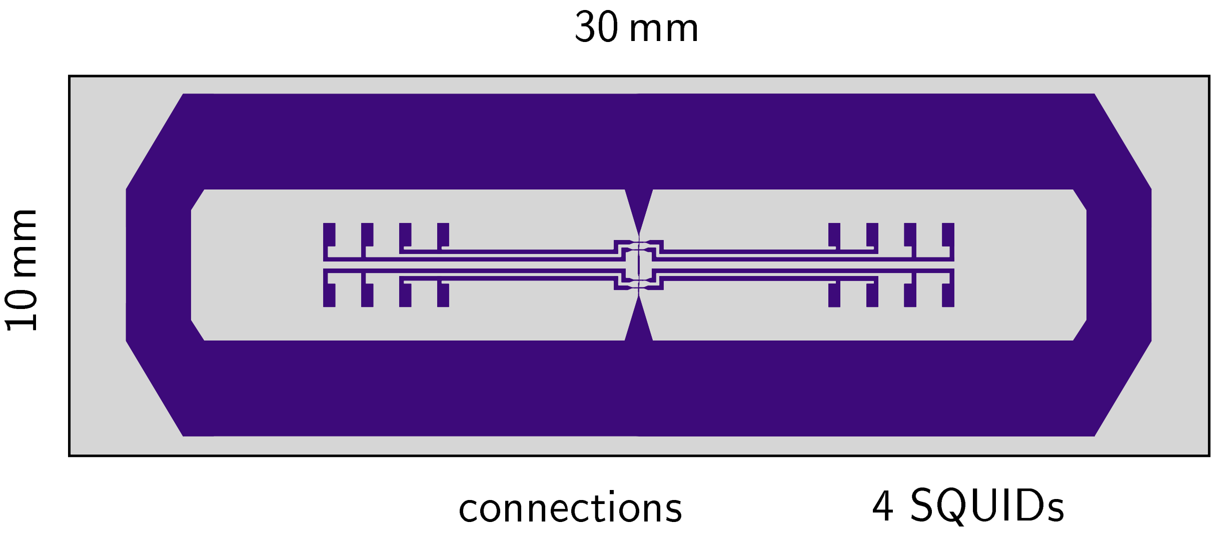
- $10 \times 30\,\mathrm{mm}^2$ substrates ⇒ improved gradient sensitivity
- Two out-of-phase SQUIDs ⇒ adjustable balance
- Made at present on bicrystal substrates

B. Single layer gradiometers with a gradiometric SQUID

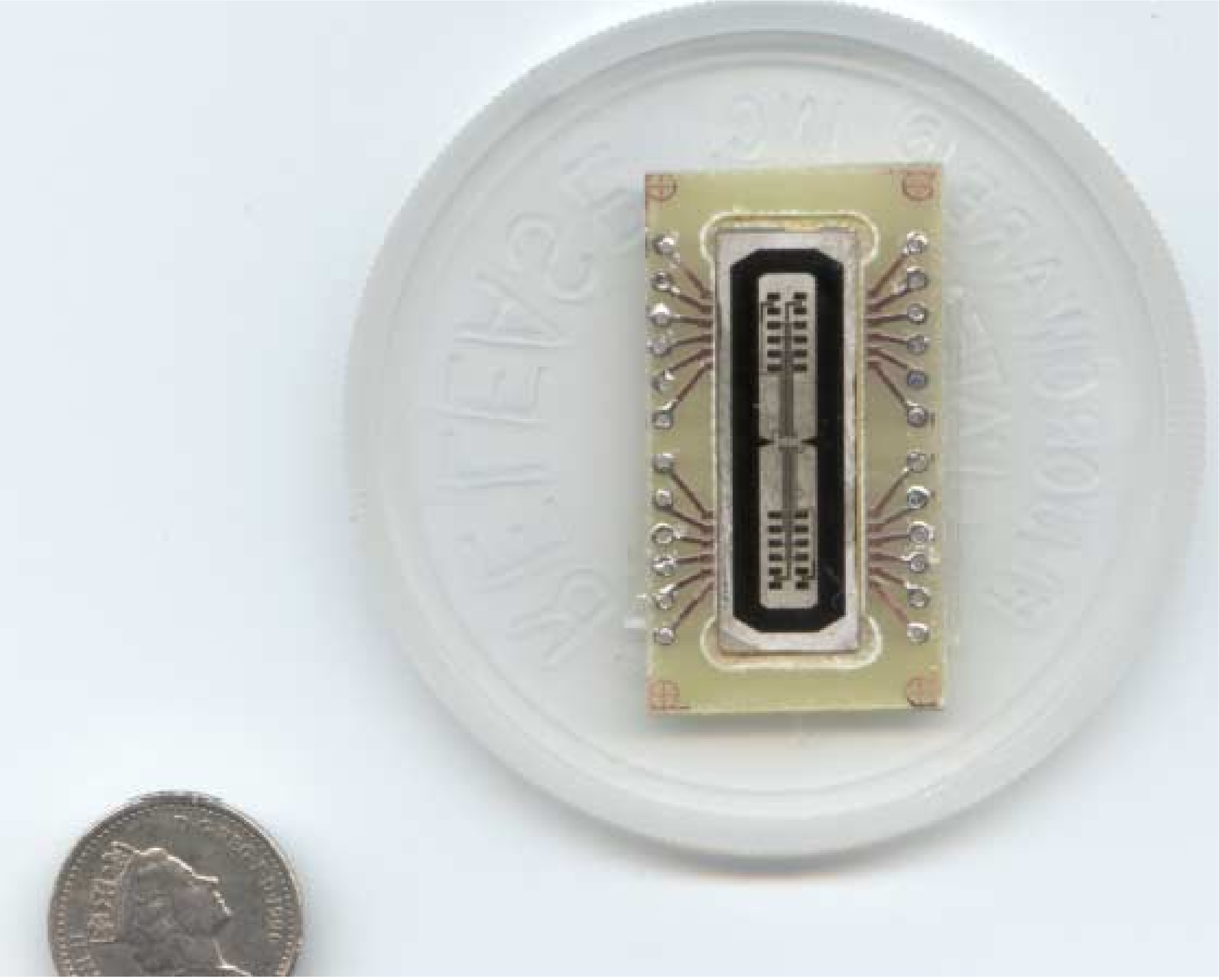
- Use step-edge junctions
- SQUID itself has minimal response to a uniform field ⇒ improved balance

A. The 2-SQUID Gradiometer Design

- Fabricated on $10 \times 30\,\mathrm{mm}^2$ 24° bicrystal substrates
- Baseline b = 13 mm
- Inductance per half loop $\approx 15\,\mathrm{nH}$
- Has two pairs of SQUIDs at its centre (only 2 of the 4 are used at one time)



- Requires a modified laser deposition process for the larger area films.



