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LEIBNIZ INSTITUTE *of* PHOTONIC TECHNOLOGY

SQUIDs – From ideas to instruments and applications

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Leibniz Association

jenaphotonics®

SQUIDs – From ideas to instruments

- Basics of SQUIDs
  - Types of SQUIDs
  - Technology
  - Cryogenics
  - Electronics
  - Noise
- Applications
  - Non-Destructive test and Evaluation
  - Biomagnetism
  - Geoscience
  - Enabling technologies

Preamble: The beast named SQUID…

- acronym **SQUID** = **Superconducting QUantum Interference Device**

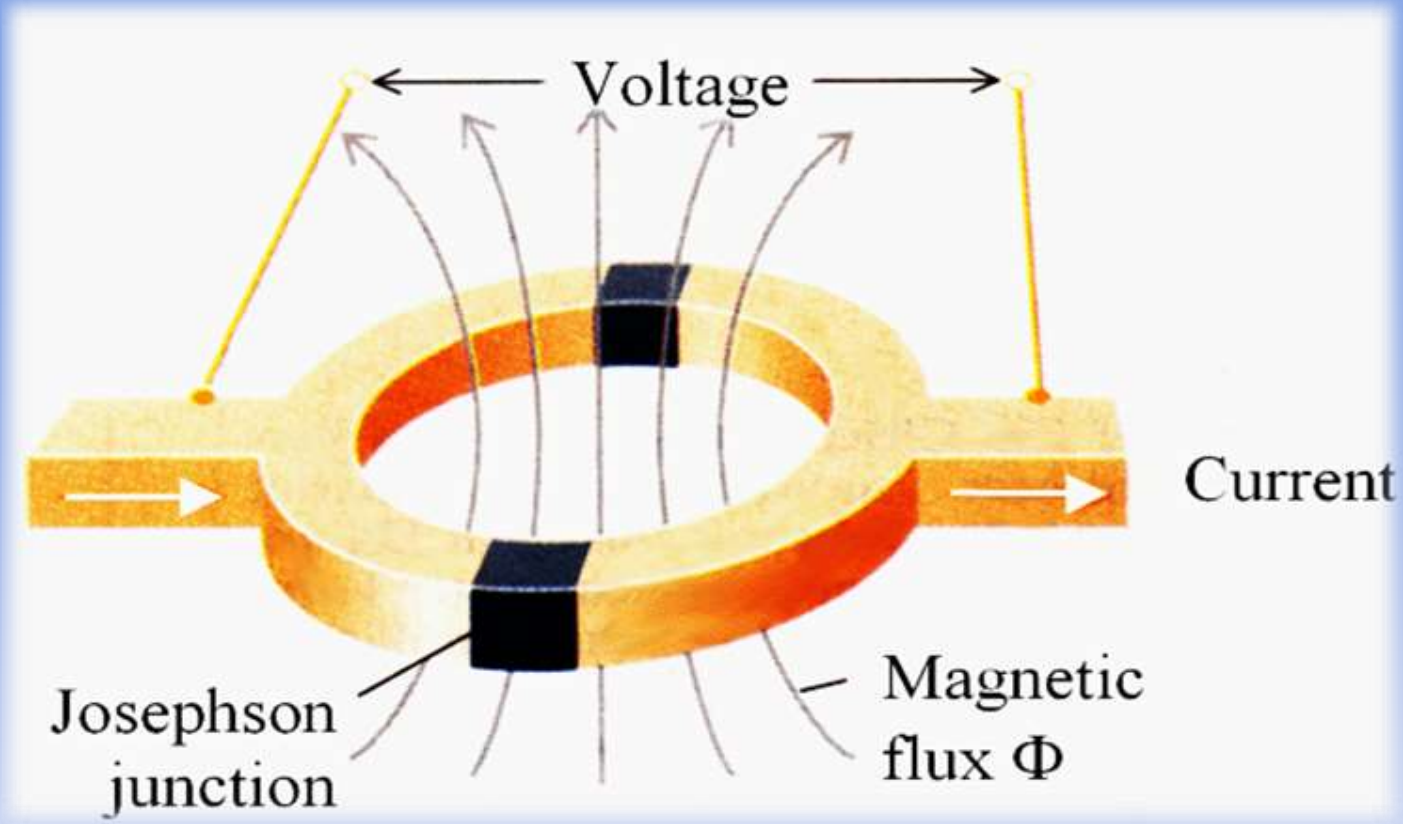
Superconductivity and it‘s various effects

Flux quantization $\boldsymbol{\Phi_0 = 2.07 \cdot 10^{-15} Vs}$

Quantum interference

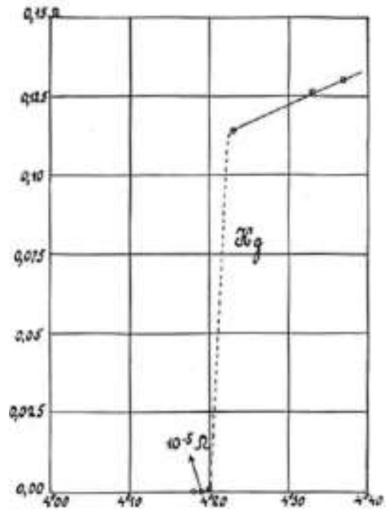
Technology

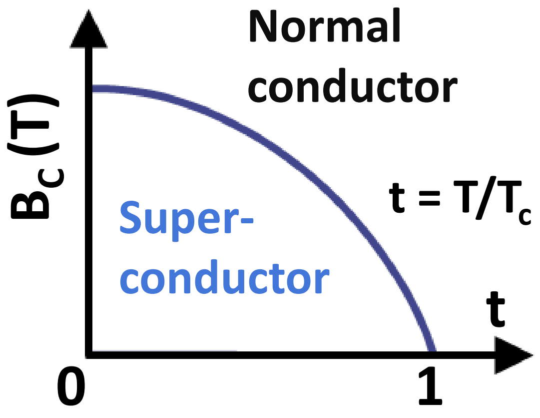
- transducer for magnetic flux into voltage:
  - ultra-wide bandwidth ($> 10 GHz$ demonstrated) from DC,
  - flat transfer function in frequency space,
  - low noise ▶approaches quantum limits ($< 10^{-30}\ J/Hz$),
  - highly linear in terms of period of interference and large dynamic range (>32bit demonstrated),
- requires cryogenic temperatures and environment (dewars or cooling units).

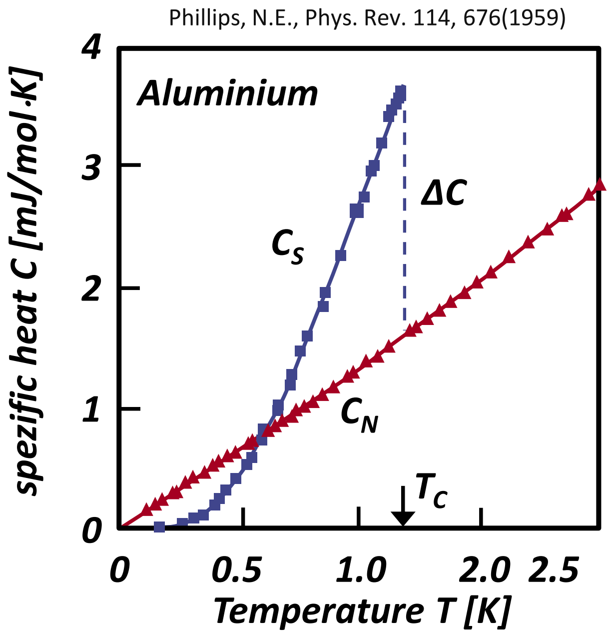


Basics on SQUIDs and Superconducting Electronics

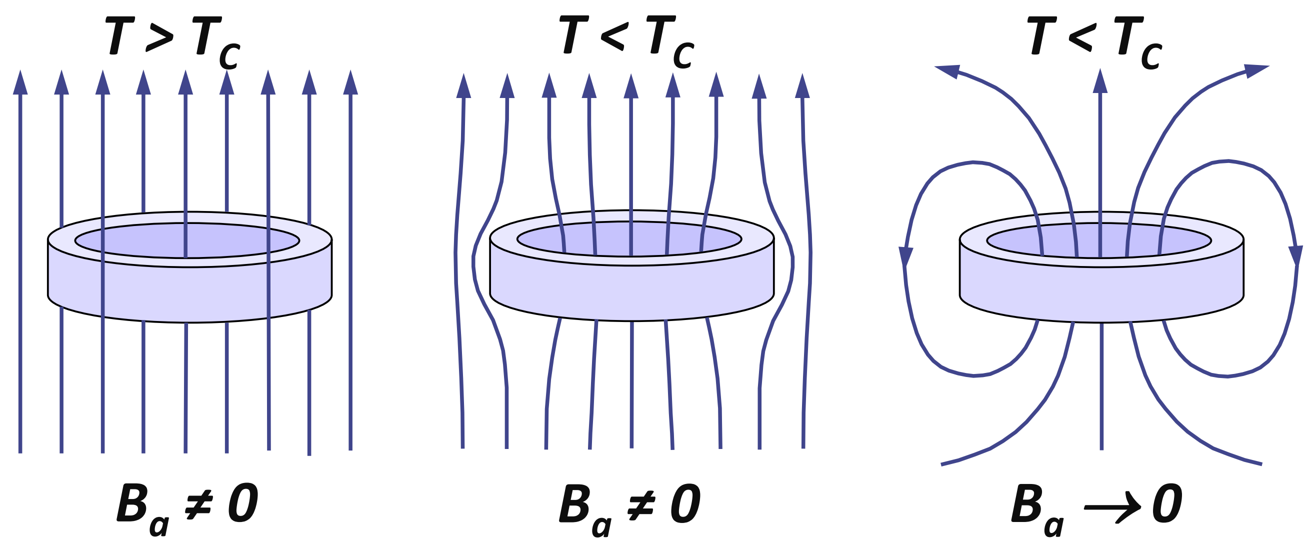
Recap: superconductivity and SQUID basics in one slide





