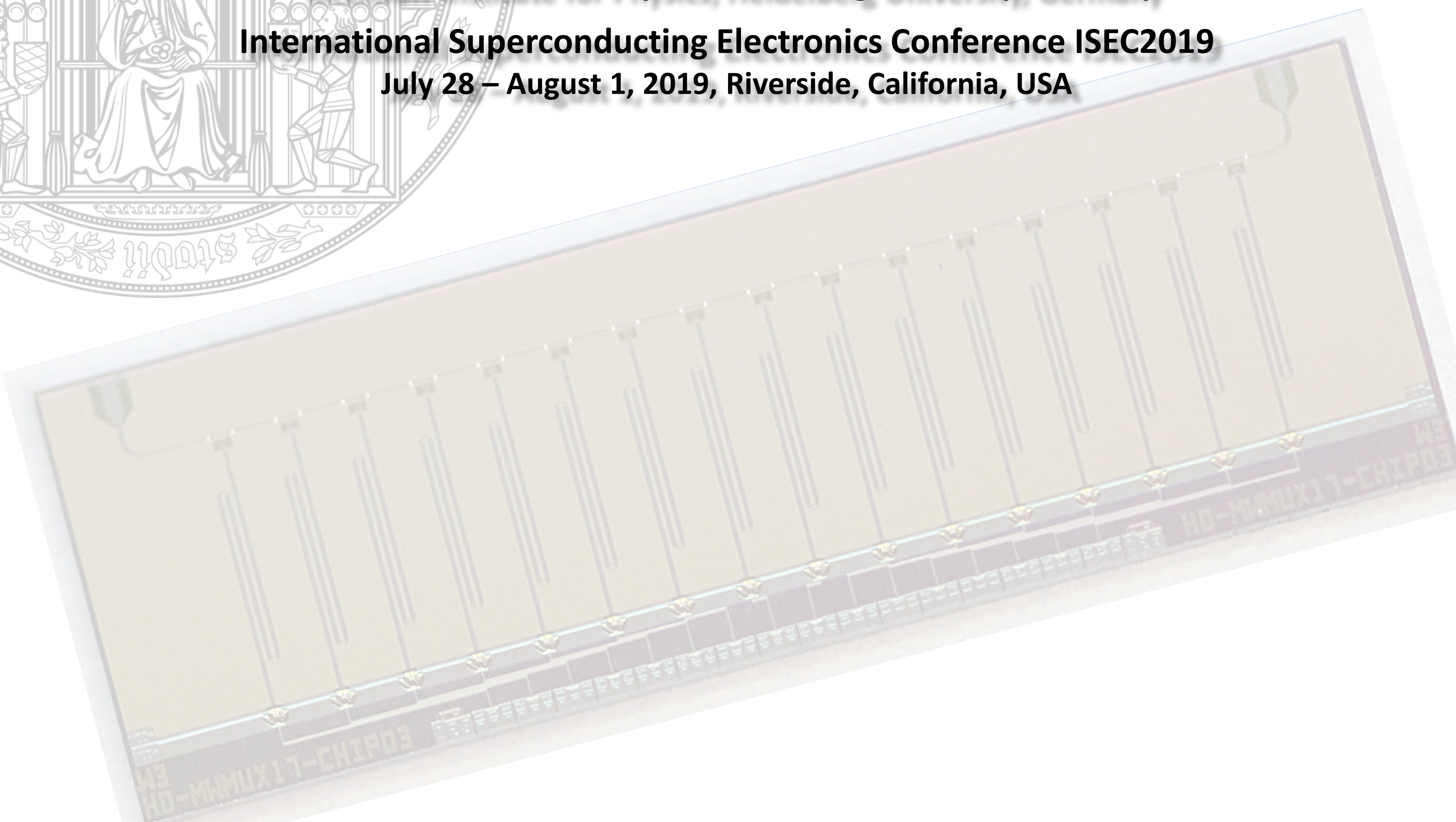
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Contributed presentation 4-SQ-C-4 given at ISEC, 28 July-1 August 2019, Riverside, USA.

DC-SQUID readout with high dynamic range and intrinsic frequency-division multiplexing capability

D. Richter, A. Fleischmann, C. Enss, and S. Kempf

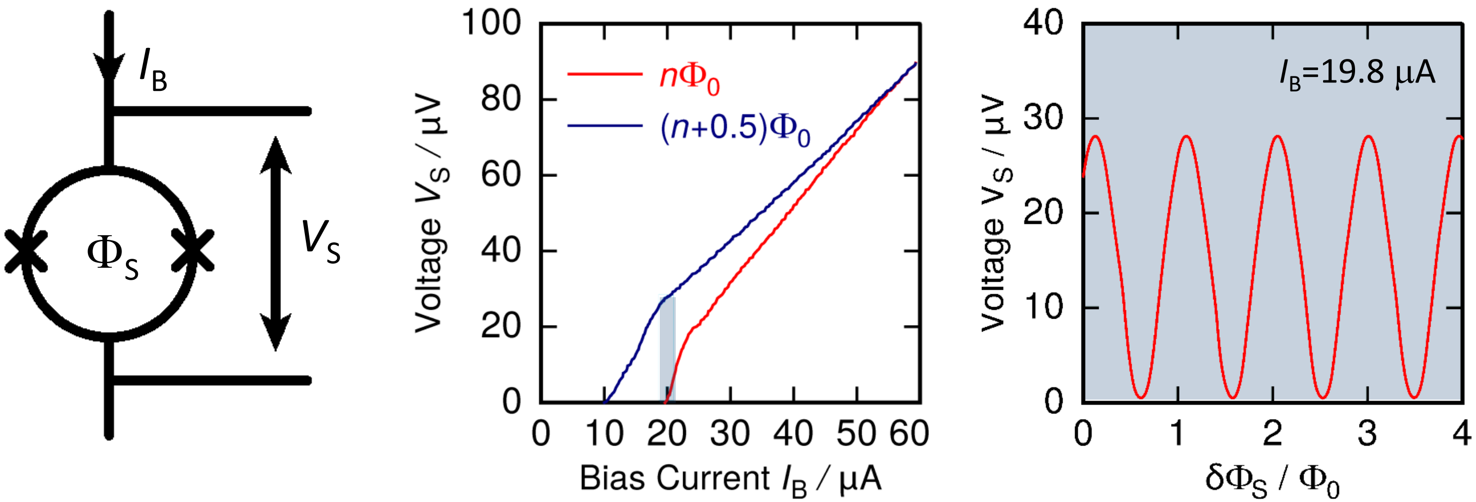
Kirchhoff-Institute for Physics, Heidelberg University, Germany

International Superconducting Electronics Conference ISEC2019
July 28 – August 1, 2019, Riverside, California, USA



dc-SQUID basics

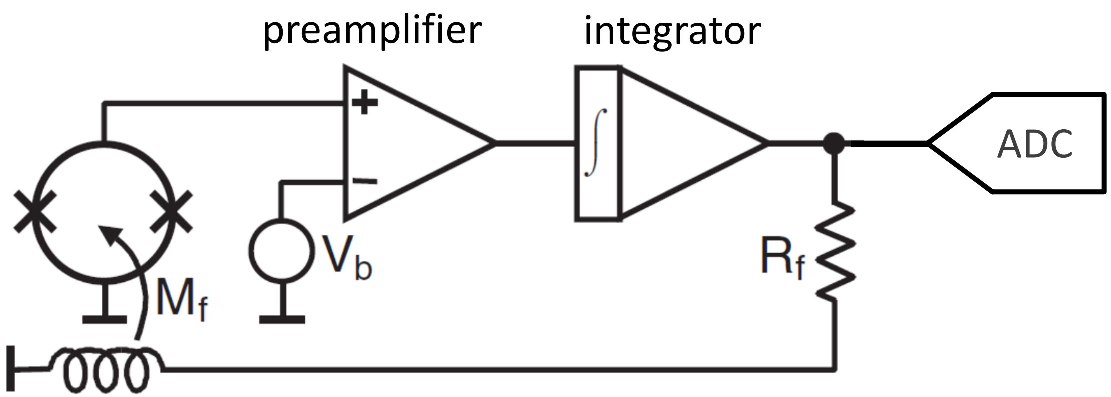
dc-SQUID = magnetic flux to voltage/current converter



- periodic $V/I - \Phi$ characteristic
- linear flux range: $\Phi_{lin} \sim \Phi_0/\pi$ ⇒ flux-locked loop
- intrinsically ‘infinitely’ large dynamic range
- very high signal bandwidth: $R/L \sim 100\,\text{GHz}$