Fabrication for $10 \times 30\,\mathrm{mm}^2$ Substrates

- Pulsed laser deposition, 820°C, 0.15 mbar O_2, 1.2 Jcm^{-2}, 6000 pulses

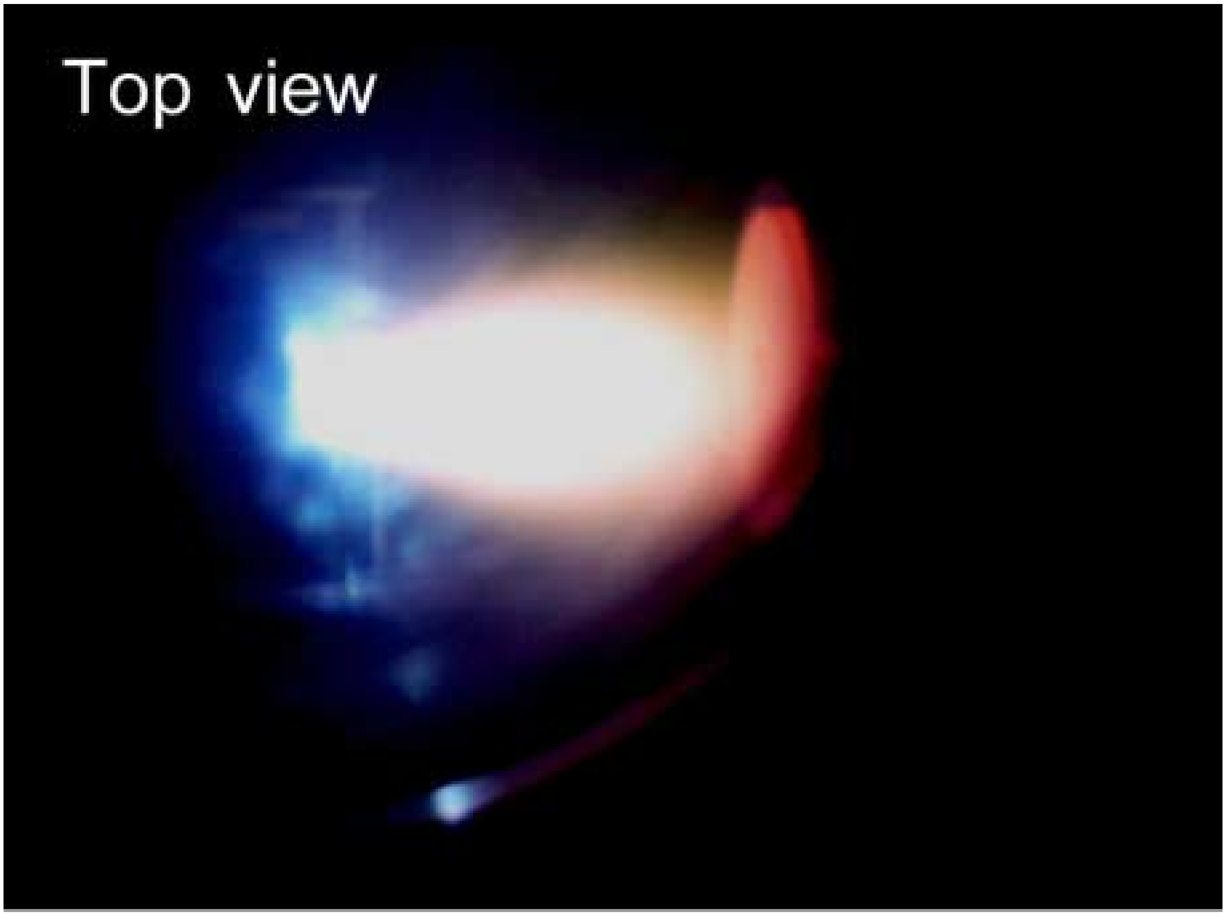
- Target to substrate distance 68 mm

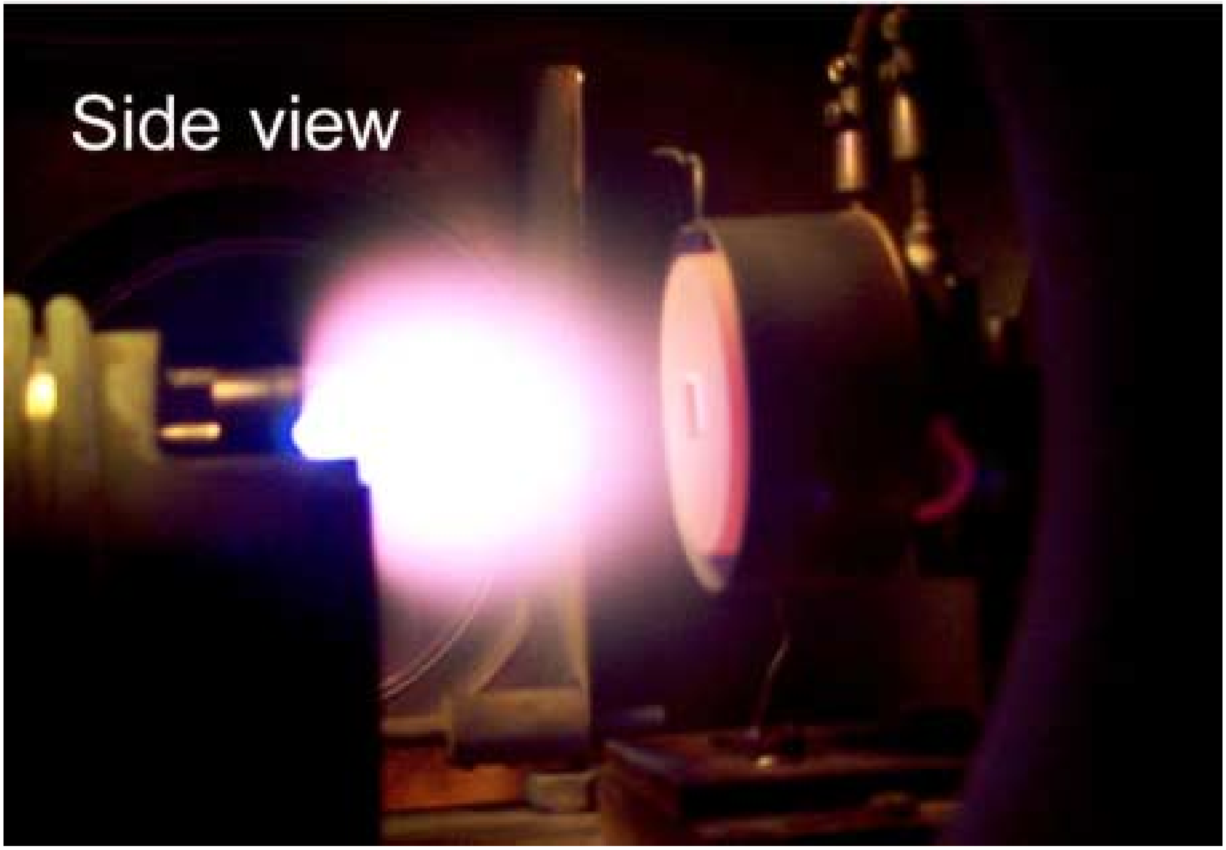
- Laser beam is focussed to a spot ≈10 mm long and ≈0.5 mm wide at the target, ⇒ a plume that expands significantly in the direction parallel to the long side of the substrate, ⇒ good homogeneity along the length of the substrate:

	Centre	Ends
T_c (K)	90	89
Thickness (nm)	200	180

- Patterning by argon ion beam etching

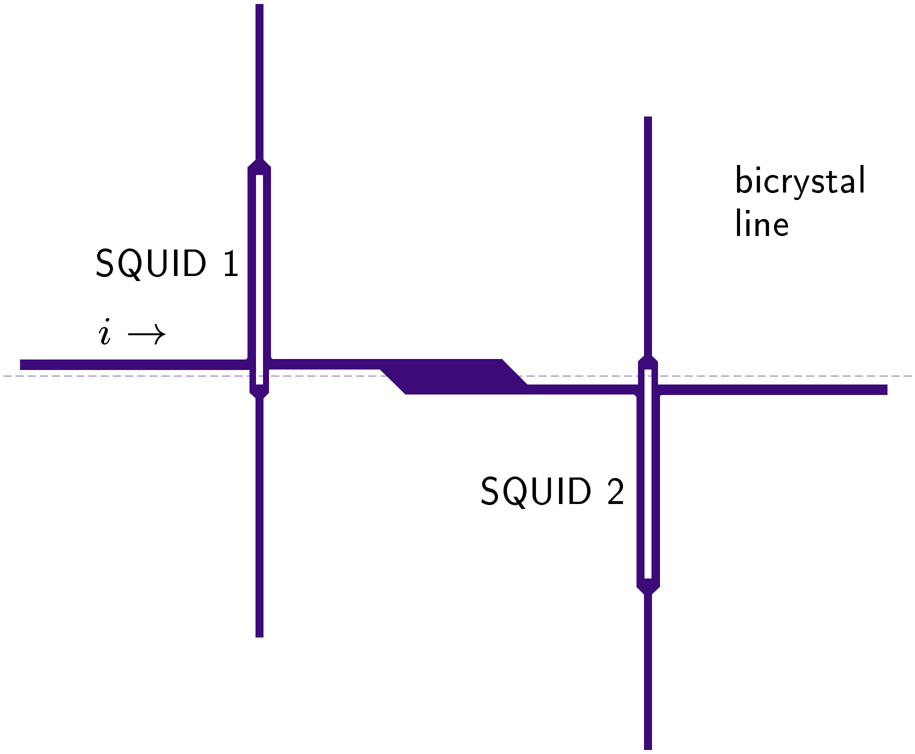
- Contacts are sputtered gold


Top view


Side view

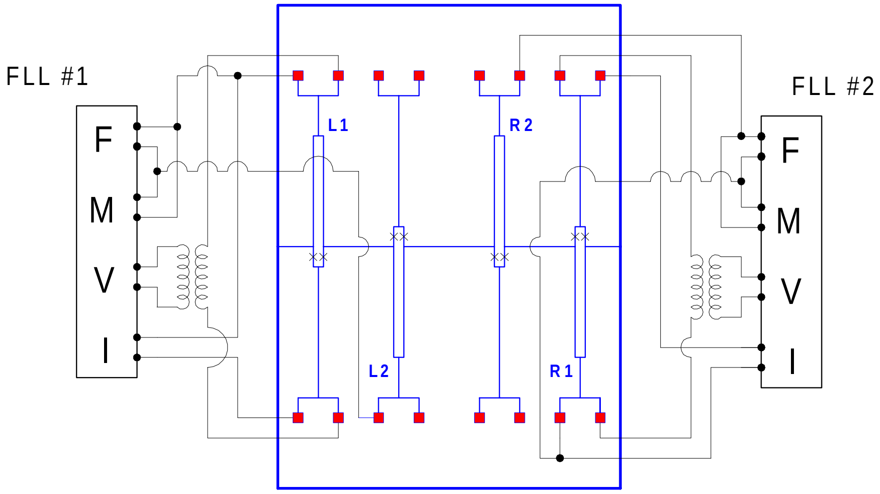
The SQUIDs

- SQUIDs have 4 μm linewidth; SQUID loop is 108 μm × 4 μm
- SQUID inductance $\approx$ 100 pH
- Junction width is 3 μm
- Each pair of SQUIDs is arranged to couple *in phase* to the current i flowing in the centre track of the gradiometer, but *out of phase* to a uniform field:



2-SQUID operation — Adjusting the Balance

Each SQUID is operated with its own flux-locked loop (FLL) electronics. Feedback and modulation is coupled directly (via connections to adjacent unused SQUIDs):



The output voltages V_{SQ1} and V_{SQ2} are summed:

$$V = V_{\mathrm{SQ1}} + \lambda V_{\mathrm{SQ2}}$$

where λ is an adjustable parameter close to 1.

λ can be adjusted to reduce significantly any uniform field response due to any combination of

- ∗ gradiometer imbalance and
- ∗ differences in effective areas of the 2 SQUIDs.

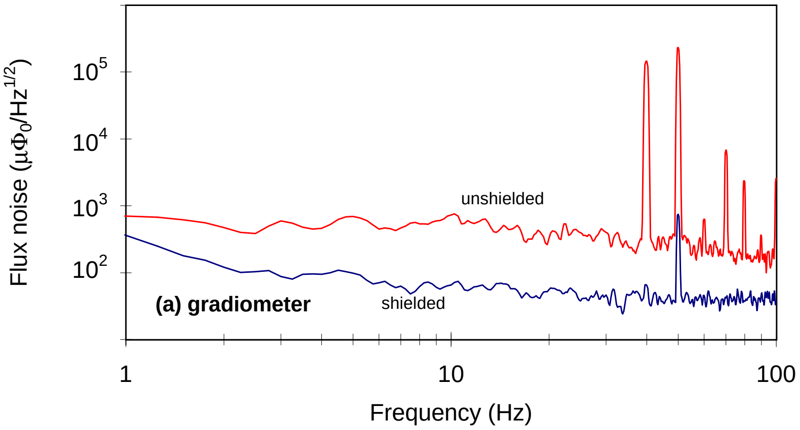
Uniform Field Response using a Single SQUID

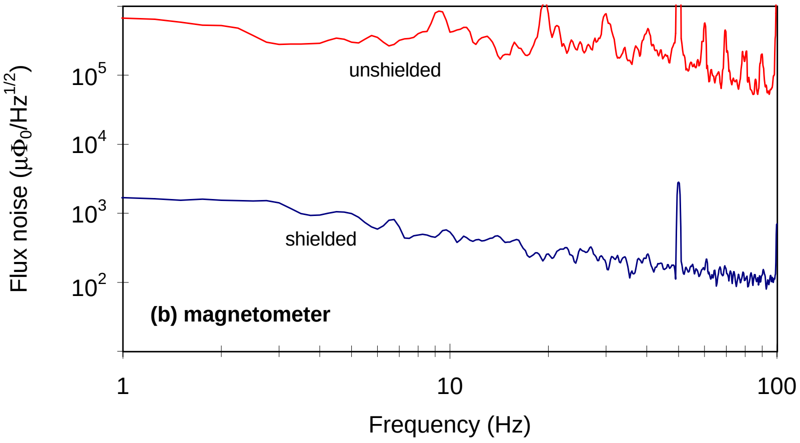
- Tested at 77 K with a Conductus PC100 SQUID system, using DC bias.
- Large Helmholtz coils provided a uniform field
- Measured effective area A_{eff} as 645 – 1160 μm^2
- These values are consistent with estimates of the effective area of the SQUID alone
- The effective area A_{mag} was measured by cutting one of the gradiometer deliberately, $\Rightarrow A_{\text{mag}} = 0.73\,\text{mm}^2$. Again consistent.