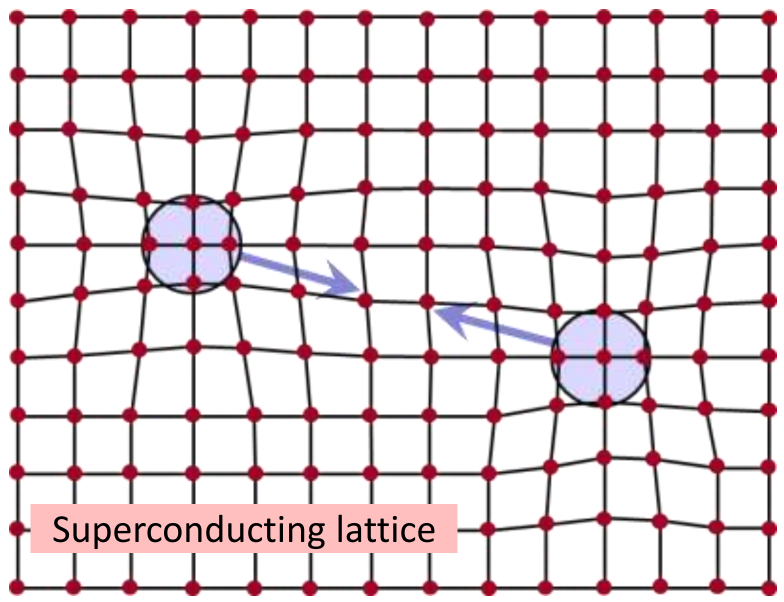


Critical temperature, current and magnetic field

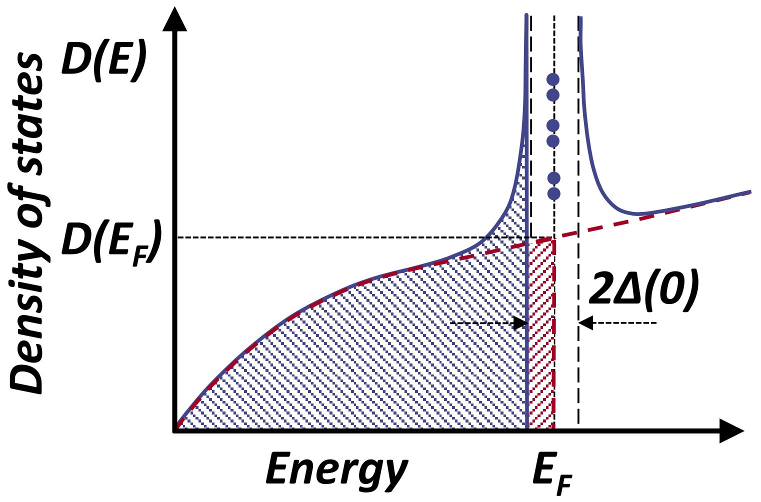


Persistent currents and „frozen“ flux

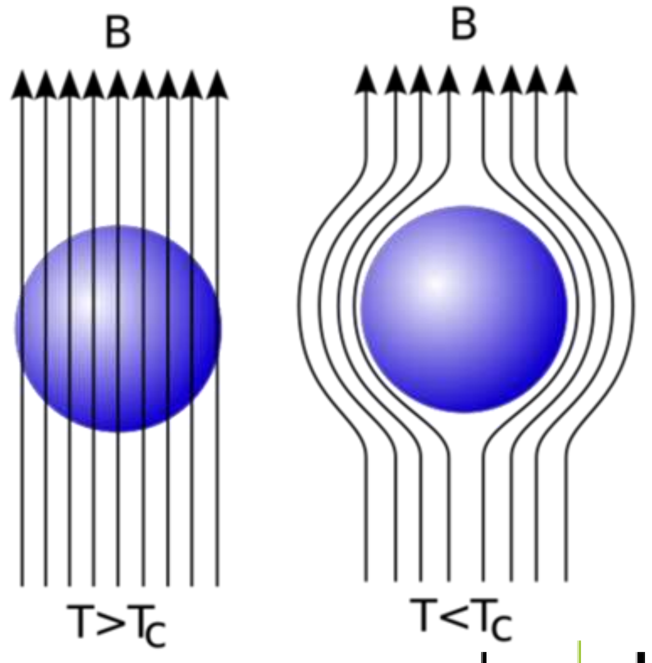
Cooper pair formation



Superconducting gap



Only small fraction of electrons (quasi-particles) condenses into cooper pairs (10^{-4})



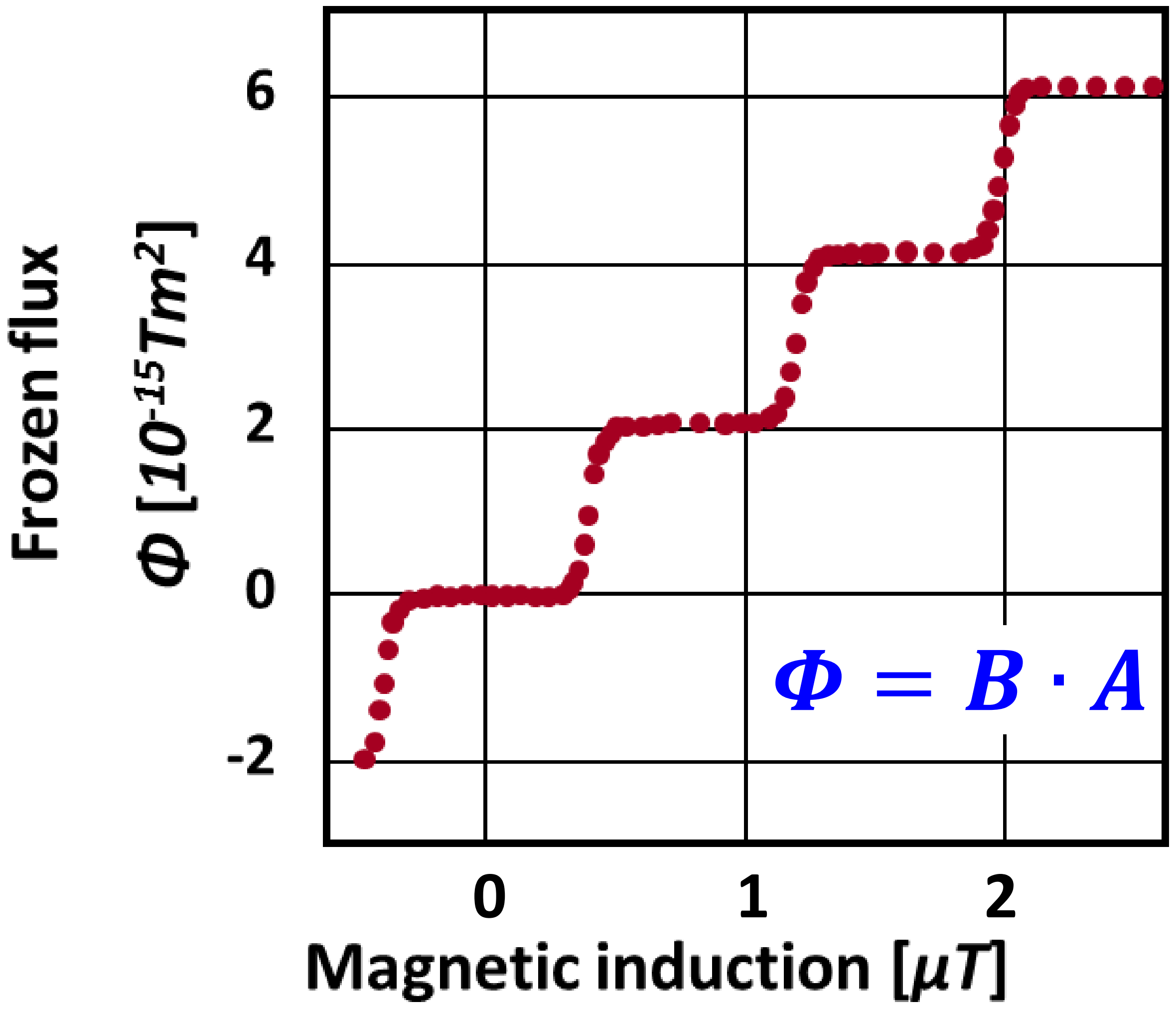
Meissner-Ochsenfeld effect

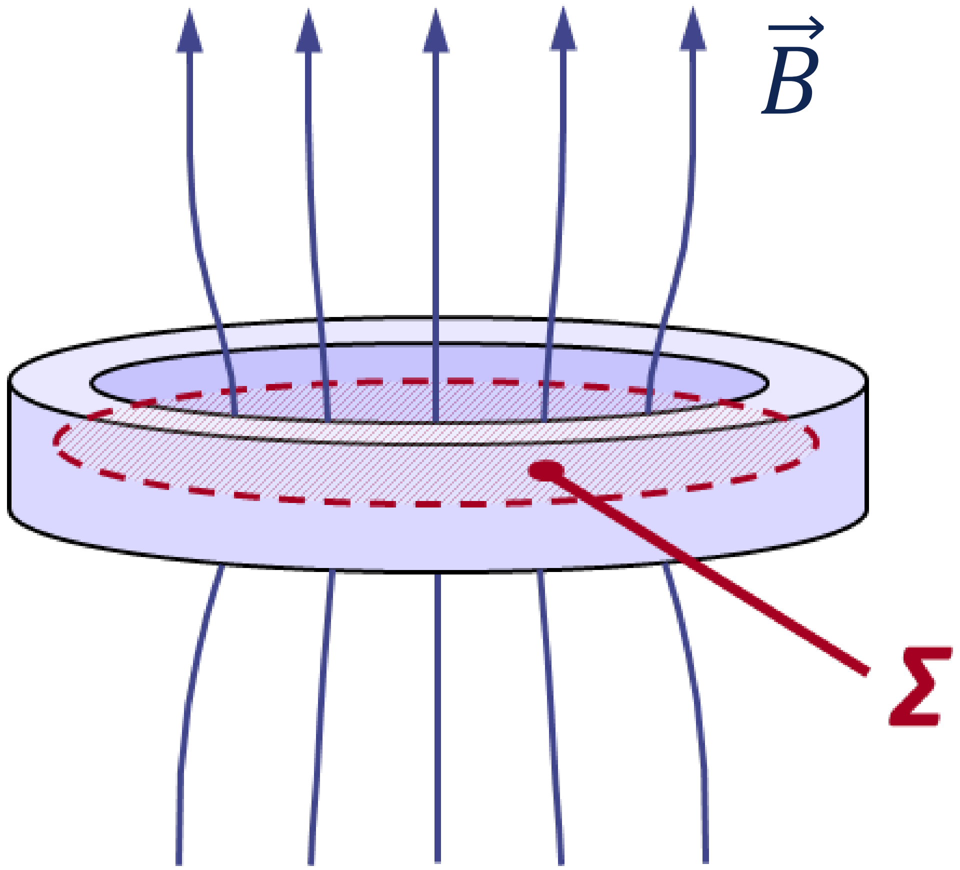
Flux quantization

1950 Prediction Fritz London: charge e

1961 Robert Doll and Martin Näbauer (at the same time and independently)
Bascom S. Deaver, Jr. and William M. Fairbank: supra-electrons carry charge of **-2e**!

L. Goodman, W.D. Willis, D.A. Vincent, B.S. Deaver, Phys. Rev. B 4, 1530 (1971)





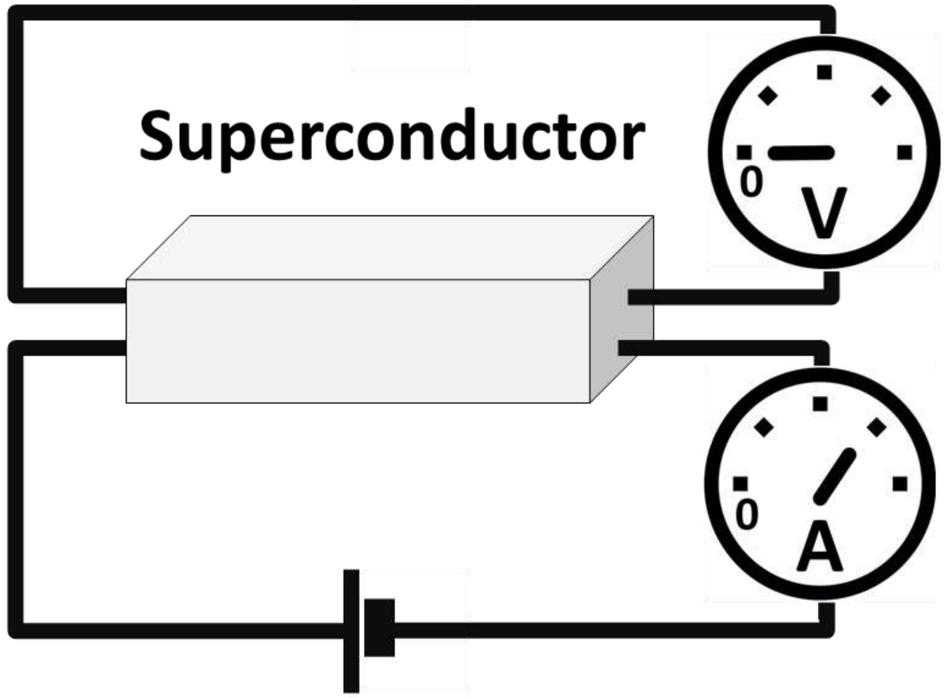
$$\Phi = \int_{\Sigma} \vec{B} \cdot d\vec{f} = n \cdot {}^{h}/_{2e}$$