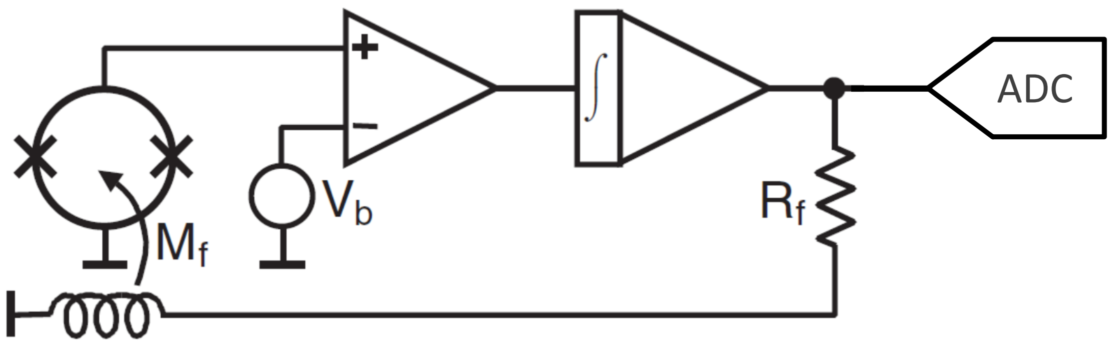
flux-locked loop (FLL)

overall flux in SQUID is kept constant by applying flux feedback compensating variations caused by input signal



flux-locked loop (FLL)

overall flux in SQUID is kept constant by applying flux feedback compensating variations caused by input signal



disadvantages / challenges:

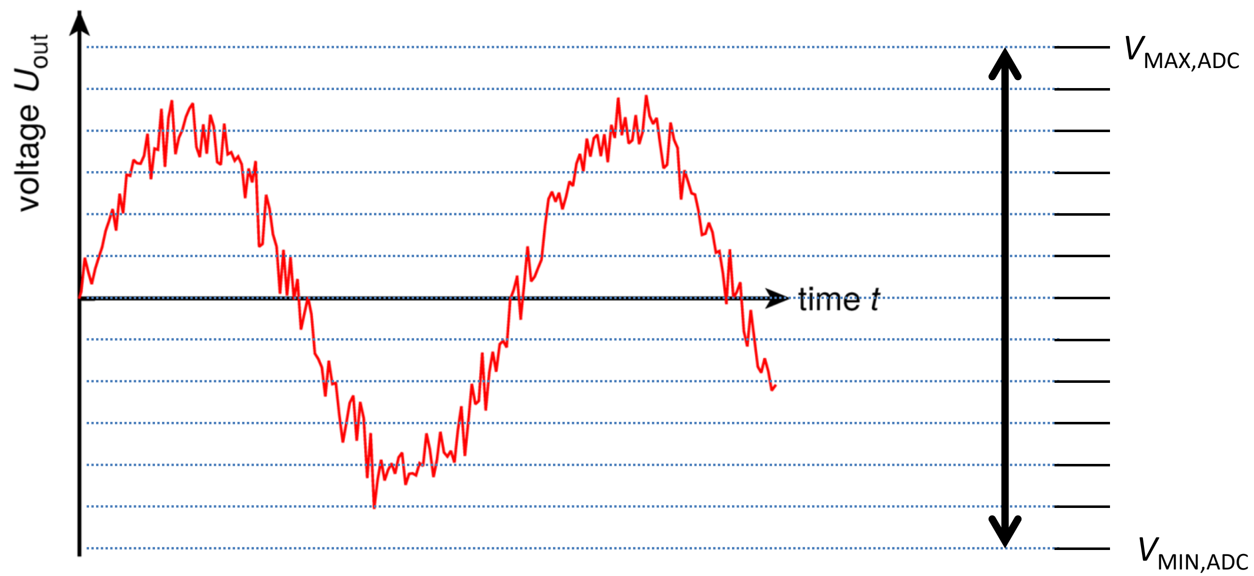
cable delay t_d →
- FLL bandwidth < intrinsic SQUID bandwidth
- slew rate (1-10 Φ_0/µs)

integrator →
- automatic reset for preventing FLL running into saturation
  slew rate limitation!

AD-converter

analog-to-digital converter (ADC)

FLL-output signal has to be compatible with input range of digitizer



signals smaller than the Least Significant Bit (LSB) can not be resolved

analog-to-digital converter (ADC)

dynamic range: ratio between largest and smallest value a quantity takes

$$\mathrm{DNR} = 20\log\left(\frac{2\Phi_{\mathrm{max}}}{\Phi_{\mathrm{noise}}\sqrt{\Delta f}}\right)$$

⇕

ADC resolution: number of discrete values over the fullrange of analog values

$$\Delta V_{\mathrm{ADC}} = \frac{V_{\mathrm{max}} - V_{\mathrm{min}}}{2^M}$$

M: ADC resolution (#bits)

example: SQUID with $\sqrt{S_\Phi} \sim 0.1\,\mu\Phi_0/\sqrt{\mathrm{Hz}}$, $\Delta f_{\mathrm{FLL}} \sim 10\,\mathrm{kHz}$

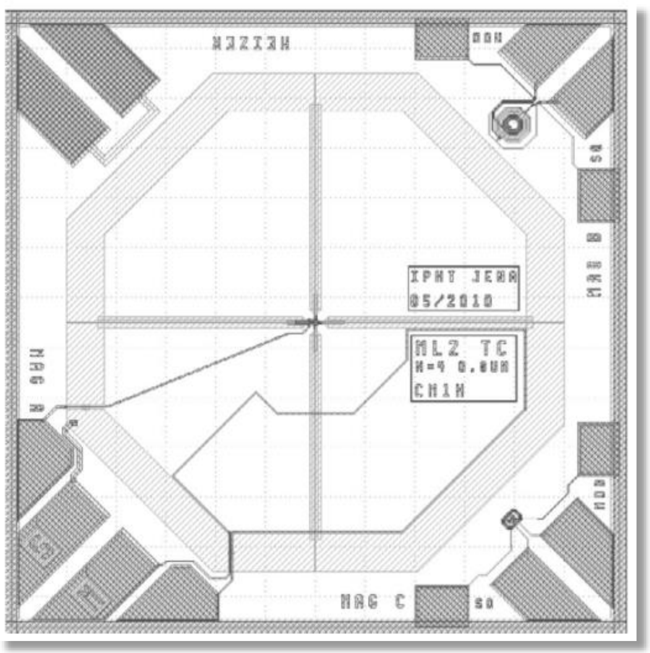
Φ_{max}	$1\,\Phi_0$	$100\,\Phi_0$	$10.000\,\Phi_0$
M_{min}	18 bit	25 bit	31 bit
DNR	186 dB	226 dB	266 dB

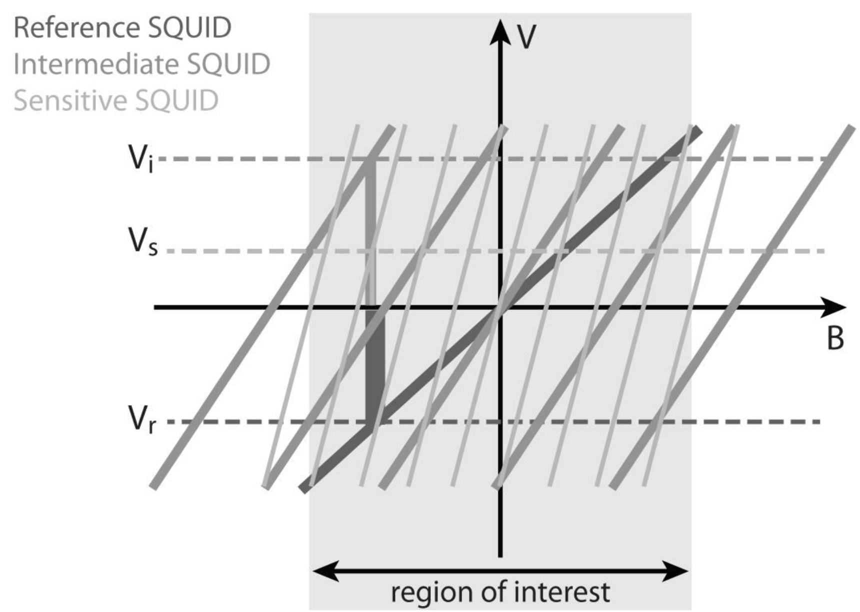
→ high requirements on ADC performance

many possibilities to increase dynamic range…

… e.g. flux counting electronics, digitial SQUIDs, SQIFs, SQUADs, SQUID cascades …

3 dc-SQUIDs with different input sensitivity
+ 3 FLL-electronics and 3 digitzier used