Result: gradiometer balance $A_{\text{eff}}/A_{\text{mag}}$ lies between 1/1000 and 1/626, which is at least a factor of two better than our previous gradiometers on 10 mm^2 substrates.

Flux and Gradient Sensitivity

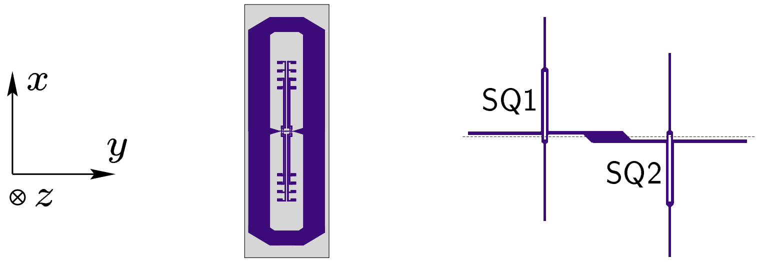
- Initially measured with only one SQUID, with DC bias

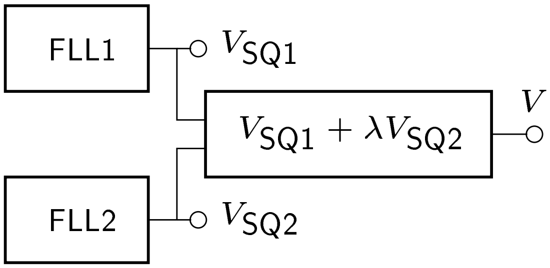




- gradient sensitivity $S_\mathrm{g}^{1/2} = S_\Phi^{1/2}/(bA_\mathrm{mag})$:
  $746\,\mathrm{fT}/(\mathrm{cm}\sqrt{\mathrm{Hz}})$ at 1 Hz and $79\,\mathrm{fT}/(\mathrm{cm}\sqrt{\mathrm{Hz}})$ at 1 kHz.
- Best reported gradient sensitivity for a single-layer gradiometer.

Enhancing the Balance with Two SQUIDs



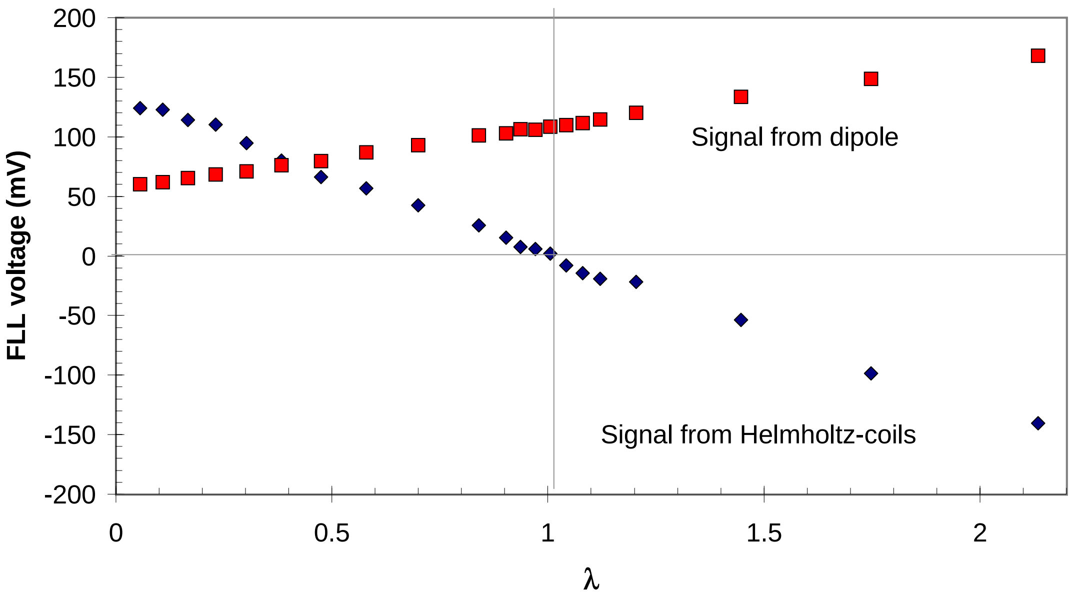


- Lock-in field detection at 320 Hz
- AC bias modulation used with the SQUIDs
- Apply uniform field B_z from Helmholtz coils, summed output from both SQUIDs is $V_{\mathsf{Hh}}(\lambda)$
- Separately create a gradient $\frac{\partial B_{\mathsf{z}}}{\partial x}$ from small dipole source, its summed output is $V_{\mathsf{d}}(\lambda)$
- Intrinsic 1-SQUID balance was defined $b_0 = A_{\mathsf{eff}}/A_{\mathsf{mag}}$
- The 2-SQUID balance is

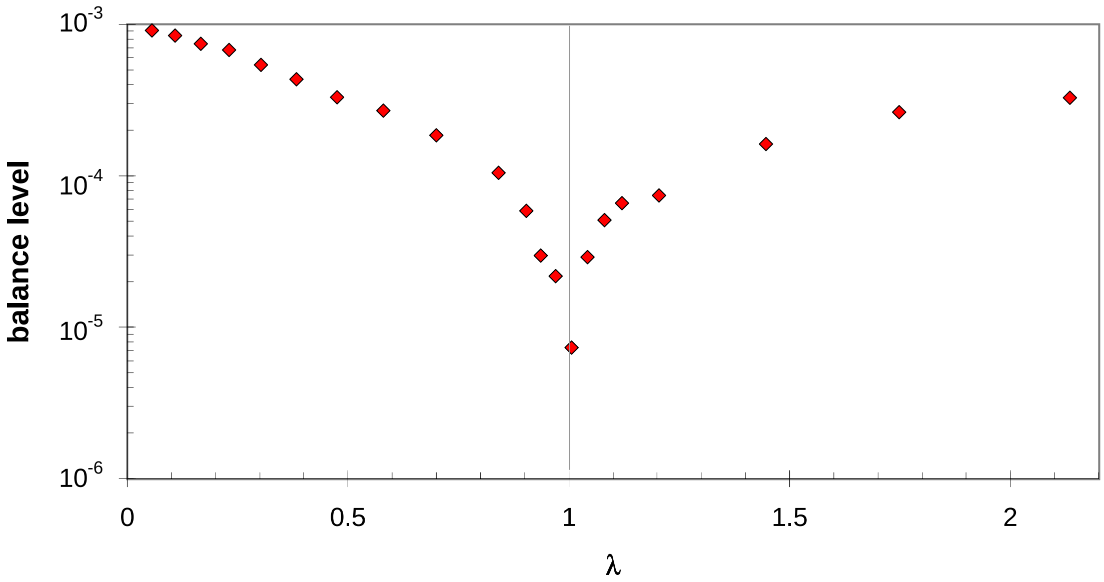
$$b = b_0 \left(\frac{V_{\mathsf{Hh}}(\lambda)}{V_{\mathsf{Hh}}(0)} \right) \left(\frac{V_{\mathsf{d}}(0)}{V_{\mathsf{d}}(\lambda)} \right)$$

- Note: SQUID channels are not processing and differencing signals with a high common-mode term — most of the uniform field rejection is done passively by the gradiometer itself.