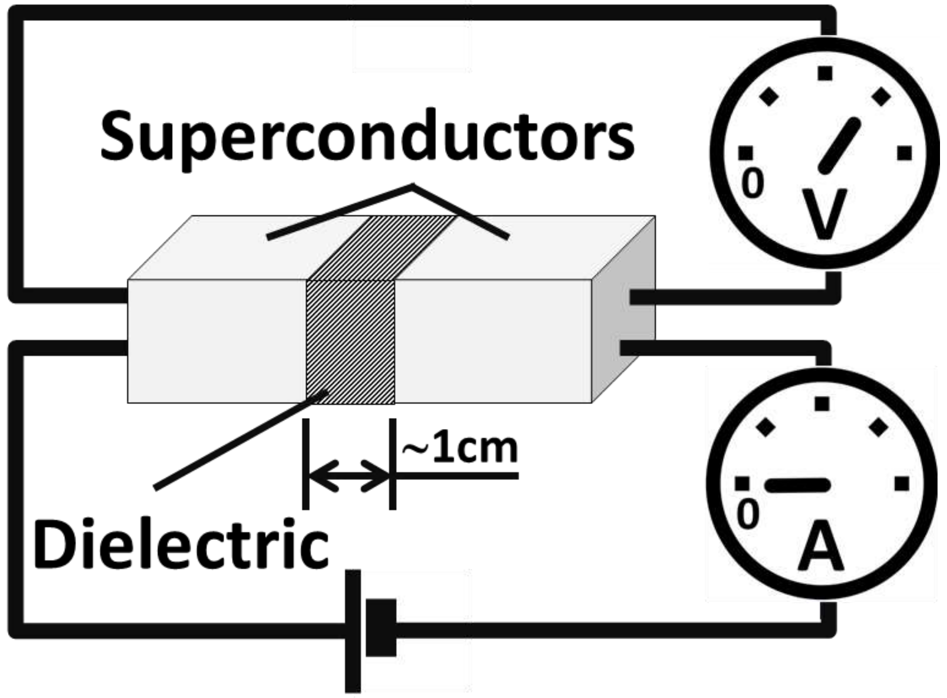
$$\Phi_0 = {}^{h}/_{2e} \approx 2.068 nT \cdot mm^2$$

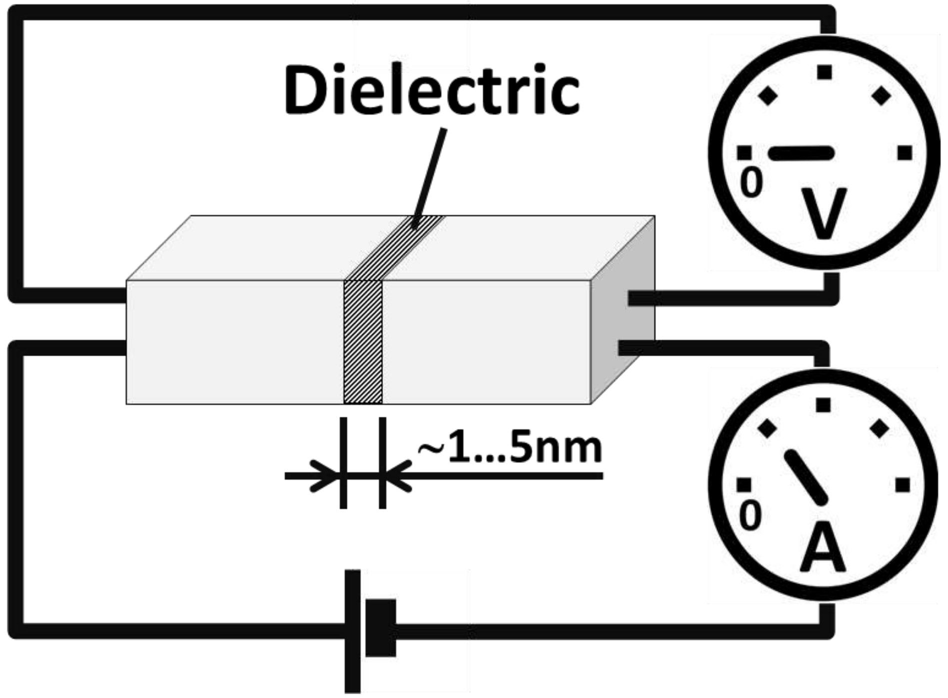
Φ_0 magnetic flux quantum

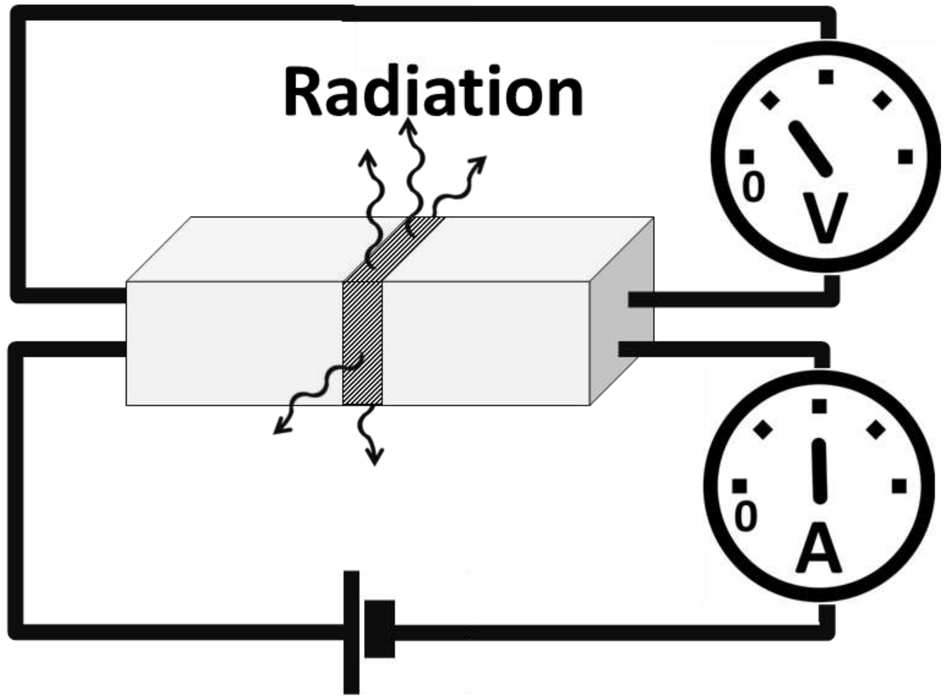
Josephson effects

Brian D. Josephson
*1940









dc Josephson effect (1962)

$$I(t) = I_C \sin[\varphi(t)]$$

with $\varphi(t) = \varphi_1(t) - \varphi_2(t)$

ac Josephson effect

$$V(t) = \frac{\hbar}{2e}\frac{\partial\varphi}{\partial t}$$

Birth of supercond. Quantum metrology…

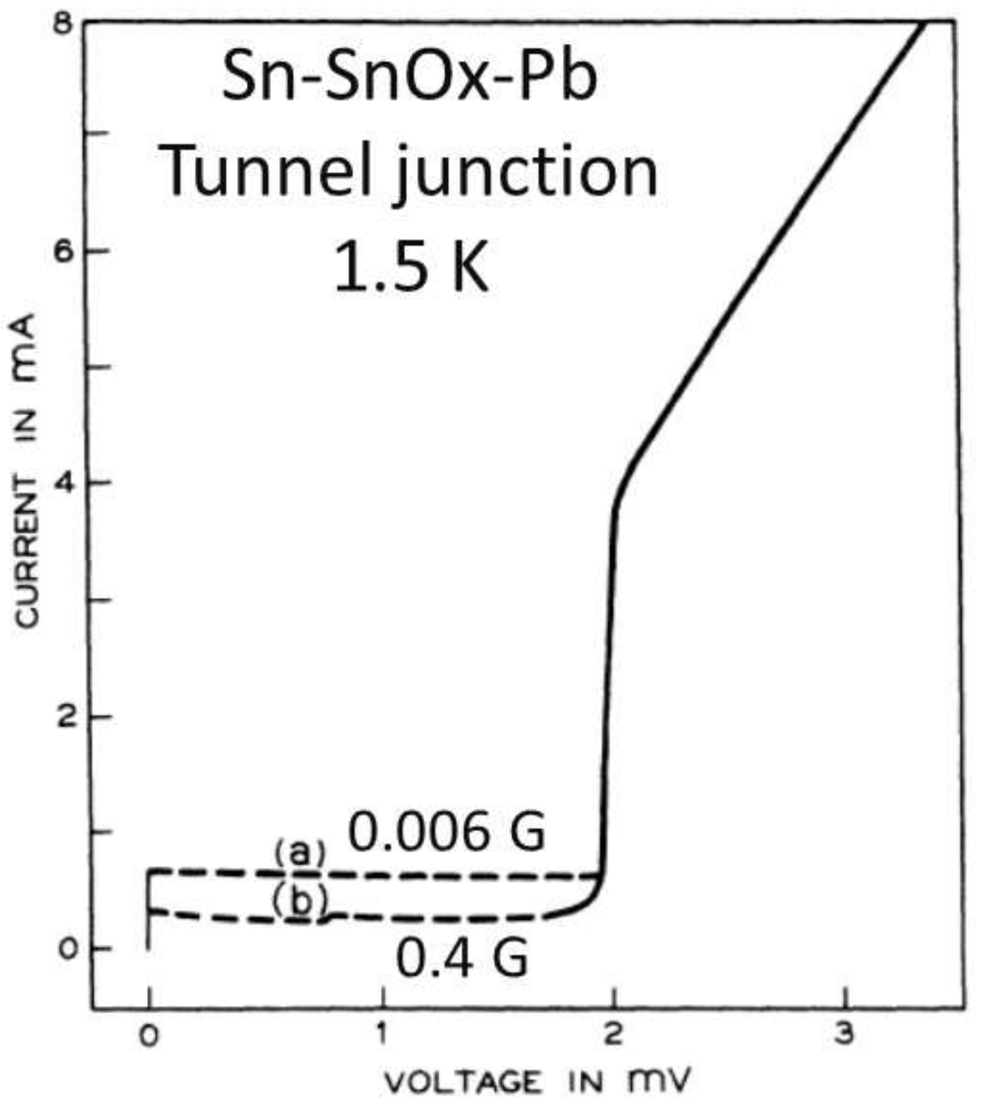
Base of superconductor electronics…

Josephson junction as “transistor“

1963 P. W. Anderson, J. M. Rowell:
experimental prove of DC Josephson effect,

1963 S. Shapiro:
indirect experimental prove of AC Jospehson effect,
▶ **Shapiro steps**,

1965 I.K. Yanson, W.M. Svistunov, I.M. Dmitrenko and independently
R.E. Eck, D.J. Scalapino, B.N. Taylor & Langenberg:
experimental prove of the AC Josephson effect,
direct measurement of the microwave radiation.