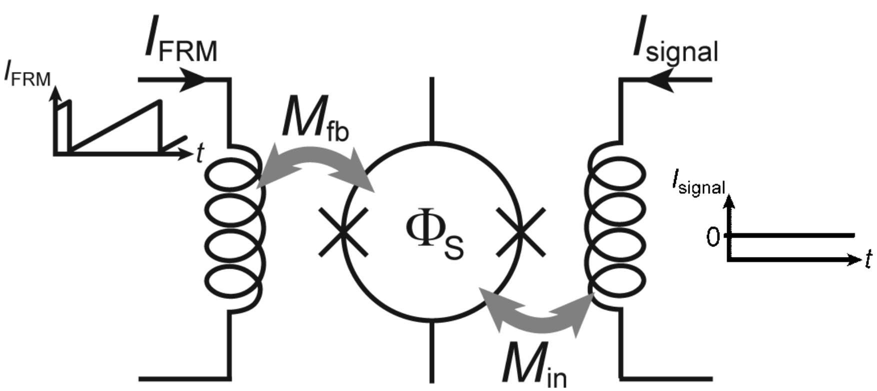


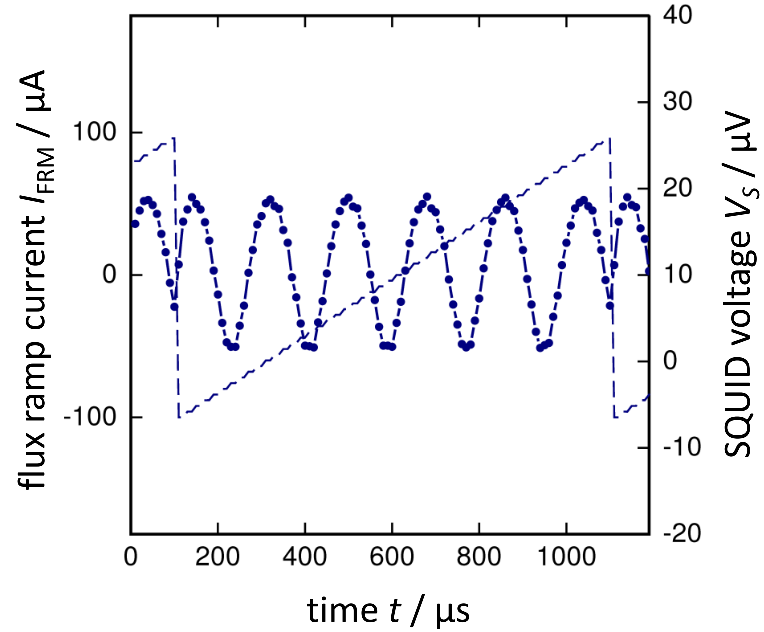


T. Schönau *et al.*, Supercond. Sci. Technol. ***26*** 035013 (2013)

flux ramp modulation

application of sawtooth-shaped current signal results in periodic SQUID characteristics

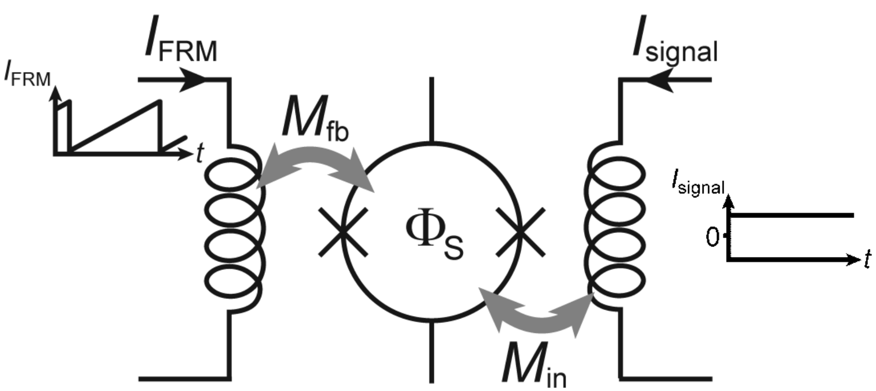


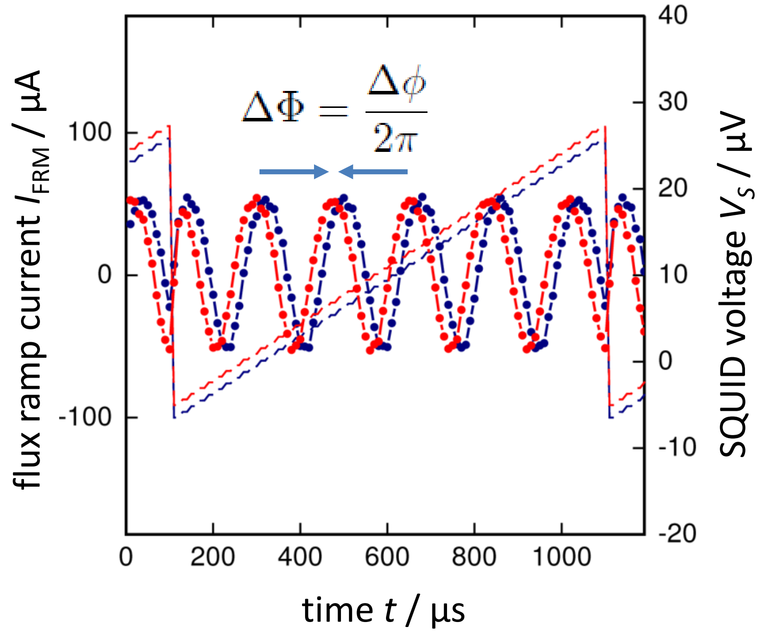


K. W. Lehnert *et al.*, IEEE Trans. Appl. Supercond., **17** (2007) 705
J. A. B. Mates *et al.*, Appl. Phys. Lett. **92** (2008) 023514
J. A. B. Mates *et al.*, J. Low Temp. Phys. **167** (2012) 707

flux ramp modulation

application of sawtooth-shaped current signal results in periodic SQUID characteristics