Dependence of Balance on λ



(This device has an intrinsic effective area $A_{\text{eff}} = 645\,\mu\text{m}^2$.)



Step-edge Junctions

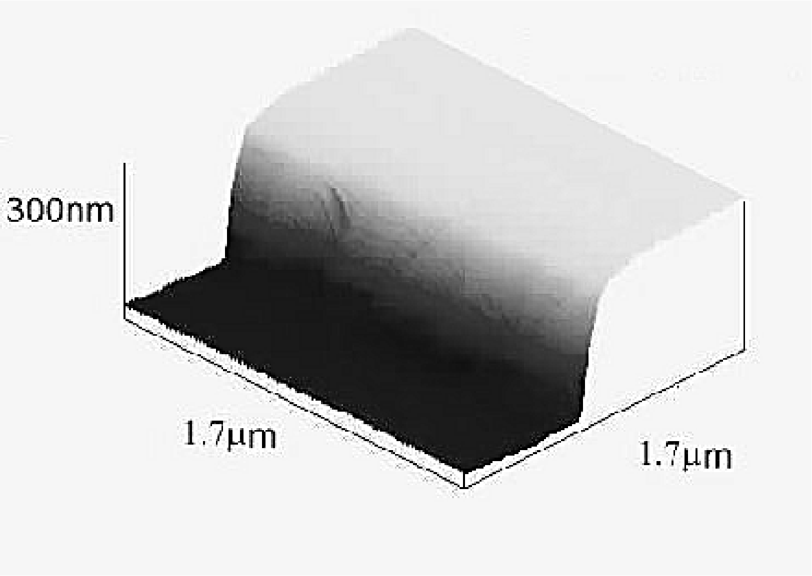
Why step-edge junctions?

- ☺ More economical for large substrates (don’t need bicrystals)
- ☺ Can have excellent junction properties
- ☺ Greater design freedom — don’t need junctions in a line

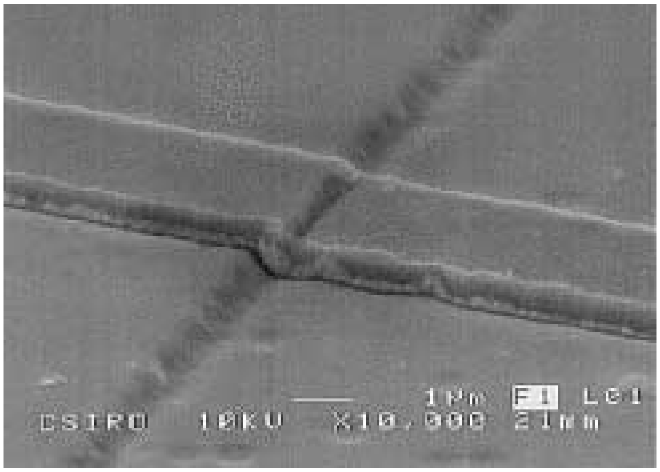
> Revisited a process we used some while ago . . . revised procedures, tighter process control → good results.

Outline of fabrication

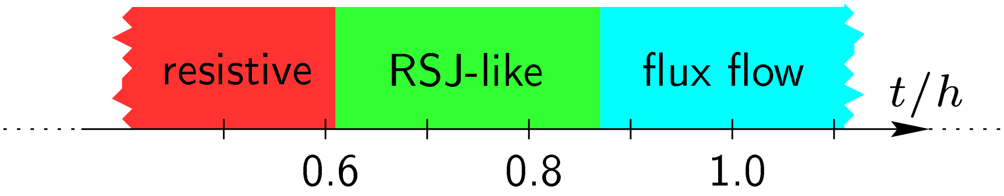
- STO substrate, photoresist mask, Ar ion milling.
- S1818 resist, 1.8 µm thick. Edge bead removal essential for close mask contact.
- Ar milling, water-cooled rotating stage, 90° incidence, 500 V

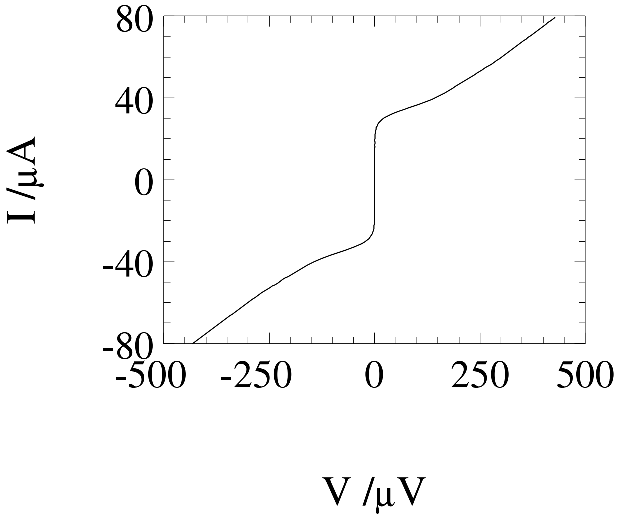


- YBCO: 200 nm by PLD (process as for bicrystal junctions)
- Patterned with Ar as above, Au contacts.

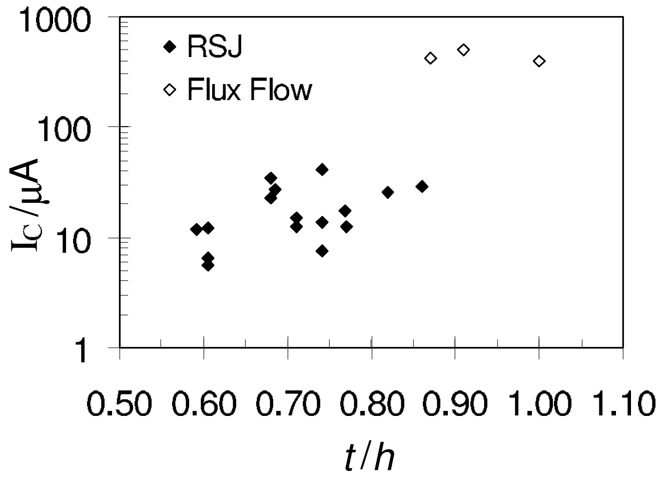


- Studied the variation of junction properties with ratio of film thickness t to step height h, keeping $t = 200\,\text{nm}$, for junctions made with track width $w = 3\,\mu\text{m}$.





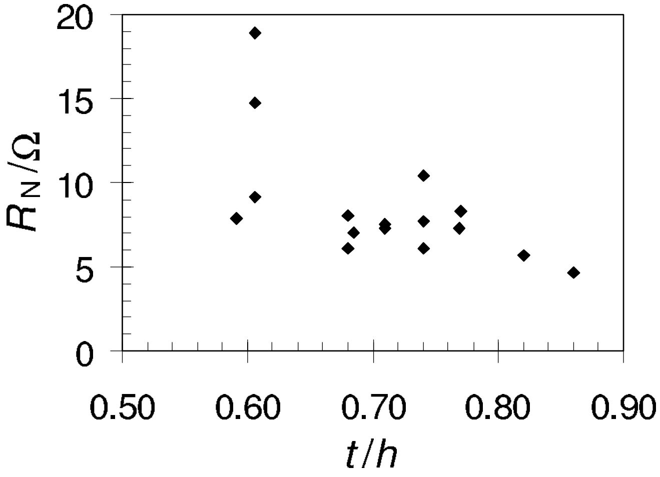
- Keeping $h = 300 \pm 30\,\text{nm}$ for $t = 200\,\text{nm}$ gives a yield of $\approx 85\%$ RSJ-like junctions (for step angles $\geq 60^\circ$).