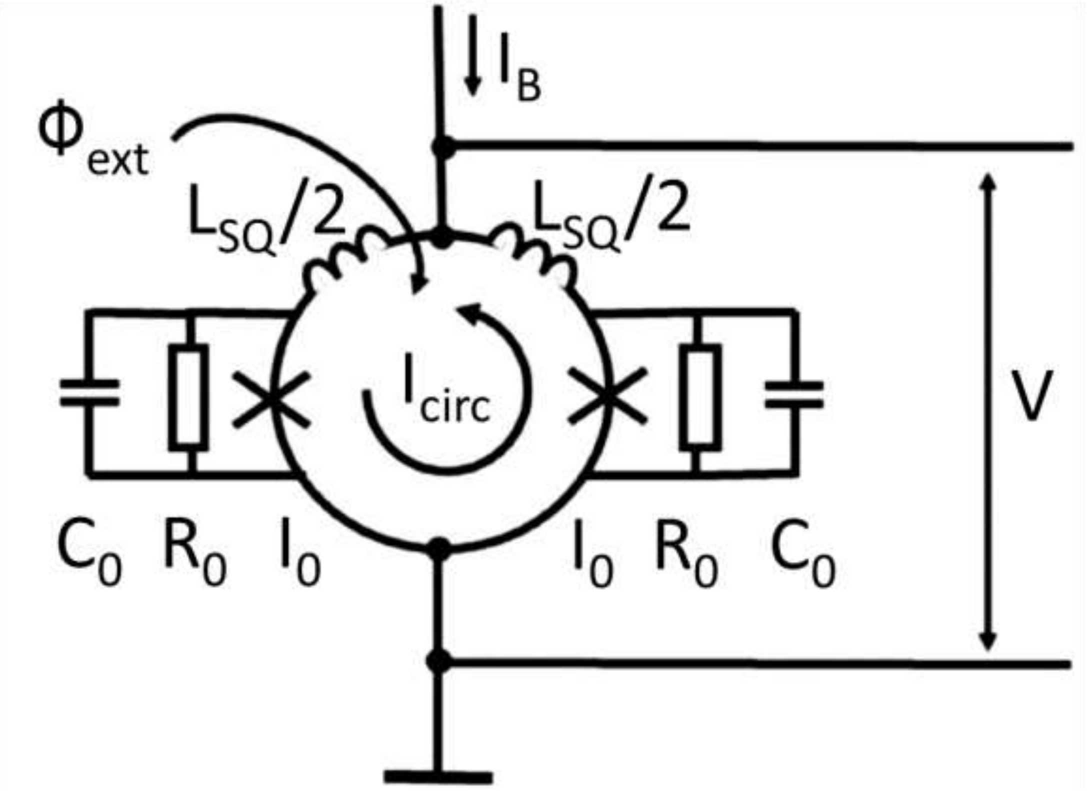


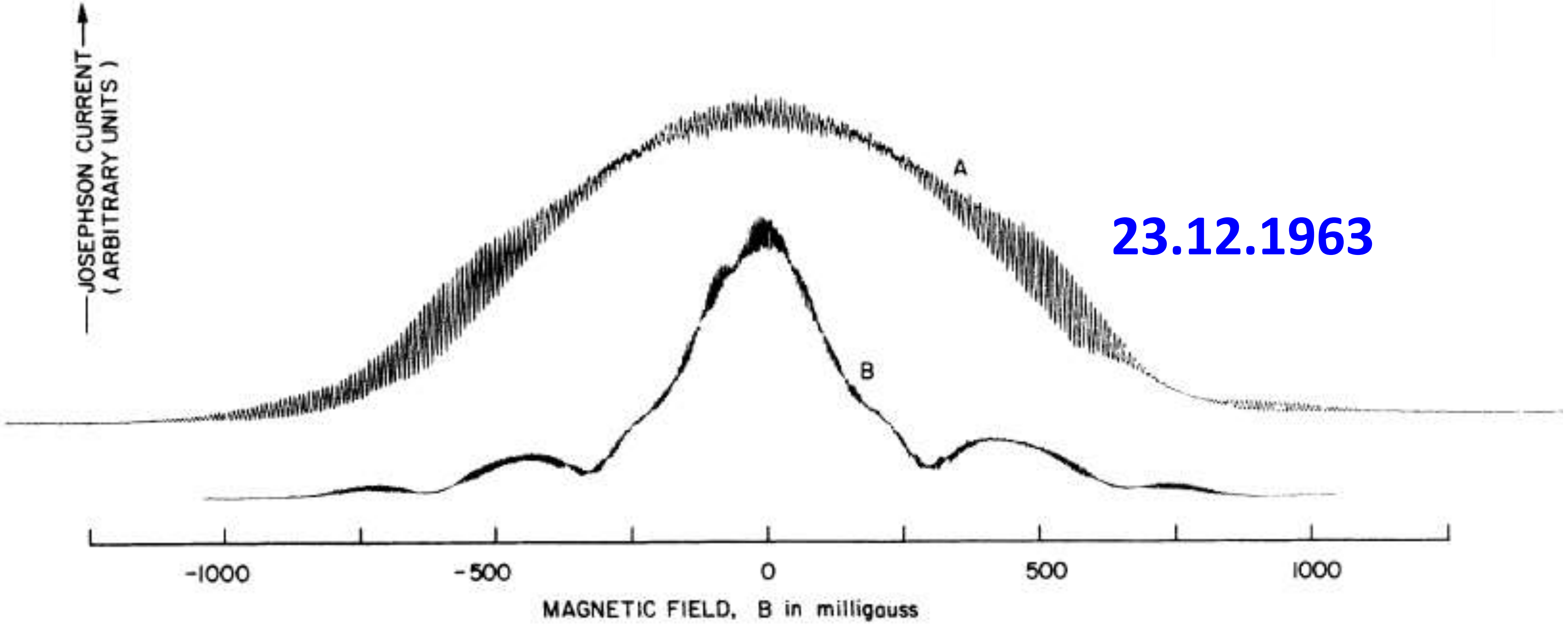
Anderson and Rowell 1963
Bell Labs

Birth of the SQUID based Quantum magnetometry

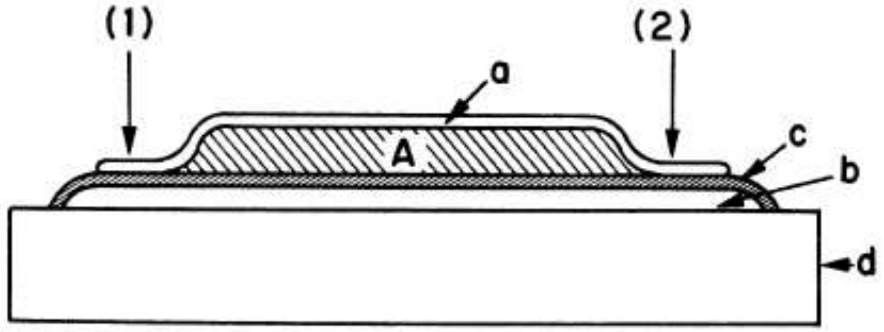
1964 R.C. Jaklevic, J. Lambe, A.H. Silver, J.E. Mercerau: invention of SQUID

- maximum supercurrent versus applied magnetic field for two different loop areas,
- rapid oscillations due to interference.