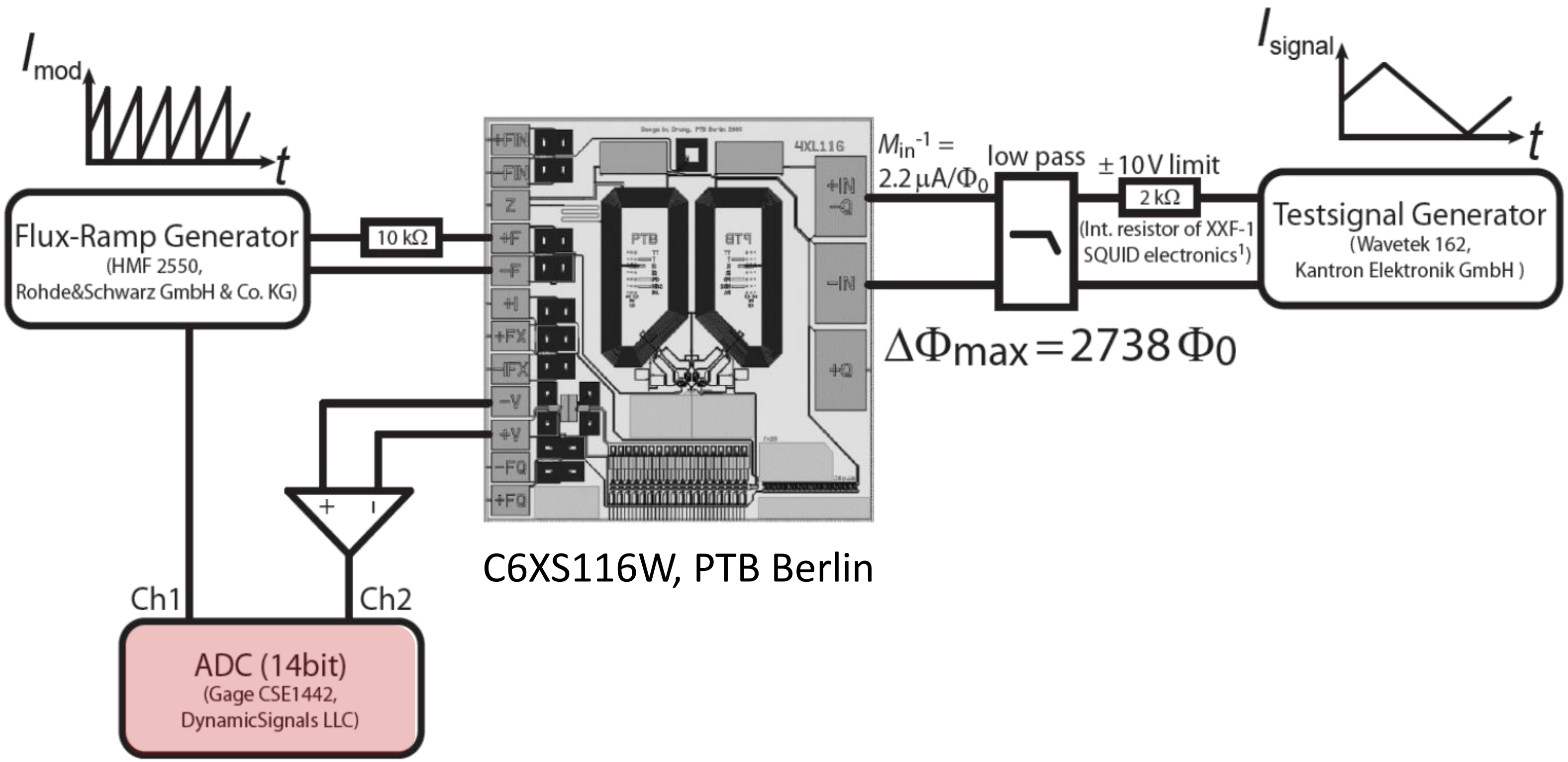


phase of SQUID characteristic linear measure of input signal

dynamic range not limited by ADC resolution + range

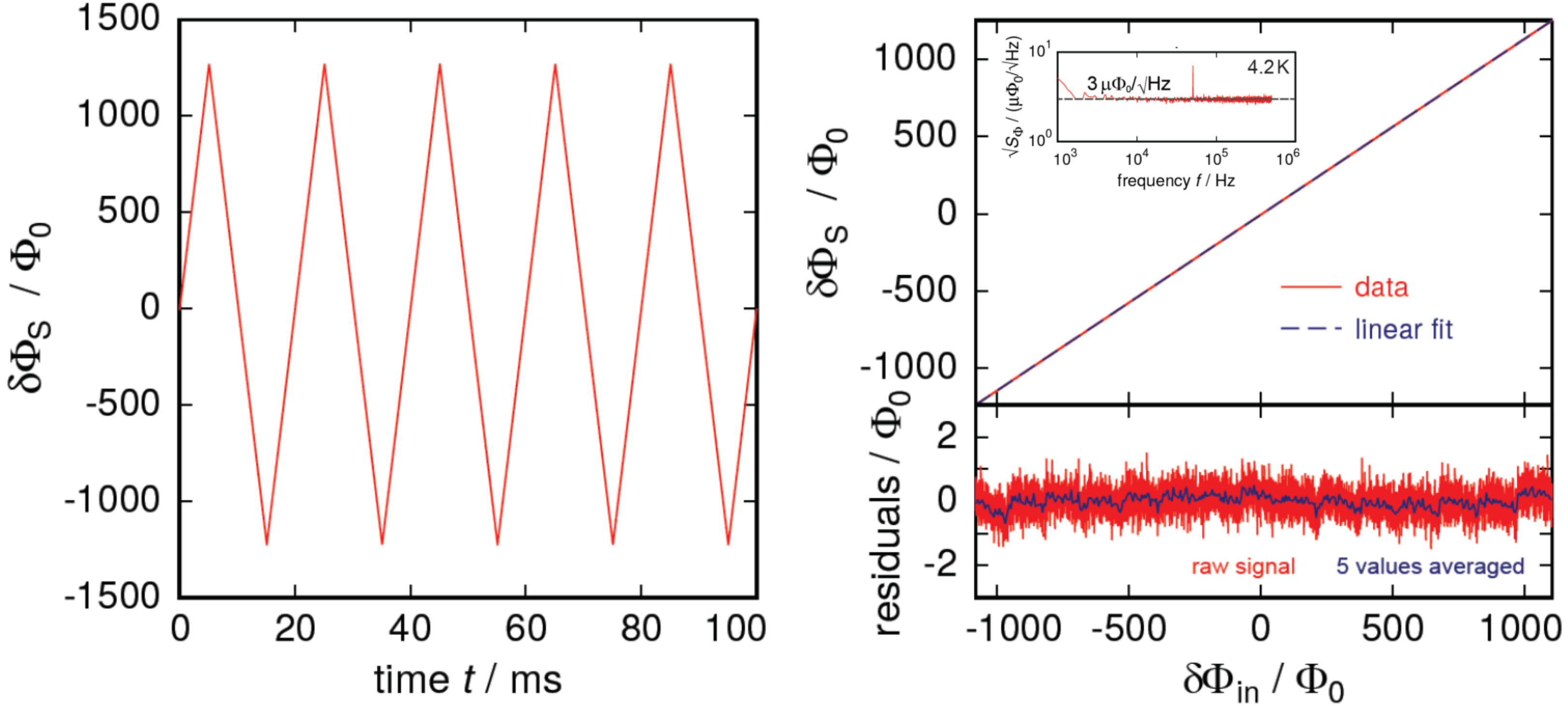
K. W. Lehnert *et al.*, IEEE Trans. Appl. Supercond., **17** (2007) 705
J. A. B. Mates *et al.*, Appl. Phys. Lett. **92** (2008) 023514
J. A. B. Mates *et al.*, J. Low Temp. Phys. **167** (2012) 707

experimental setup for proof-of-concept



linearity and dynamic range

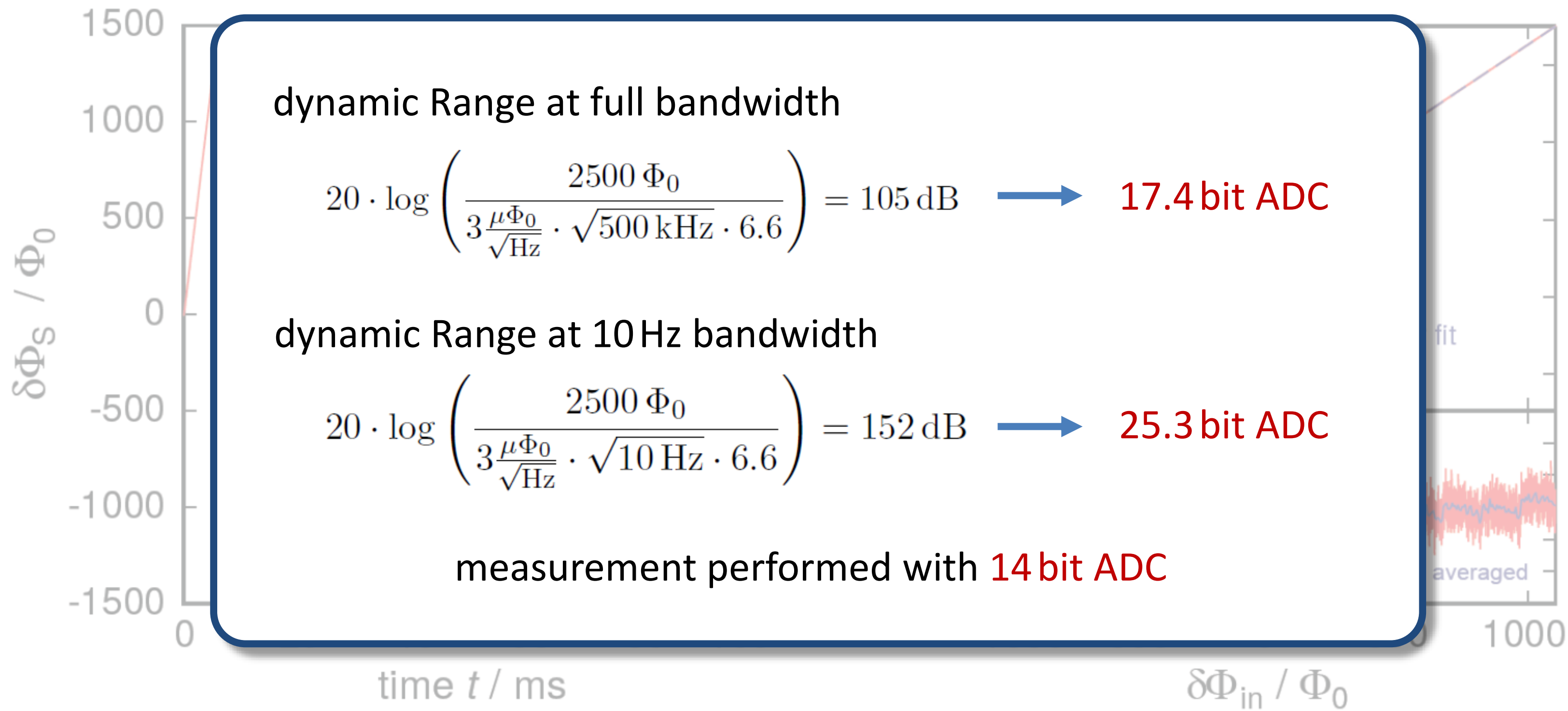
application of flux ramp with 1 MHz repetition rate and 4.2Φ_0 amplitude



measurement of input signal with amplitudes between 100 mΦ_0 and 2500 Φ_0

linearity and dynamic range

application of flux ramp with 1 MHz repetition rate and $4.2\Phi_0$ amplitude



dynamic Range at full bandwidth

$$20 \cdot \log\left(\frac{2500\,\Phi_0}{3\frac{\mu\Phi_0}{\sqrt{\mathrm{Hz}}} \cdot \sqrt{500\,\mathrm{kHz}} \cdot 6.6}\right) = 105\,\mathrm{dB}$$ → 17.4 bit ADC