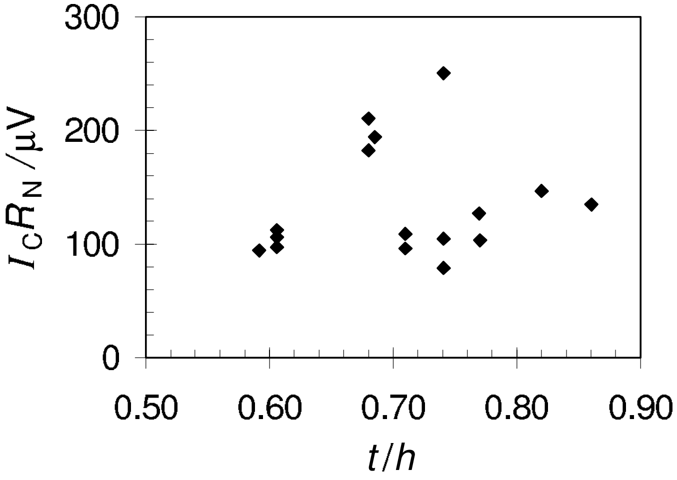


$t = 200\,\mathrm{nm}$

$w = 3\,\mu\mathrm{m}$

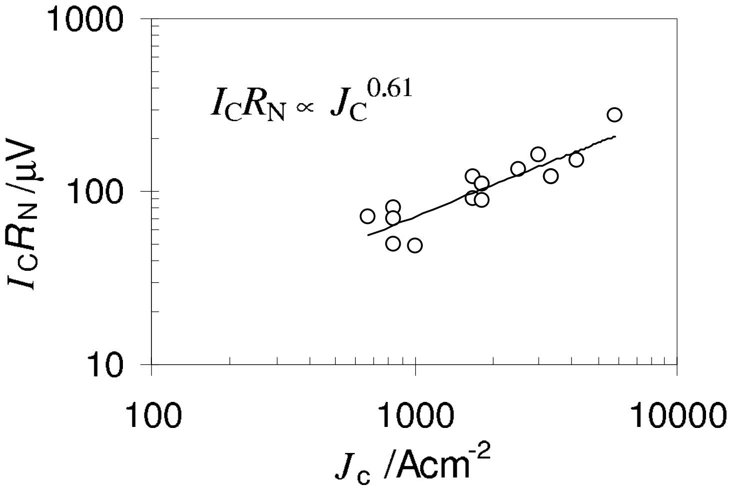
$T = 77\,\mathrm{K}$



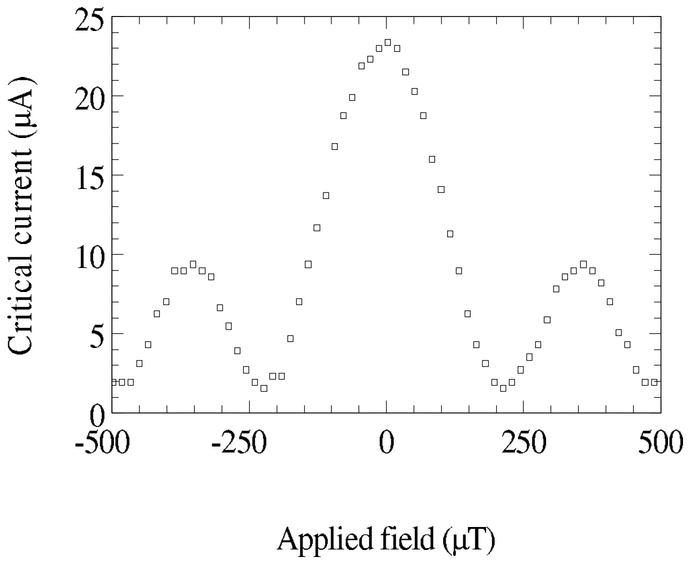


$\overline{I_c R_n} = 135 \pm 50\,\mu\mathrm{V}$

- J_c scales in the manner seen for many types of grain-boundary junctions:



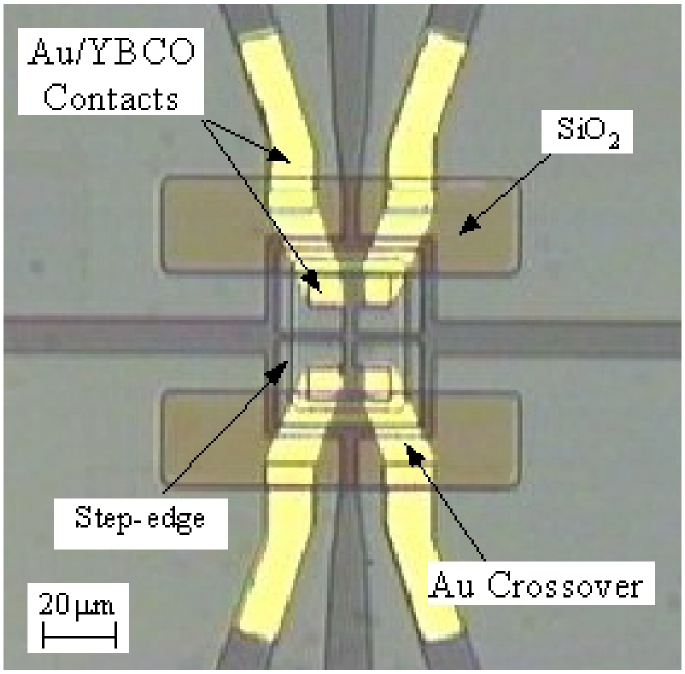
- The field dependence is almost Fraunhofer-like, but subsidiary peaks are somewhat suppressed and suggest that J_c is slightly higher at the junction edges:



- No flux jumps are seen for $0 < B < 0.5\,\mathrm{mT}$

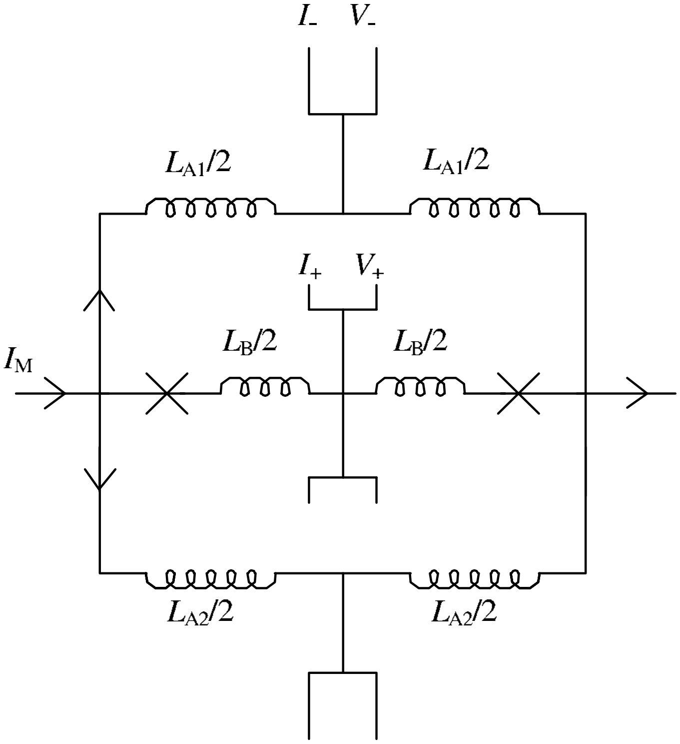
Gradiometric SQUIDs with step-edge Junctions