23.12.1963

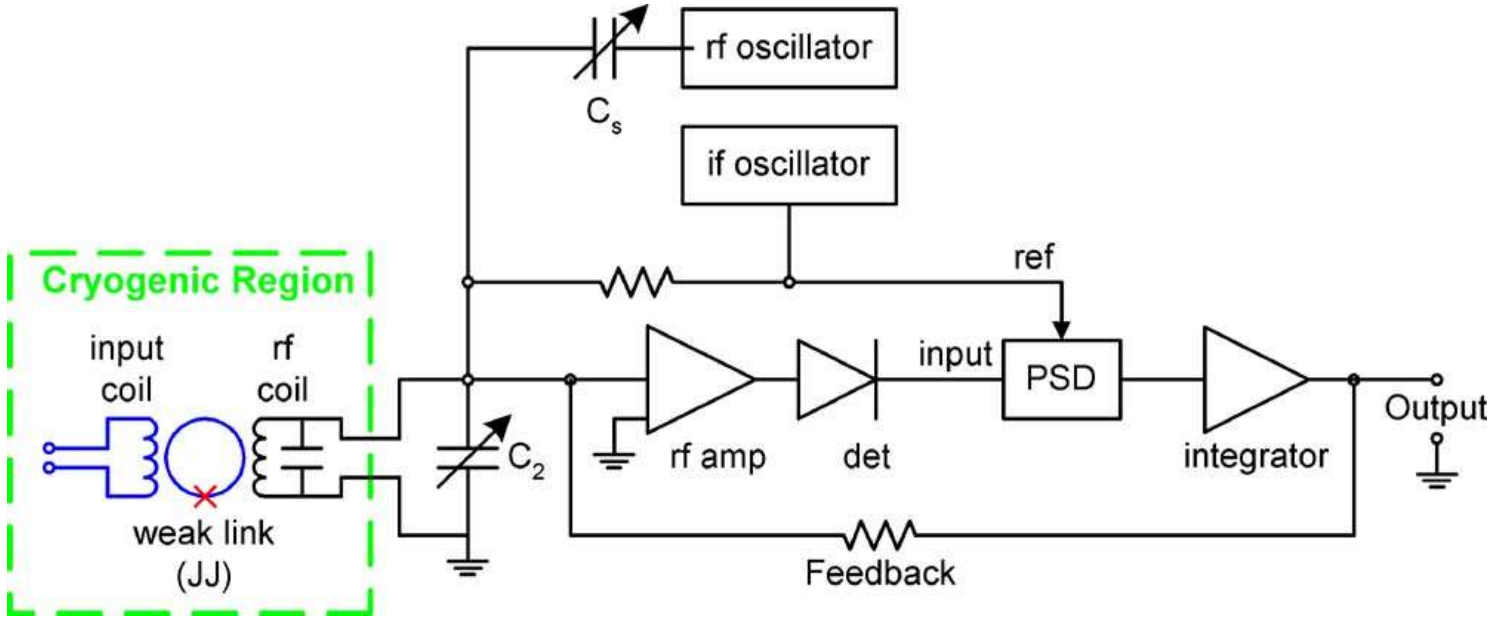


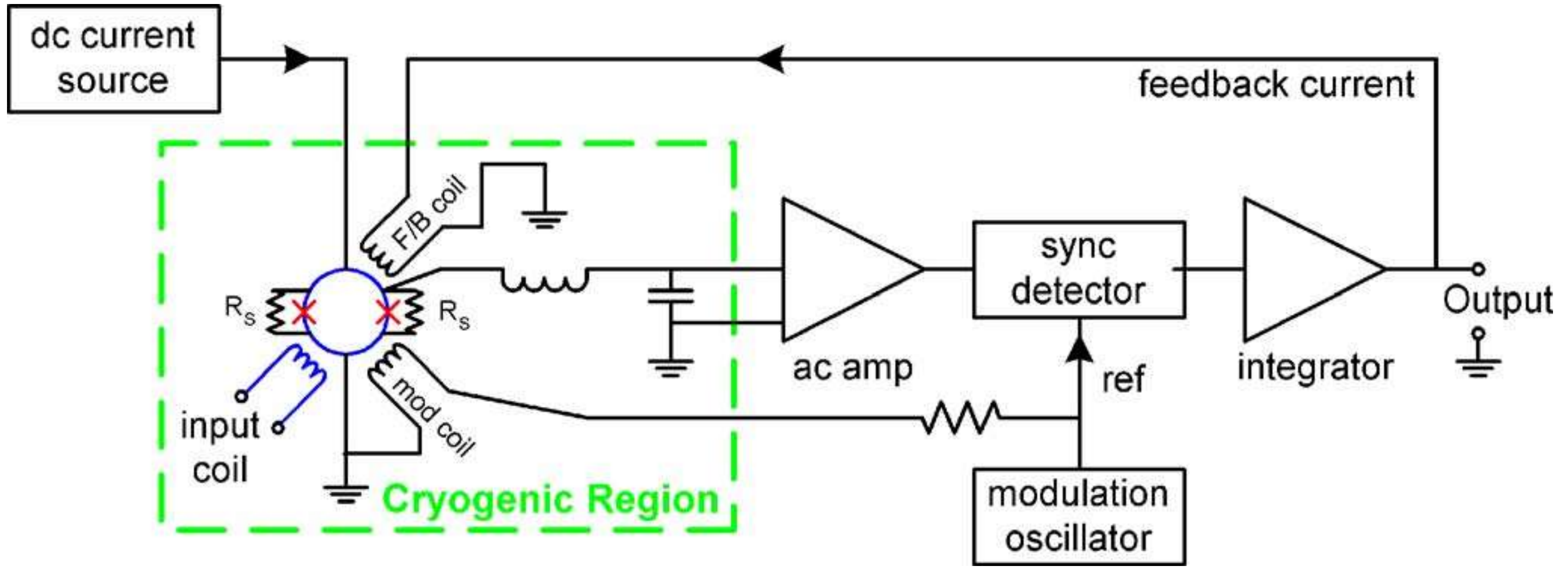
Sn-SnOx-Sn junctions

SQUID types

RF vs. DC SQUID

With courtesy of B. Fagaly





- single junction SQUID,
- rf current bias and inductive coupling to electronics to measure its impedance,
- simple cryogenics: 2 wires,
- $E_n = L_{input} \cdot I_n{}^2 = \frac{\Phi_n{}^2}{L_{input}} \sim \frac{1}{\sqrt{f_{pump}}}$
  - ▶ demand for high pump frequency,
  - ▶ at 1 GHz, a HTS rf SQUID may have lower noise than a dc HTS SQUID.

- double junction SQUID,
- dc current applied directly to the SQUID,
- various variants to couple electronics,
- more simple to implement wide-band electronics
  - ▶ demands sufficient voltage swing of the SQUID.

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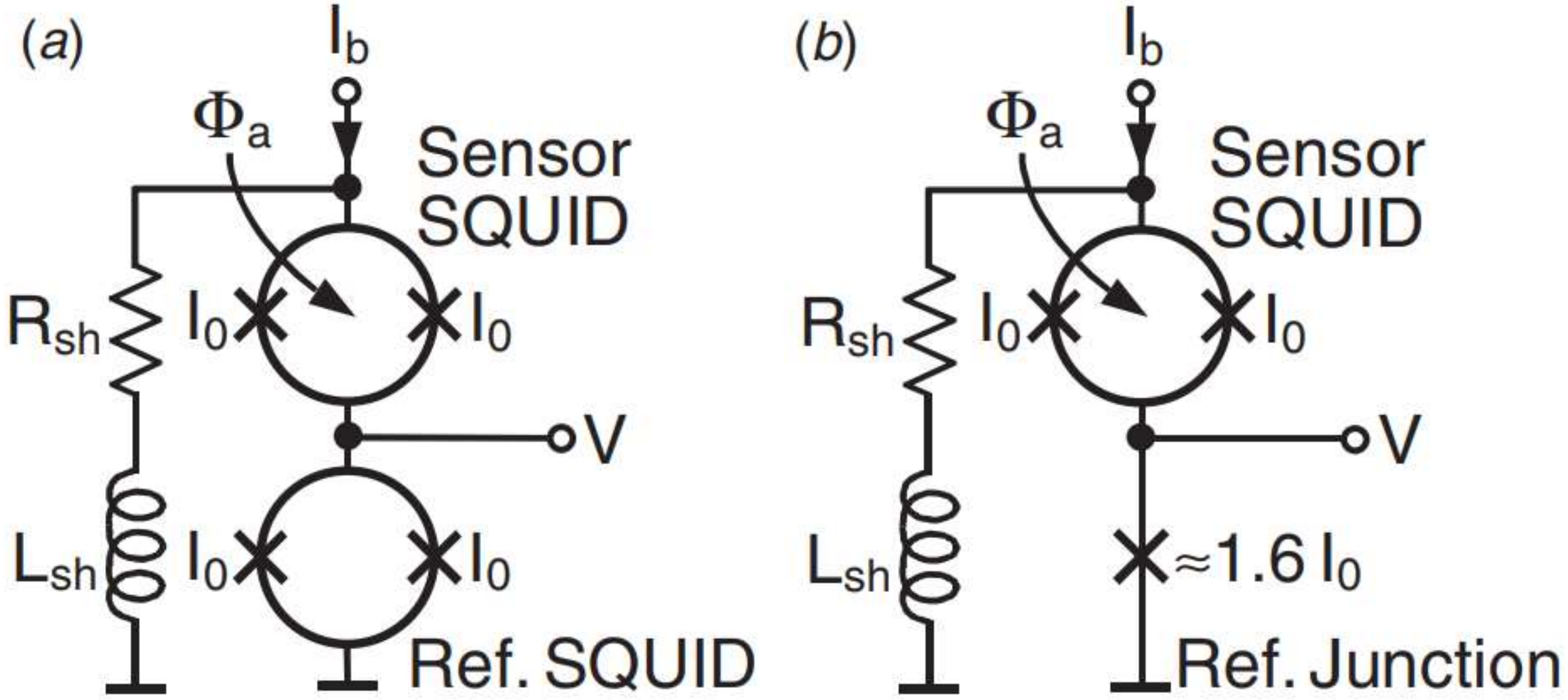
Relaxation oscillation SQUIDs: ROS and DROS

- ***relaxation oscillation SQUID (ROS)***: a dc SQUID with hysteretic junctions, which is shunted by resistor R_{SH} and inductor L_{SH} in series (comparable to APF circuit, later),
- R_{SH} & L_{SH} properly chosen (Adelerhof et al. J. Appl. Phys. 76 3875 (1994)): relaxation oscillation occurs if ROS biased with dc current above SQUID's critical current,
- flux-to-frequency (frequency modulated electronics) or flux-to-voltage converter; large voltage swings V_{pp} and transfer functions V_Φ,

- V_Φ and V_{pp} of ROS increased by using two SQUIDs in series = ***balanced (double) ROS*** or ***DROS***,
- external flux only applied to sensing SQUID,
- similar to ROSs, DROSs need relaxation oscillation frequencies >1GHz and proper resonance damping for low noise,
- base for simple digital SQUID,
- application: Lee et al. SUST 14 1022 (2001).

Drung et al. SUST 16 1320 (2003)



Other types

Asymmetric SQUID
(by design or bias injection),

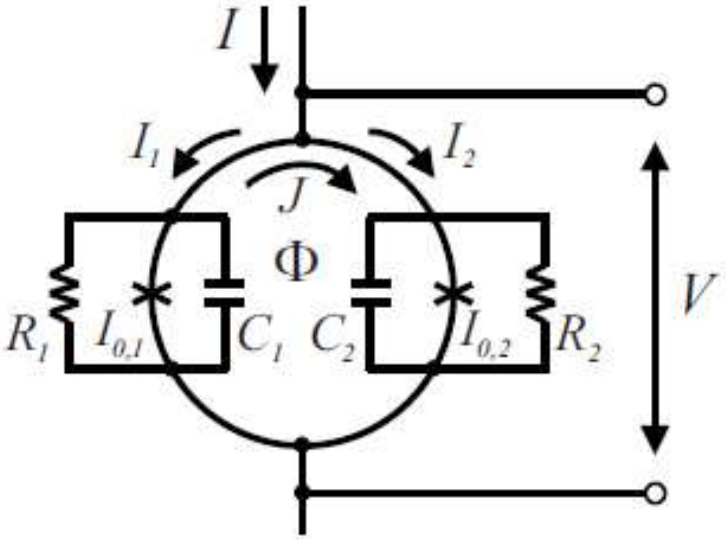
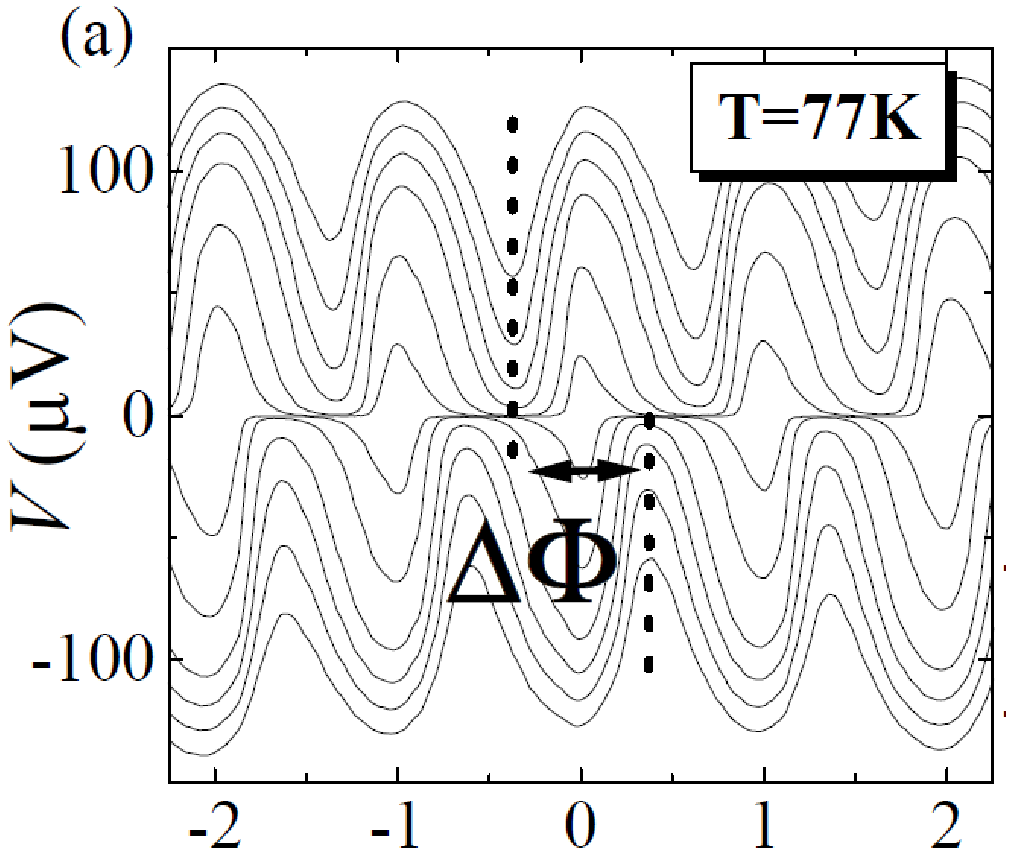
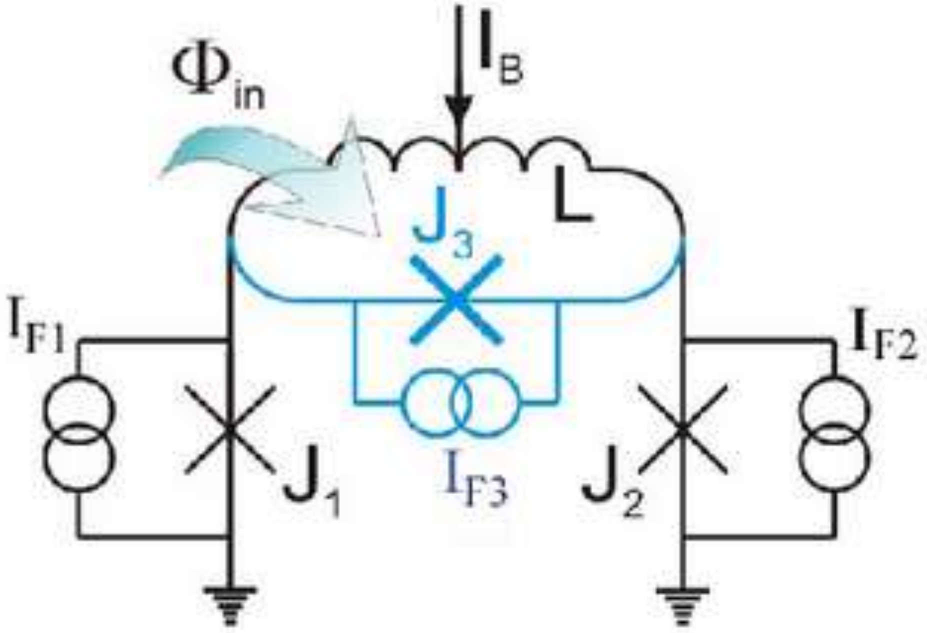