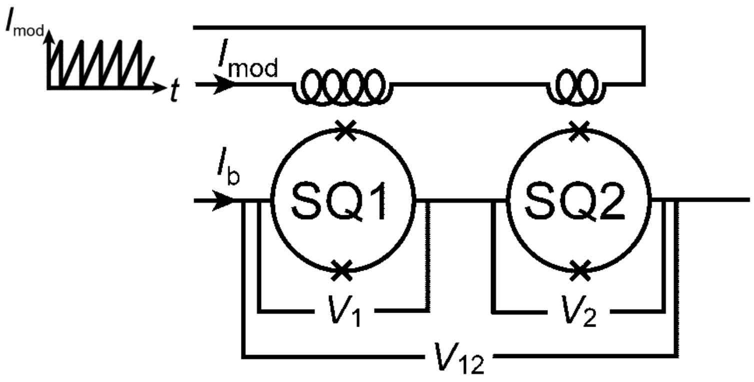
dynamic Range at 10 Hz bandwidth

$$20 \cdot \log\left(\frac{2500\,\Phi_0}{3\frac{\mu\Phi_0}{\sqrt{\mathrm{Hz}}} \cdot \sqrt{10\,\mathrm{Hz}} \cdot 6.6}\right) = 152\,\mathrm{dB}$$ → 25.3 bit ADC

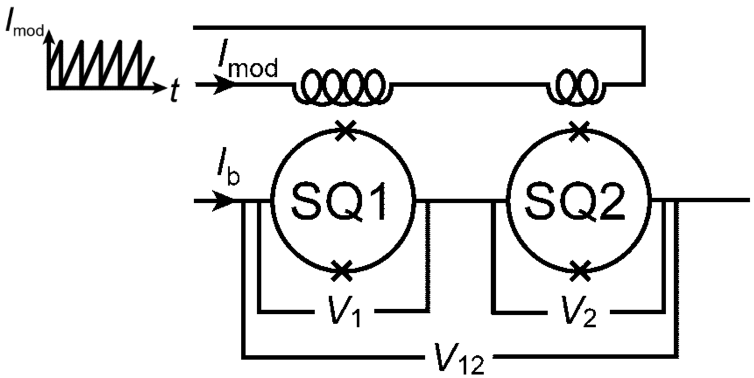
measurement performed with 14 bit ADC

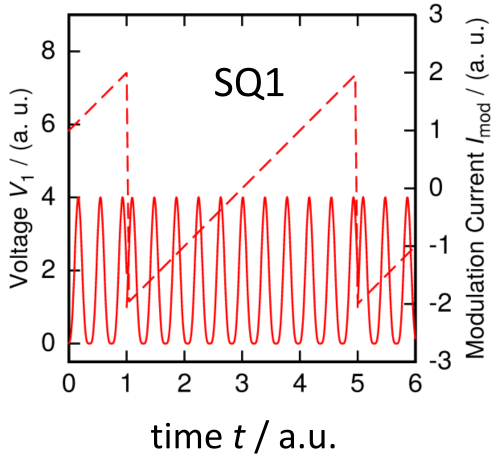
measurement of input signal with amplitudes between $100\,\mathrm{m}\Phi_0$ and $2500\,\Phi_0$

frequency-divison multiplexing capability

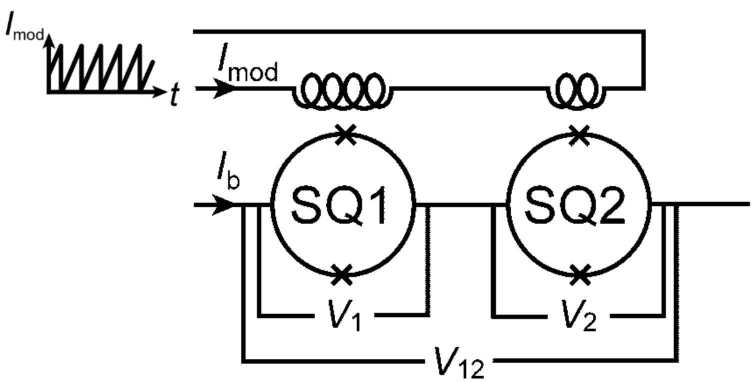


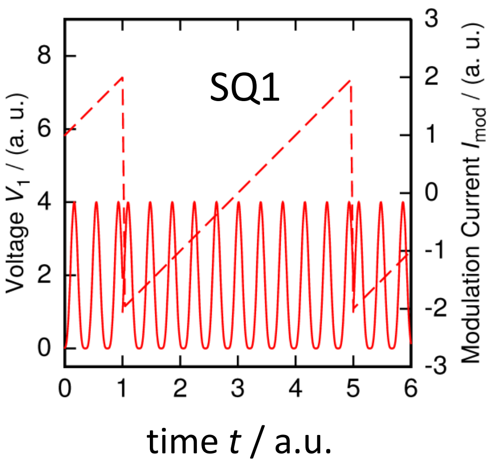
frequency-divison multiplexing capability

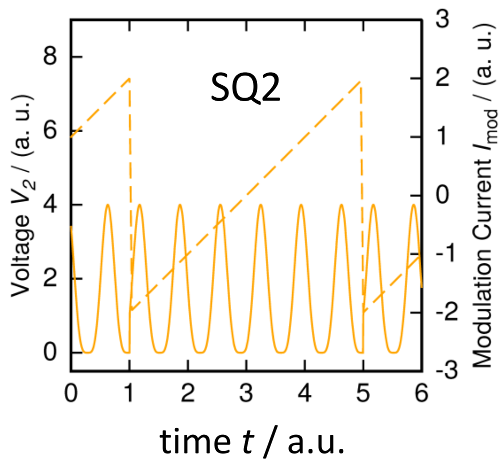




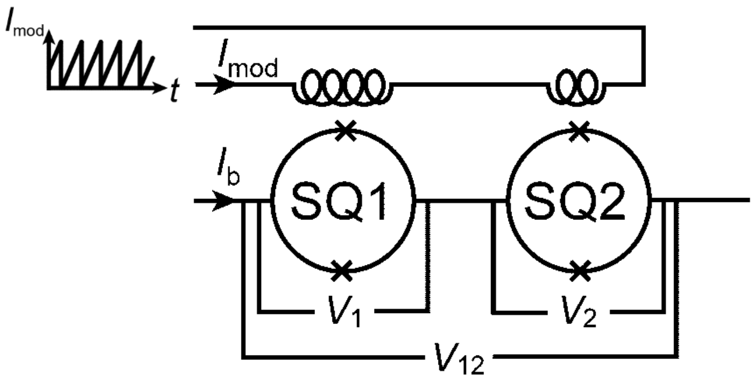
frequency-divison multiplexing capability