- G-SQUID has highly symmetric layout ⇒ minimal uniform field response
- Needs only a single layer of YBCO
- Ex situ Au layer #1 immediately after YBCO PLD (+ O_2 anneal)
- Patterned into SQUID structure, leaving Au contact pads
- SiO_2 layer RF-sputtered, 300 nm thick
- Au layer #2 deposited and patterned to complete contacts



- $L_{sq} \approx 67\,\mathrm{pH}$
- Effective area $\approx 2\,\mu\mathrm{m}^2 \ldots 200 - 500 \times$ smaller than for a non-gradiometric SQUID of similar inductance

G-SQUID Inductances and Coupling



The SQUID inductance is give by

$$L_{\mathsf{sq}} = \frac{L_{\mathsf{A}}}{2} + L_{\mathsf{B}}.$$

Mutual inductance L_{m} can be derived from the flux Φ injected by the current I_{M} into either the upper or lower loop, so

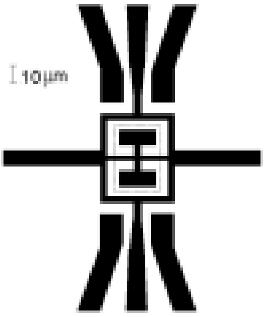
$$\Phi = \frac{I_{\mathsf{M}}}{2}(L_{\mathsf{A1}} - M_{\mathsf{A}}) - I_{\mathsf{M}} M_{\mathrm{I}}$$

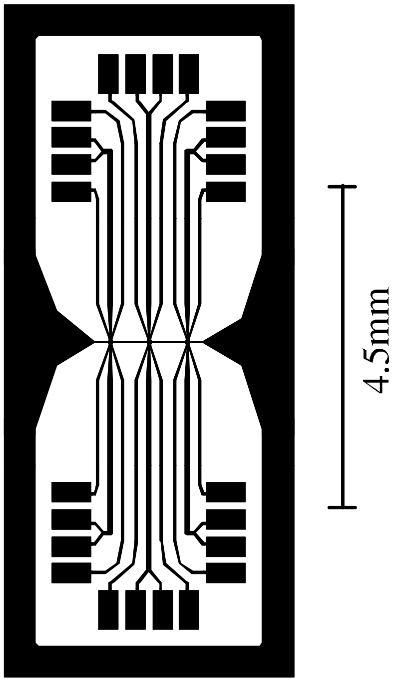
$$\Rightarrow L_{\mathsf{M}} = \frac{L_{\mathsf{A}} - M_{\mathsf{A}}}{2} - M_{\mathrm{I}}$$

Current design has $L_{\mathsf{sq}} = 67\,\mathrm{pH}$ and $L_{\mathsf{M}} \approx 25\,\mathrm{pH}$.

A Gradiometric SQUID Gradiometer

- Prototypes on $10 \times 10\,\mathrm{mm}^2$ substrates

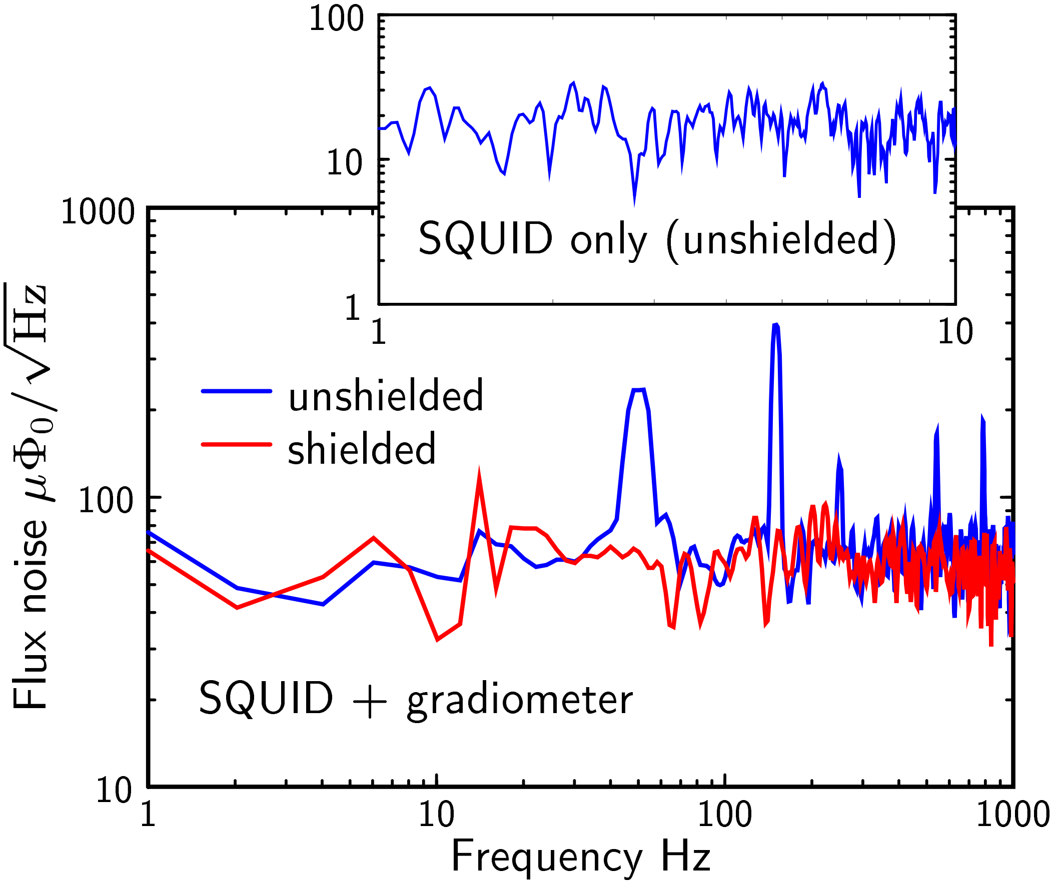




- Pick-up look linewidth = 400 μm; estimated inductance per loop = 10 nH
- Parasitic effective area of gradiometer $\approx 95\,\mu\mathrm{m}^2$ — much larger than effective area of the SQUID itself, perhaps due to differences in the areas of the two pick-up loops of the gradiometer, or local field distortion from residual superconducting material.