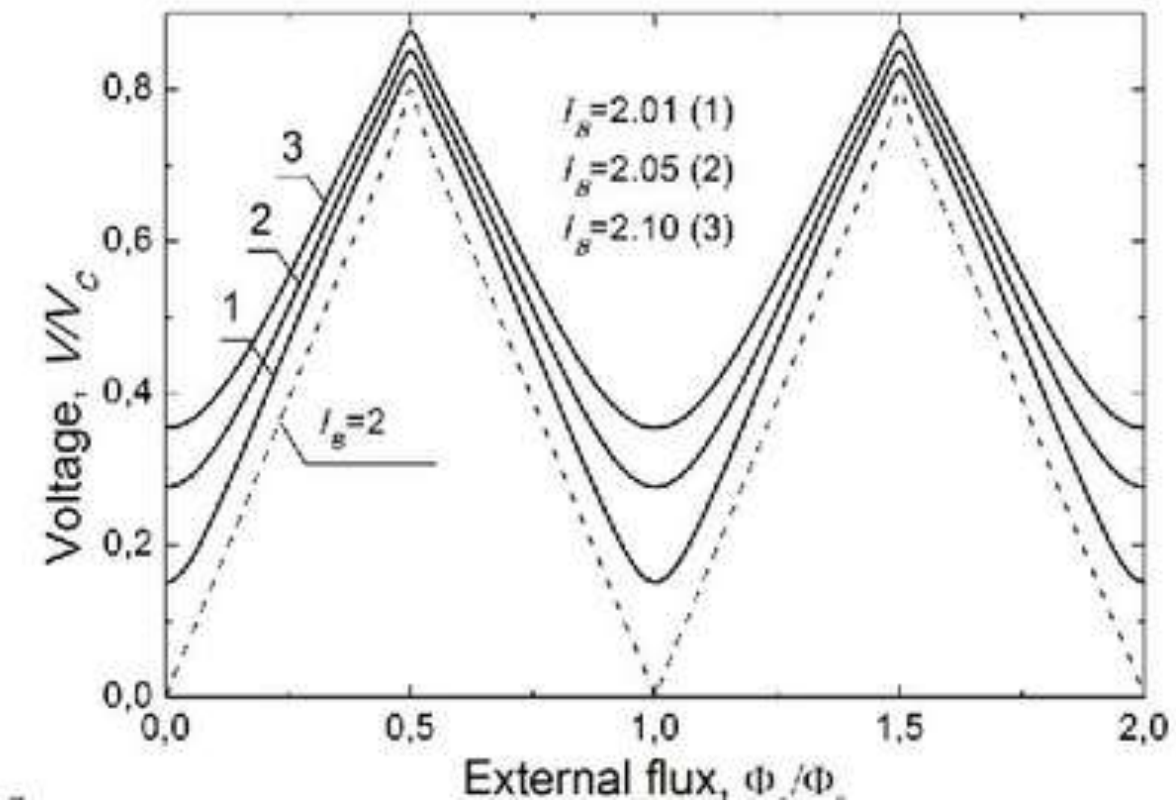
Fig. 1
THE ASYMMETRIC DC SQUID



Müller et al. IEEE Trans. Appl. Supercond. 10 (2001)

Bi-SQUID

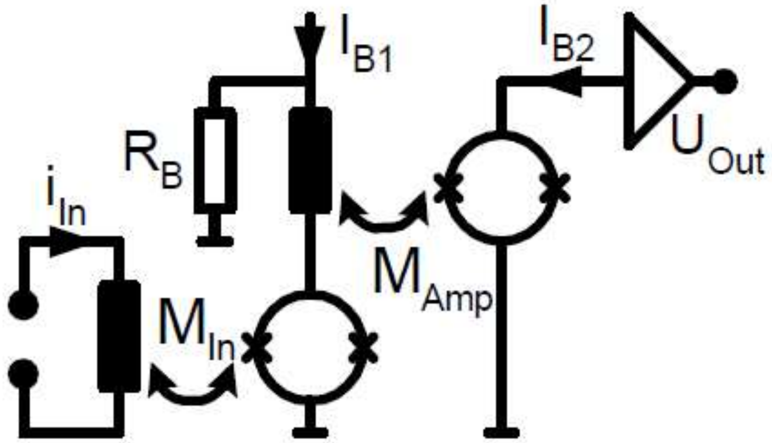




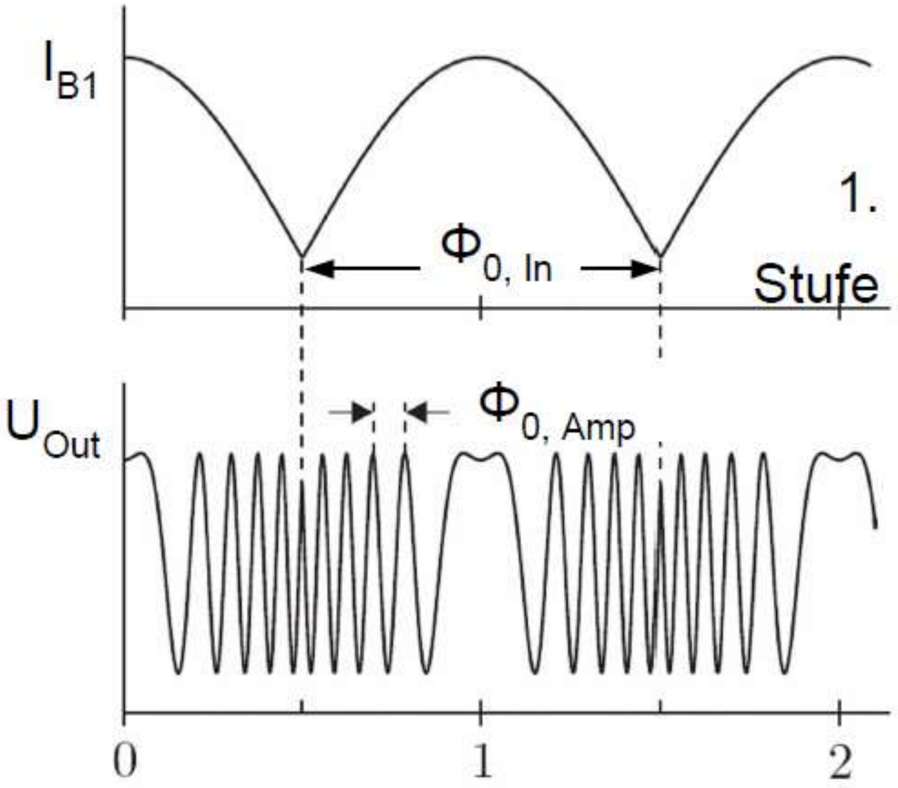
Kornev et al. SUST 22 114011 (2009)
Sharafiev et al. Bi-SQUID noise simulation, 2013 ISEC

Double stage SQUID

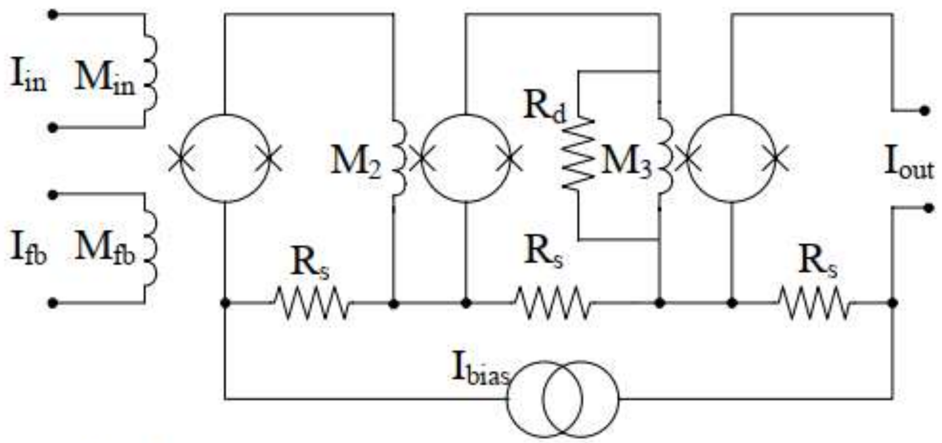
- **double SQUID** readout scheme: Koshelets et al. IEEE Trans. Magn. 25 (1989),
- additional flux gain increases V_Φ
  - ▶ reduce amplifiers voltage noise contribution
- flux gain $G_\Phi = M_{amp} \frac{\partial I_1}{\partial (i_{In} \cdot M_{In})} \leq 2$
  - ▶ characteristics shaped like single SQUID with increased V_Φ,
- higher complexity and more supply lines required,
- leads directly to **SQUID operational amplifier** (flux offsets and multiple stable bias points
  - ▶absolute value of feedback current is unpredictable).