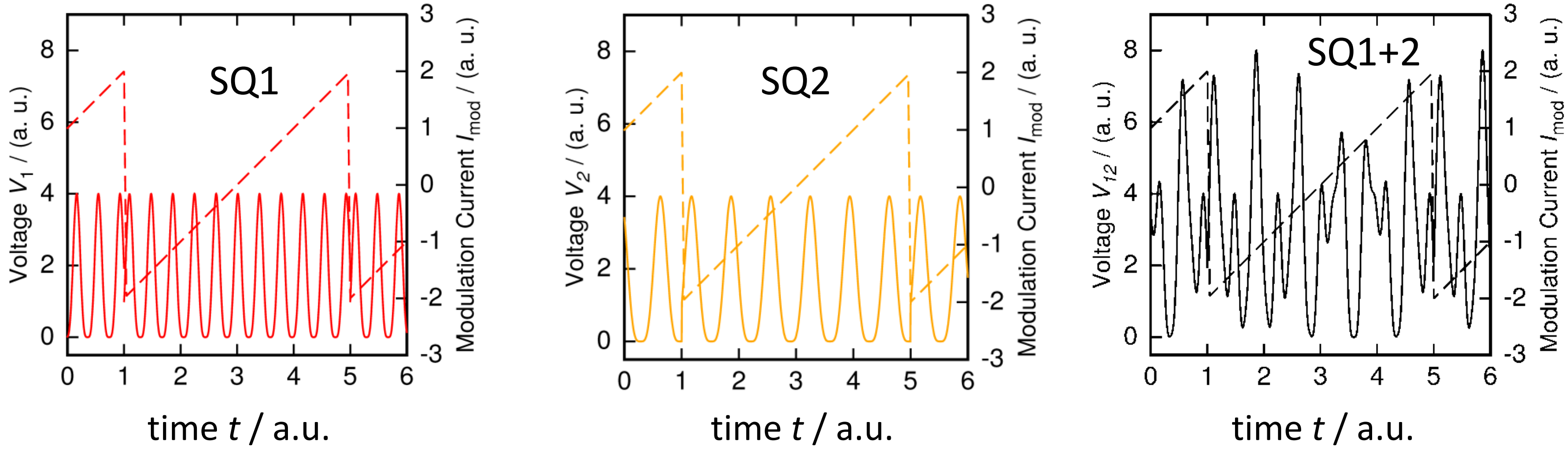






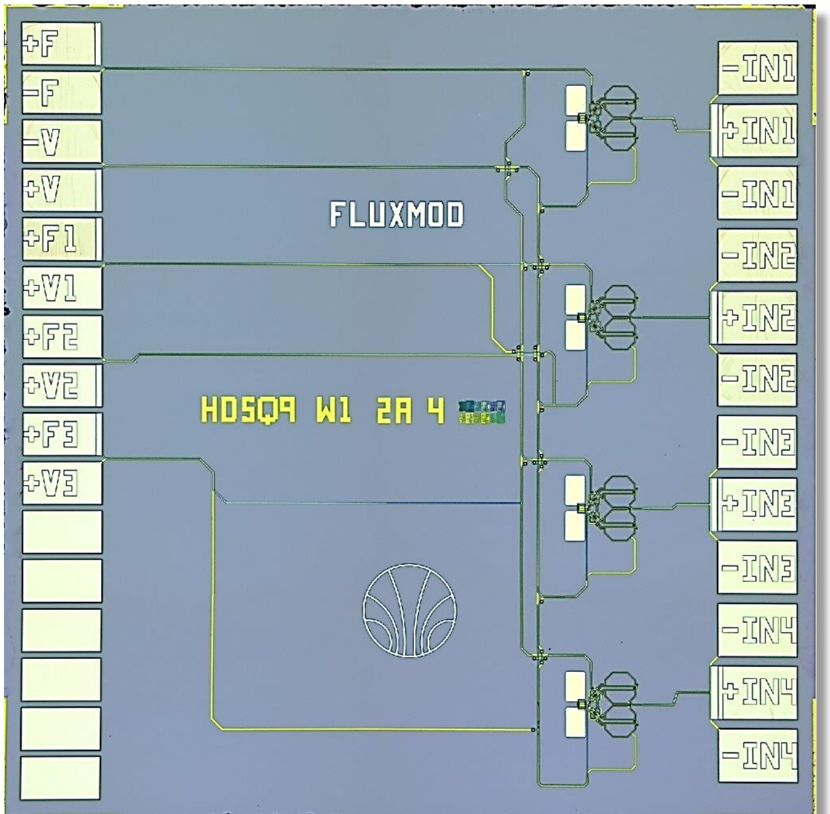
frequency-divison multiplexing capability





proof-of-concept: HDFRMux1

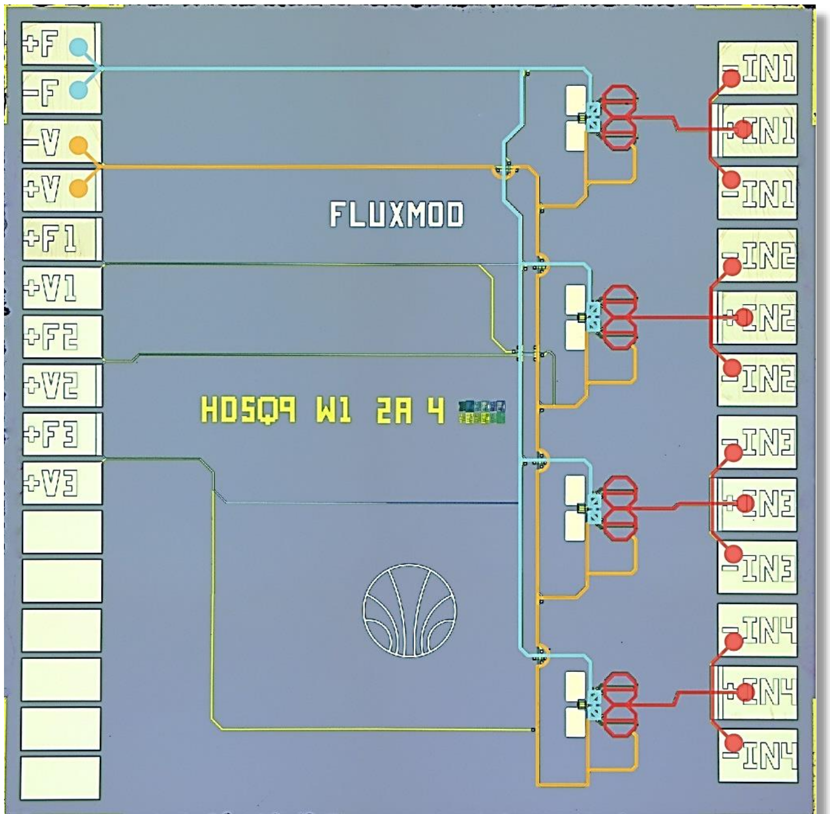
flux ramp modulation based four-channel dc-SQUID multiplexer

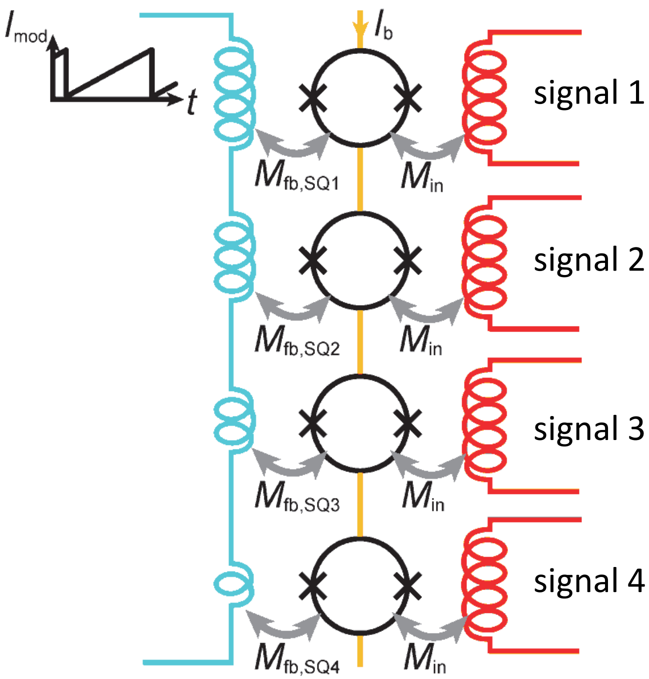


IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Contributed presentation 4-SQ-C-4 given at ISEC, 28 July-1 August 2019, Riverside, USA.