G-SQUID Gradiometer Flux Noise

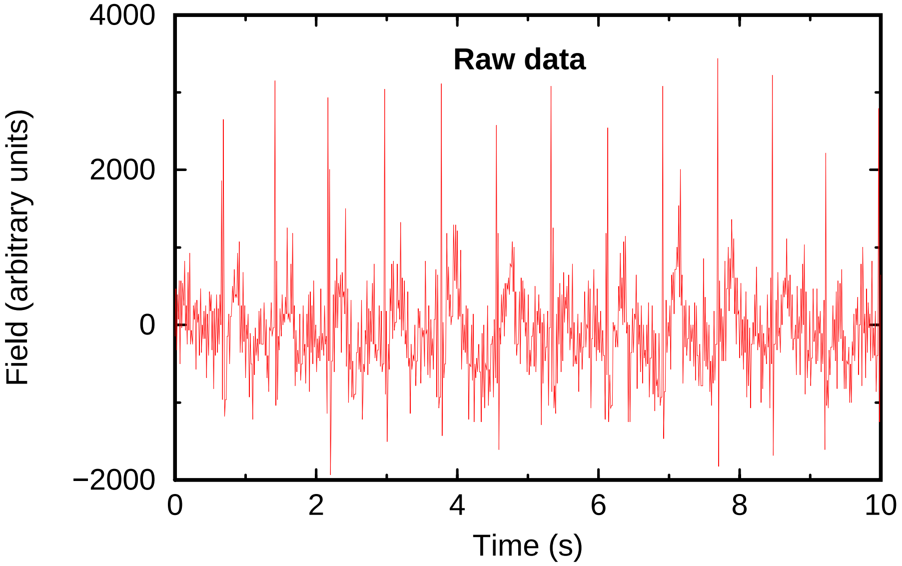
- Measured at 77 K with 64 kHz AC bias modulation.

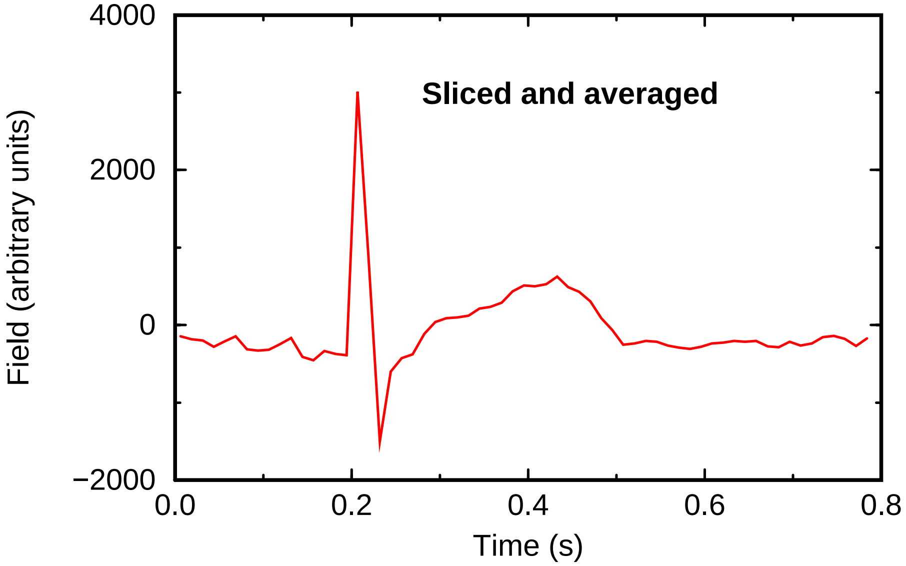


- Gradient sensitivity 4.6 pT/(cm$\sqrt{\mathrm{Hz}}$)
- Note little difference between shielded and unshielded operation — confirms reductions of effective area for uniform field response

Magnetocardiography

Adult magnetocardiogram (MCG), in aluminium eddy-current shielded room, recorded with a long baseline single-layer gradiometer





Future Directions . . .

① Many measurements really need 2nd-order gradiometers — the degree of rejection of sources of interference is often not sufficient with 1st-order devices.

We aim to achieve this in two ways:

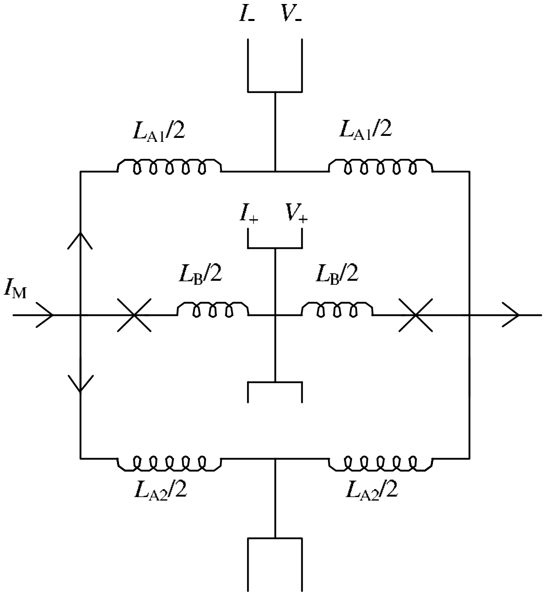
Make a 2nd-order gradiometer using two 2-SQUID gradiometers and 4 channels of SQUID electronics ⇒ a system in which both the magnetometric and 1st-order responses can be independently adjusted electronically to zero. But a little complicated!

and/or

Make larger $10 \times 30\,\mathrm{mm}^2$ or larger 1st-order gradiometers using gradiometric SQUIDs with edge-junctions. Two of these can be electronically differenced to make a 2nd-order gradiometer.

- ∗ Since only gradiometer *length* needs to be increased, existing YBCO PLD process will be able to be used for $10 \times 40\,\mathrm{mm}^2$ or even $10 \times 50\,\mathrm{mm}^2$.

② Improve G-SQUID coupling: the mutual inductance L_m can be increased while keeping the self-inductance L_sq in the optimum range.



$$L_\mathsf{sq} = \frac{L_\mathsf{A}}{2} + L_\mathsf{B}$$

$$L_\mathsf{m} = \frac{L_\mathsf{A} - M_\mathsf{A}}{2} - M_\mathsf{I}$$

$L_\mathsf{A} = 67\,\mathsf{pH}$, $L_\mathsf{B} = 33\,\mathsf{pH}$ (modelled by FASTHENRY)

$\Rightarrow L_\mathsf{sq} = 66.5\,\mathsf{pH}$ and $L_\mathsf{m} = 25\,\mathsf{pH}$ (we measure $23\,\mathsf{pH}$)

$L_\mathsf{A} = 167\,\mathsf{pH}$, $L_\mathsf{B} = 15\,\mathsf{pH}$ (modelled)

$\Rightarrow L_\mathsf{sq} = 98\,\mathsf{pH}$ and $L_\mathsf{m} = 74\,\mathsf{pH}$

Currently evaluating this version.

Short and fat ⇒ tall and thin!

Conclusions

- $30 \times 10\,\mathrm{mm}^2$ bicrystal substrates produce acceptable junctions and can be patterned and processed OK
- Intrinsic balance (using only 1 SQUID) is 2 – 3 times better than for smaller gradiometers on $10 \times 10\,\mathrm{mm}^2$ substrates
- Flux noise and gradient sensitivity are excellent
- The 2-SQUID method works well, with direct coupling of modulation and feedback to parts of each SQUID, to avoid inductive cross-coupling (using Conductus electronics)
- Electronic nulling of the magnetometric response has been demonstrated to improve the balance to better than 2×10^{-5}
- Have established a method for producing good-quality step-edge junctions
- Have demonstrated the G-SQUID principle with negligible effective area
- Advances feed into our biomagnetism and NDE programmes