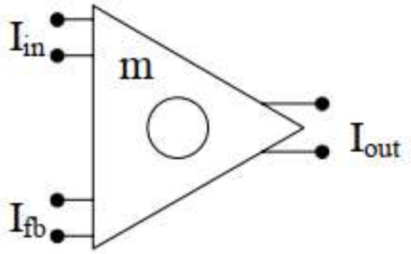
Ruede Diss. TU Berlin, 2008



(a) Three-stage SQUID op-amp circuit



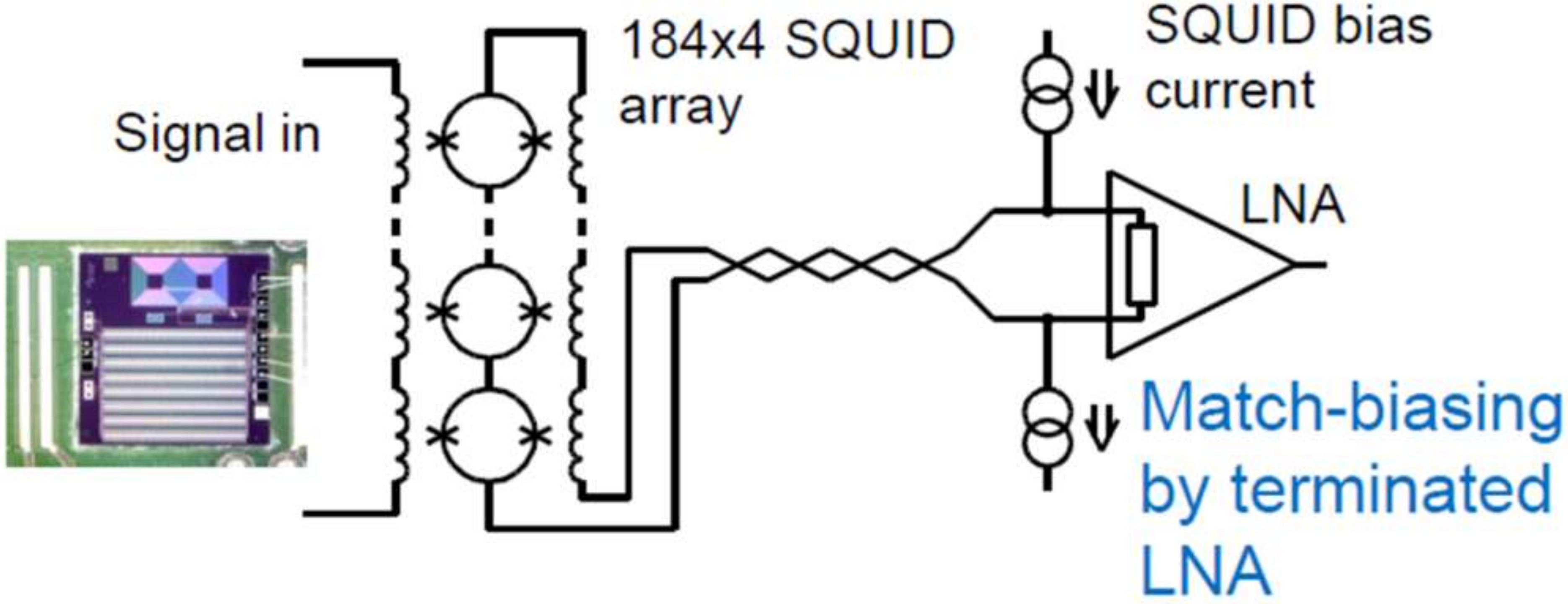
(b) SQUID op-amp symbol

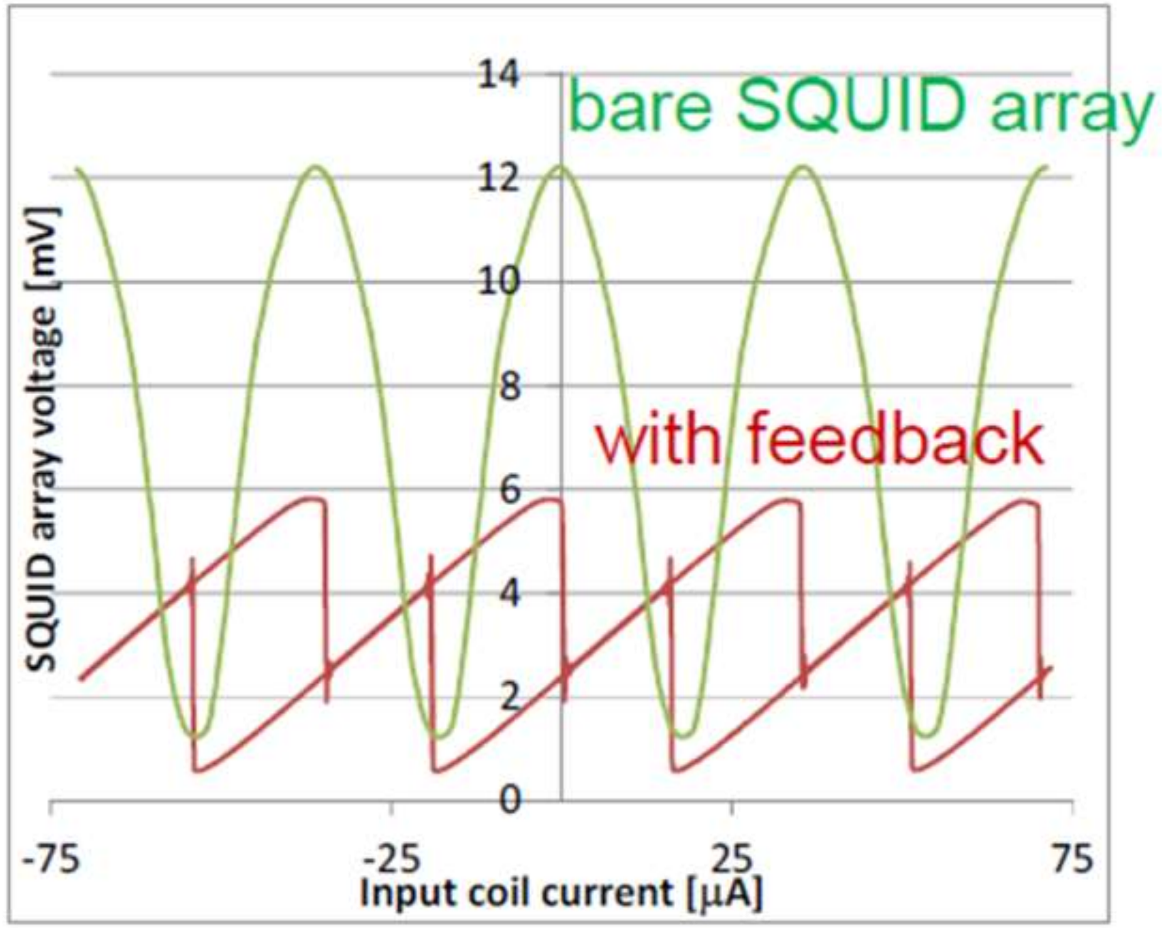


Irwin & Huber IEEE Trans. Appl. Supercond. 11(1) 1265 (2001)

SQUID arrays

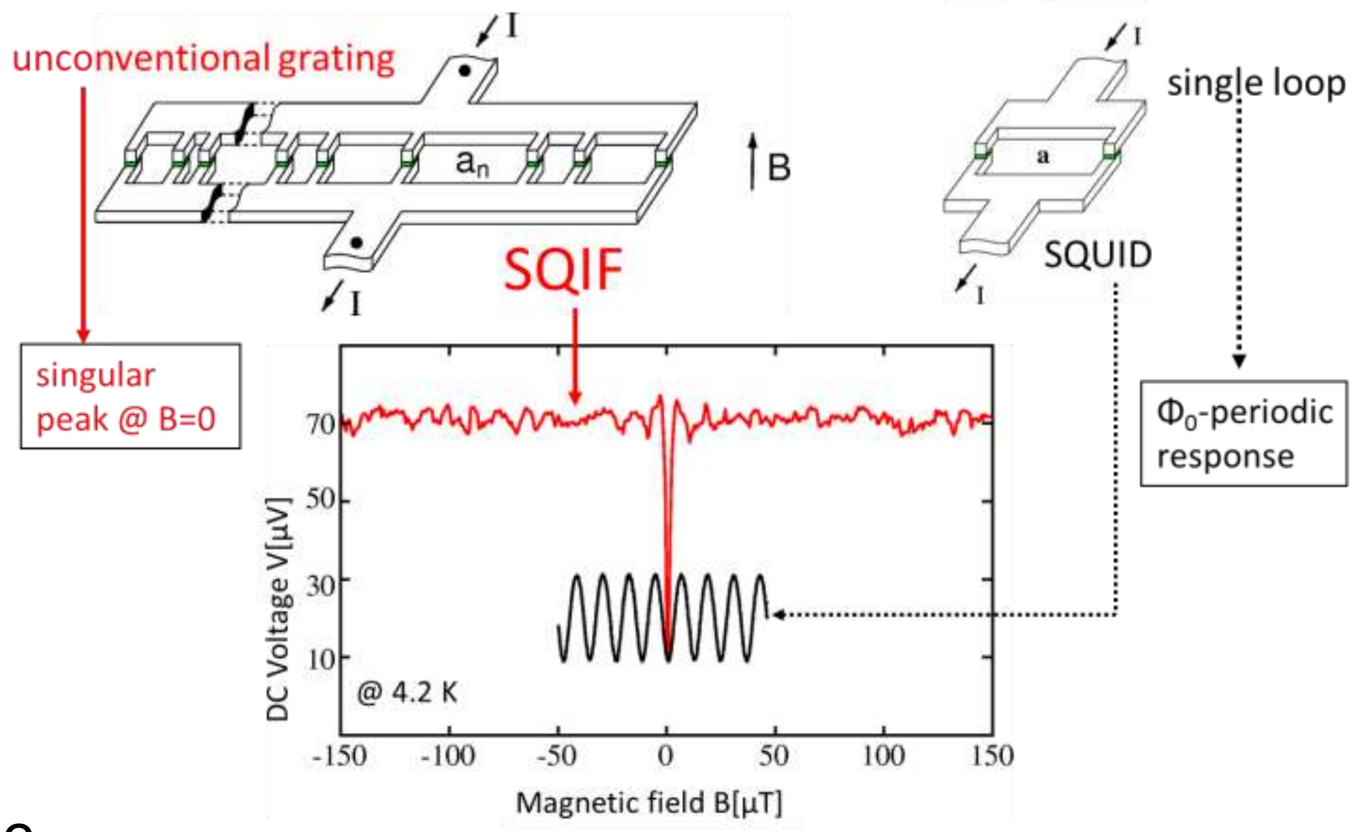
- increased output voltage, input resistance & dynamic range,
- highly non-linear V-Φ response,
- high demand for precise technology: „Beat“ due to stochastic deviations from the nominally equal loop size and junction parameters
  ▶ idea of SQIF was borne in trial of fabricating high performance HTS SQUID arrays.





M. Kiviranta, FLUXONICS Summerschool 2016

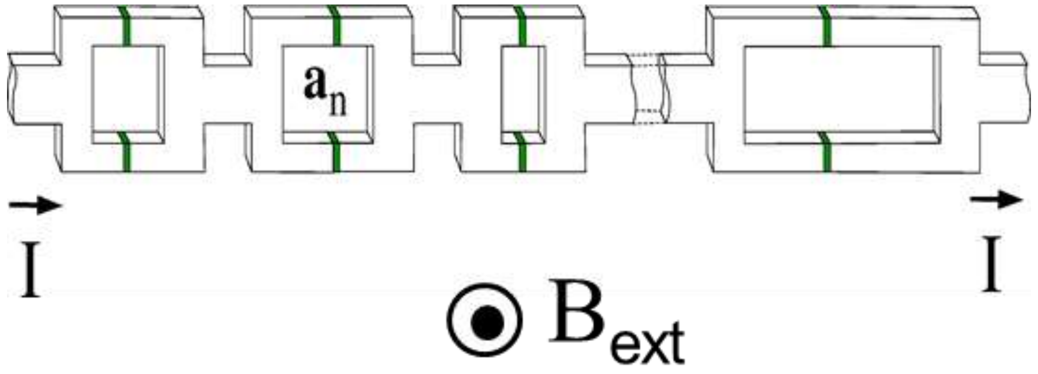
SQIFs and SQUAD



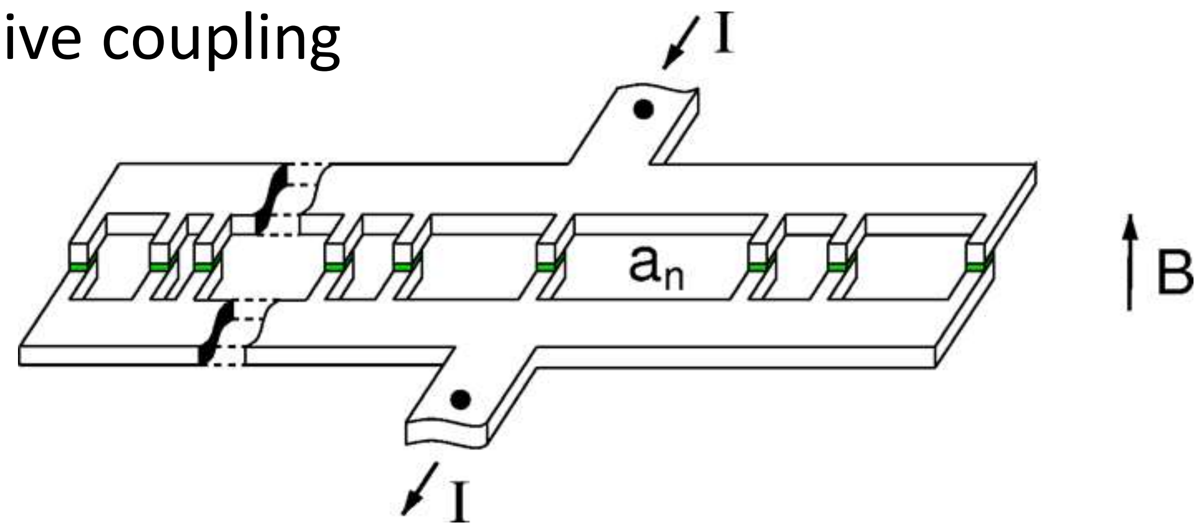
- increased output voltage & dynamic range,
- highly non-linear V-Φ response ▶high sensitivity,
- 2D-SQIF - properties scale N parallel, M series loops

Output voltage	M	maximize
Power gain	M×N	maximize
SNR	M×N	maximize
Spur-free dynamic range	$(M\times N)^{2/3}$	maximize
Output resistance (50 Ω)	M/N	target value

- HTS SQIF fabrication today with more than 10^6 elements,
- SQUAD – SQUID series array with stochastic distribution of inductive coupling
  Drung & Beyer
  SUST 21(9) 095012
  (2008).