proof-of-concept: HDFRMux1

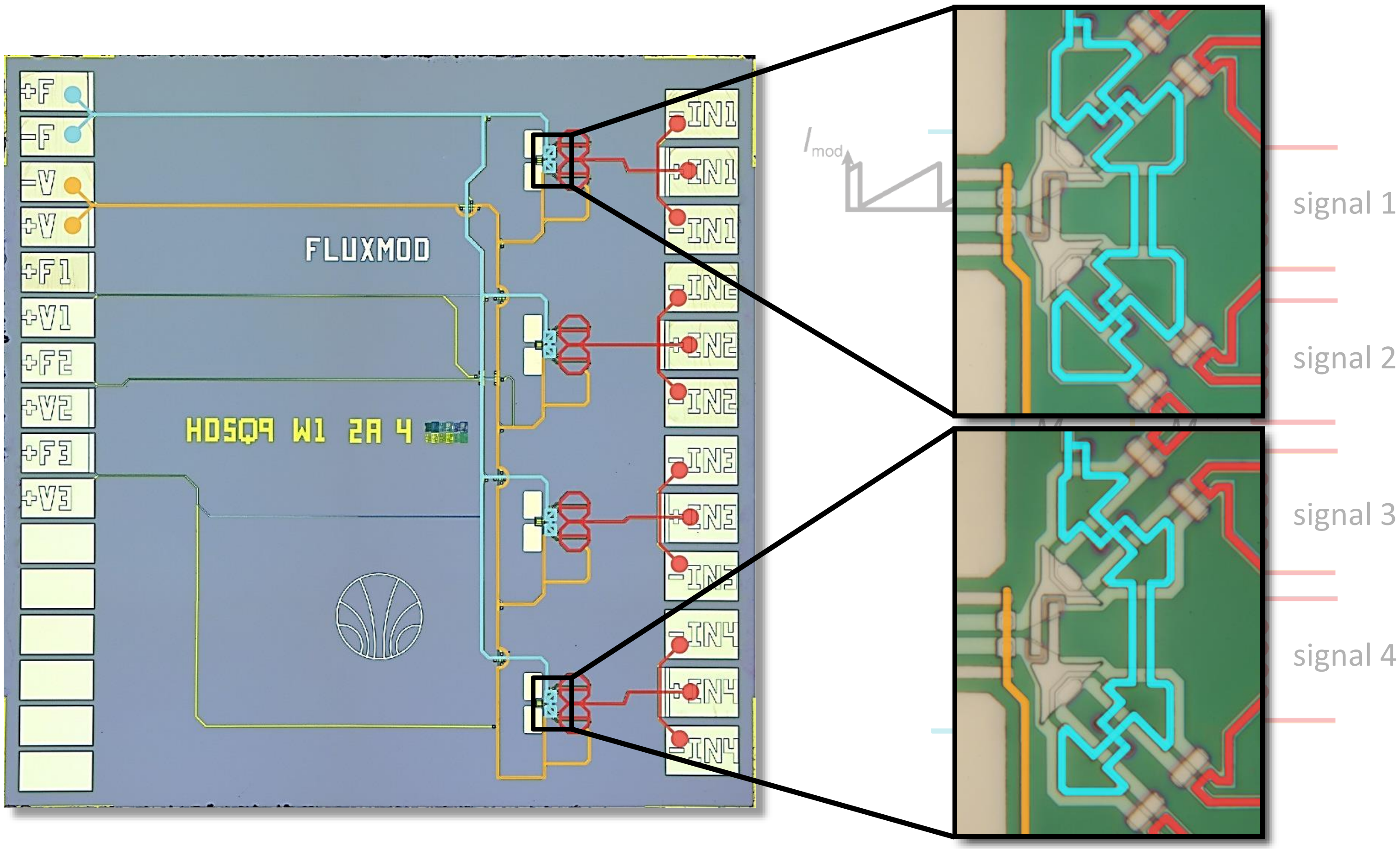
flux ramp modulation based four-channel dc-SQUID multiplexer





proof-of-concept: HDFRMux1

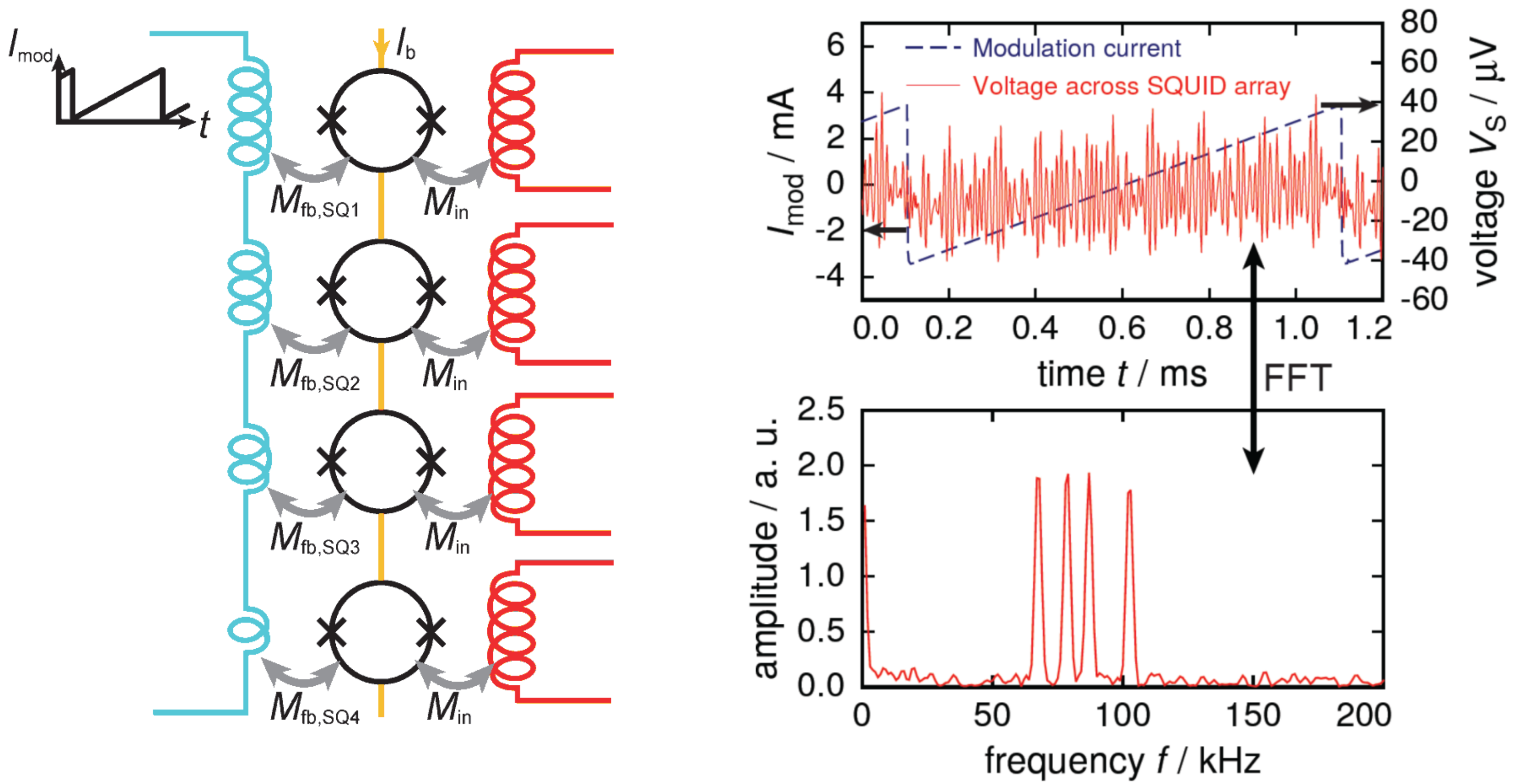
flux ramp modulation based four-channel dc-SQUID multiplexer



M_{mod} adjusted by varying overlap between SQUID washer and modulation coil

HDFRMux1 – modulation demonstration

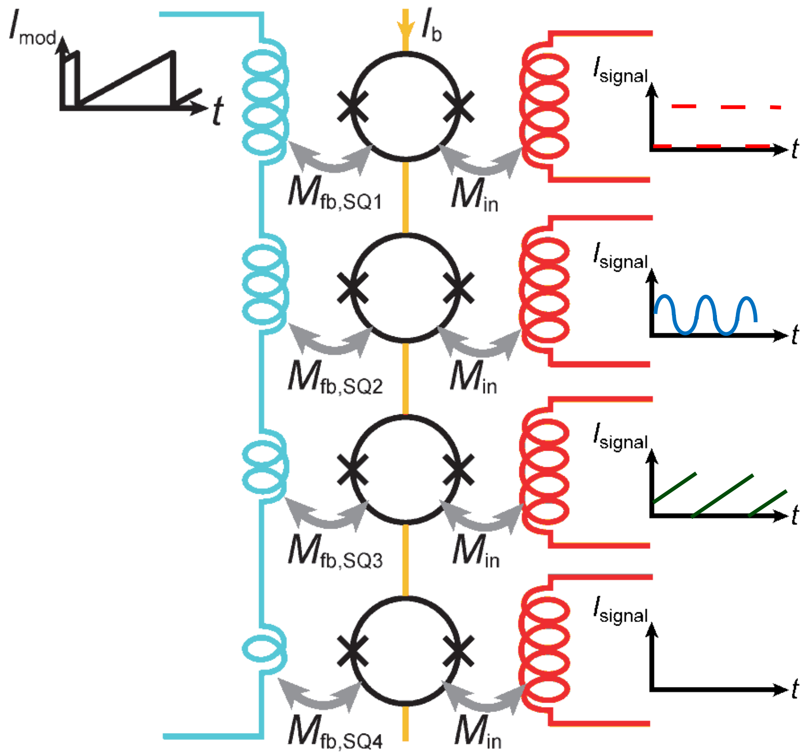
1 kHz flux ramp repetition rate

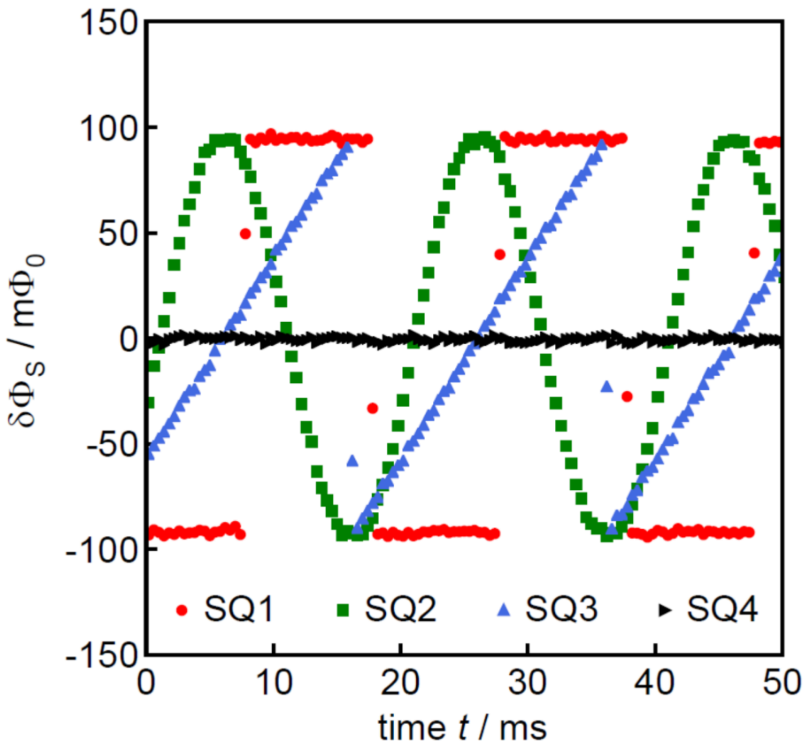


different carrier frequencies clearly visible in spectrum of output signal

performance of HDFRMux1 – multiplexing capability

different signal on SQUID inputs, 250 kHz flux ramp repetition rate

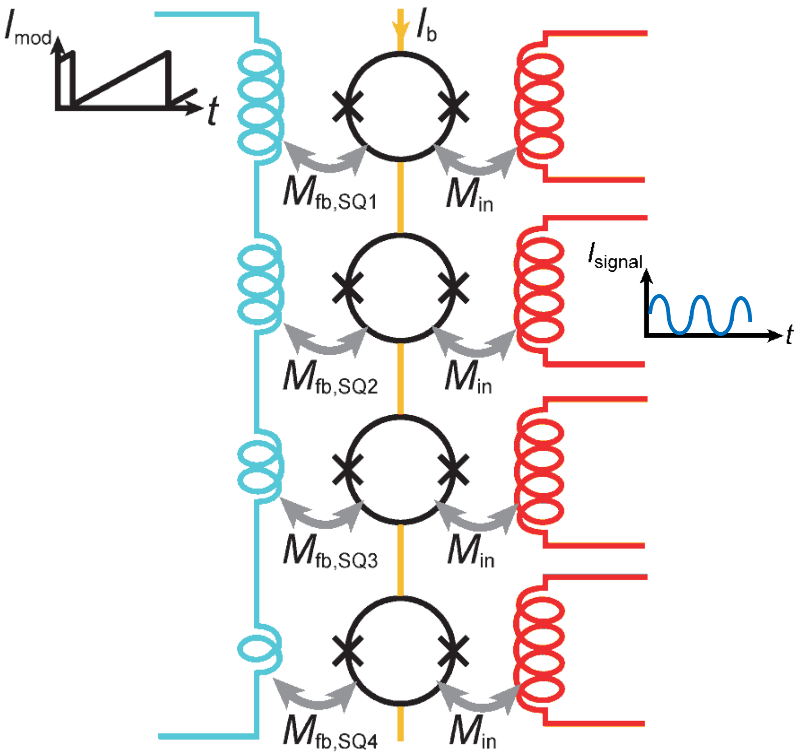




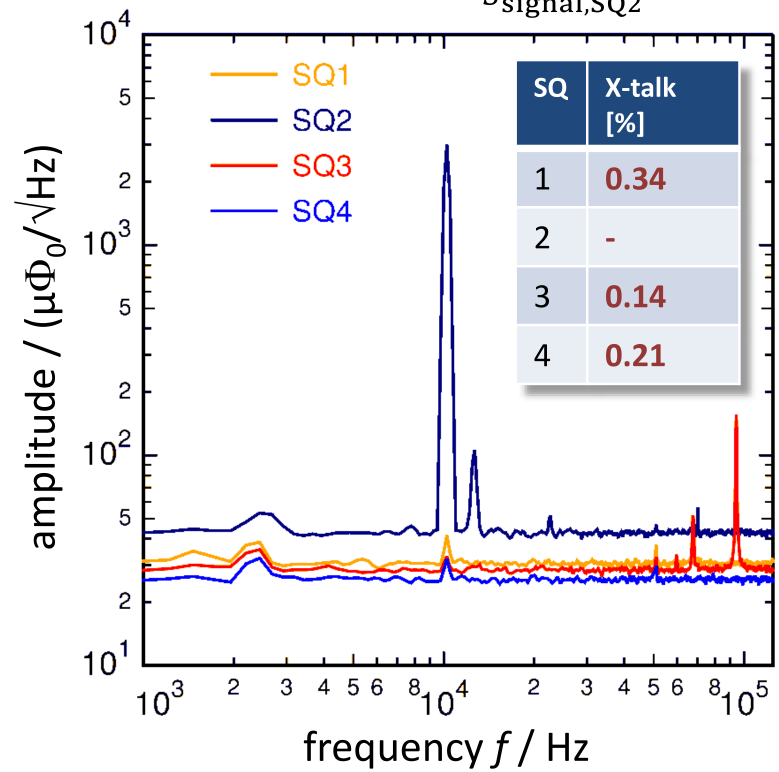
successful demonstration of flux ramp modulation based dc-SQUID multiplexing technique

performance of HDFRMux1 – crosstalk

10 kHz sinusoidal signal in SQ2, 250 kHz flux ramp repetition rate



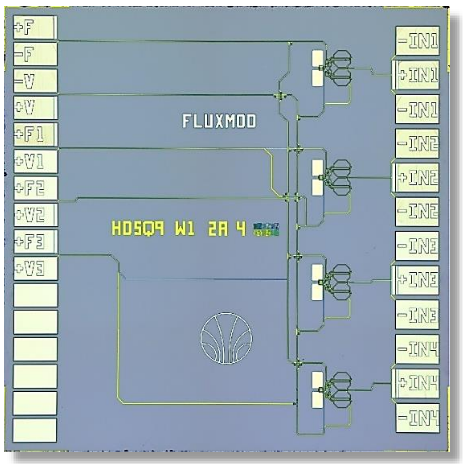
$$\text{crosstalk} = \frac{S_{\text{signal,SQX}}}{S_{\text{signal,SQ2}}}$$



SQ	X-talk [%]
1	0.34
2	-
3	0.14
4	0.21

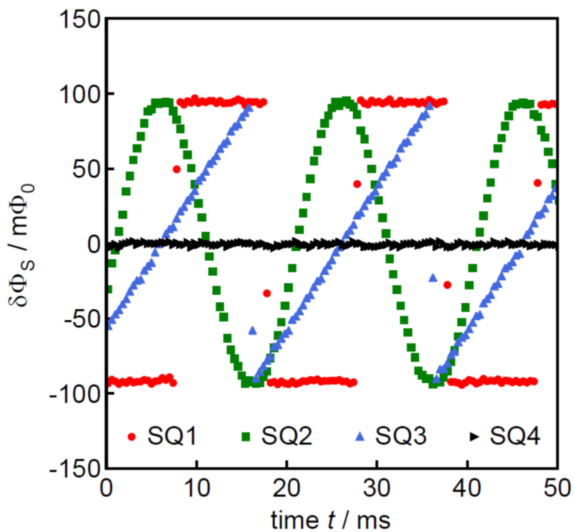
measured crosstalk between channels < 0.5 %

summary and outlook



novel dc-SQUID readout technique

- ‘infinitely’ large dynamic range
- no slew rate limitations
- MHz frequency domain multiplexing capability



what’s next?

- ‘optimized’ devices
- Further reduce crosstalk in FRM-muxing
- readout noise optimization (preamplifier)
- dedicated readout electronics (FPGA based)

DC-SQUID readout with high dynamic range and intrinsic frequency-division multiplexing capability

D. Richter, A. Fleischmann, C. Enss, and S. Kempf

Kirchhoff-Institute for Physics, Heidelberg University, Germany

International Superconducting Electronics Conference ISEC2019

July 28 – August 1, 2019, Riverside, California, USA