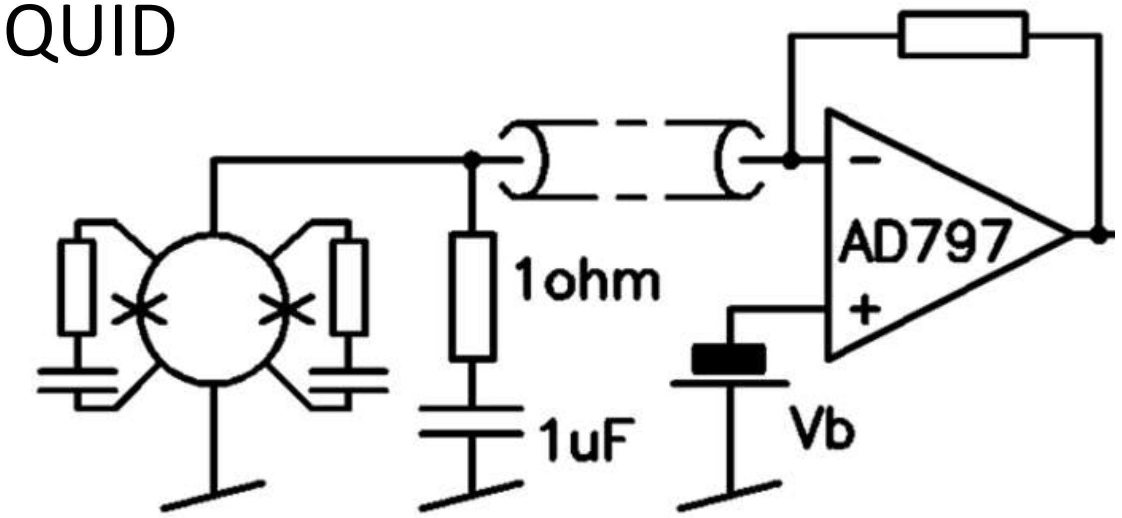
Serial SQIFs = 1D SQUID series array with unconventional loop size distribution



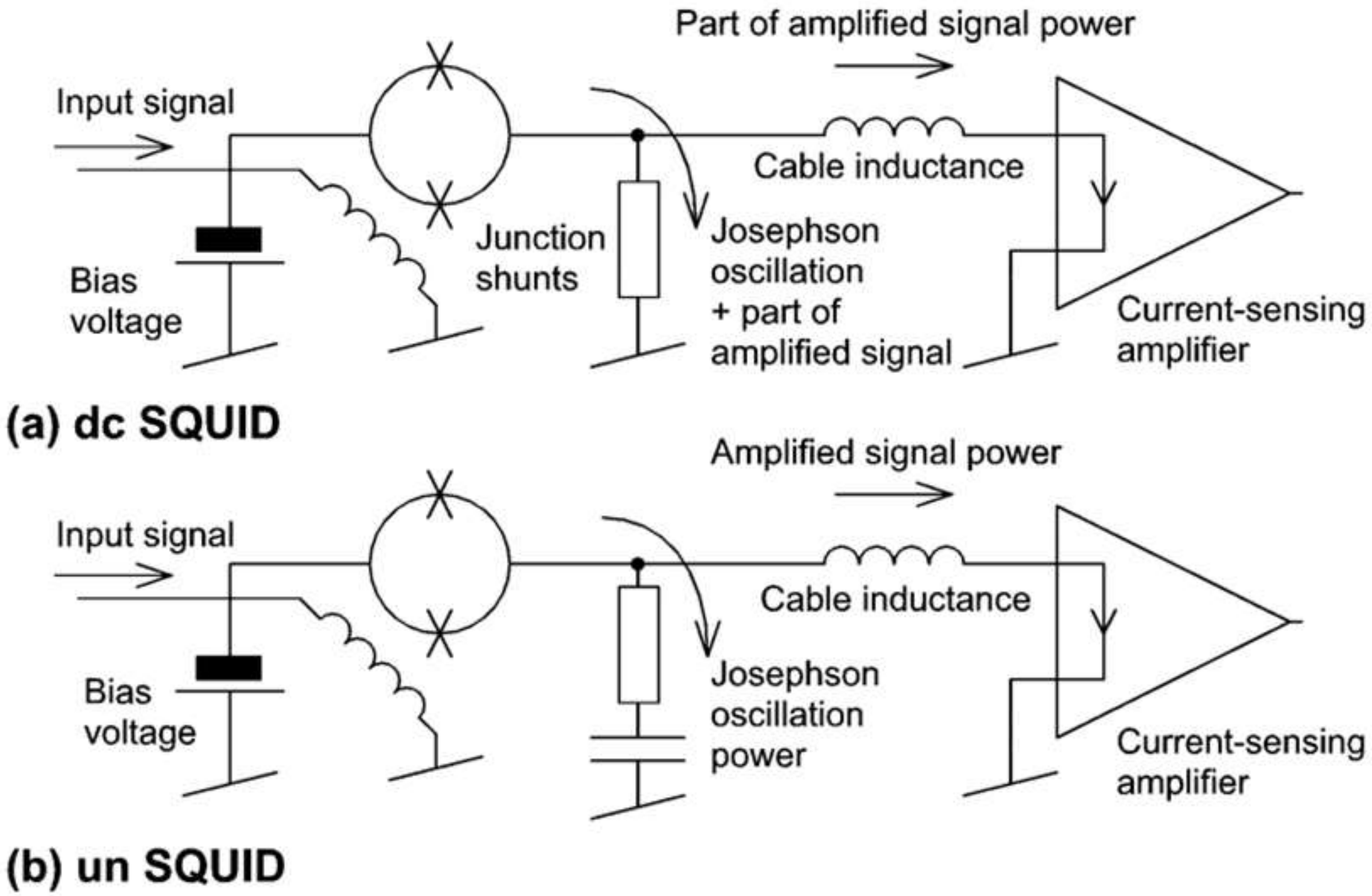
Parallel SQIFs = 1D array of parallel loops with unconventional size distribution

Alternative structures

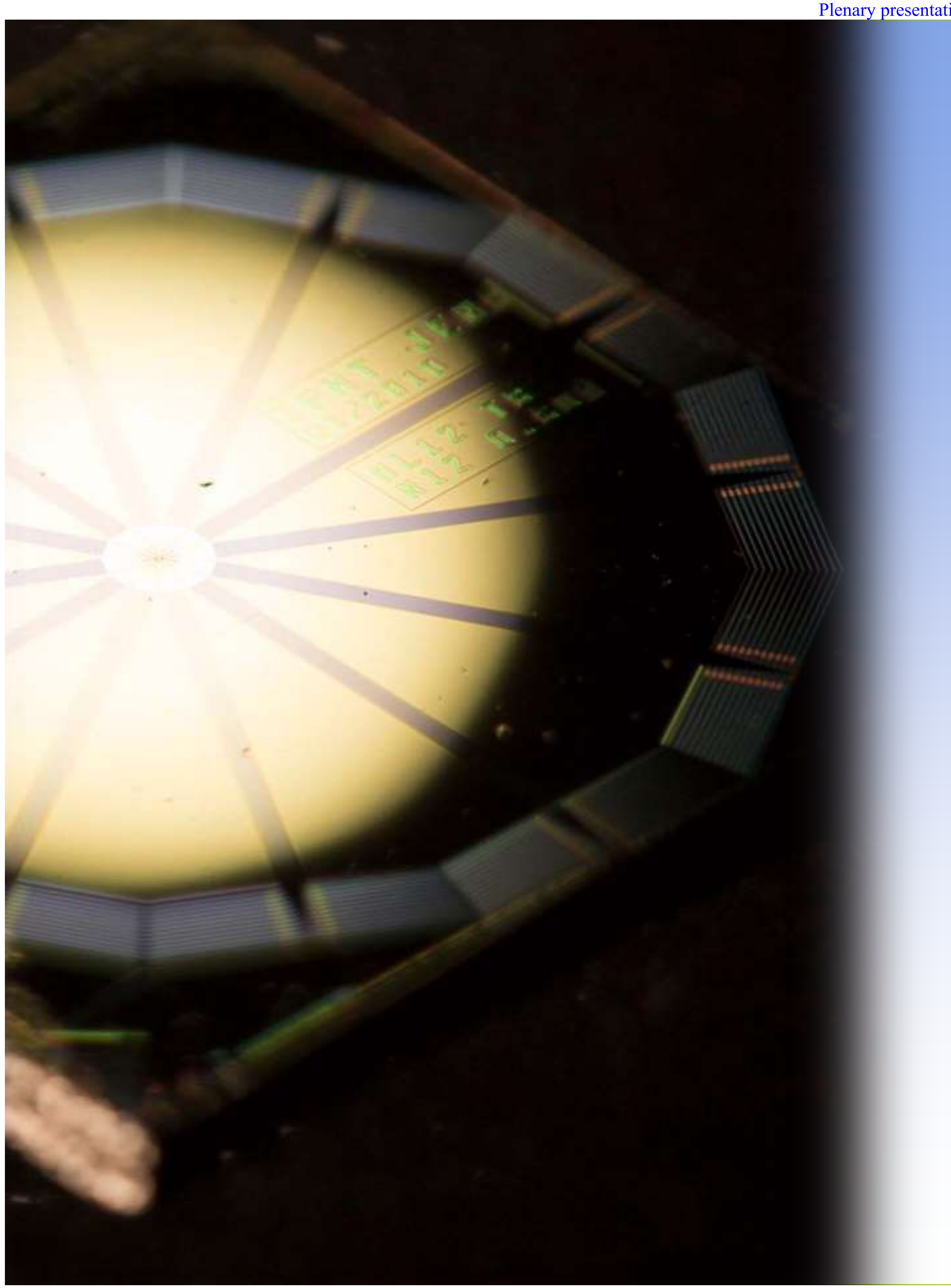
- unSQUID



Kiviranta et al. IEEE Trans. Appl. Supercond. 13(2) 614 (2003)

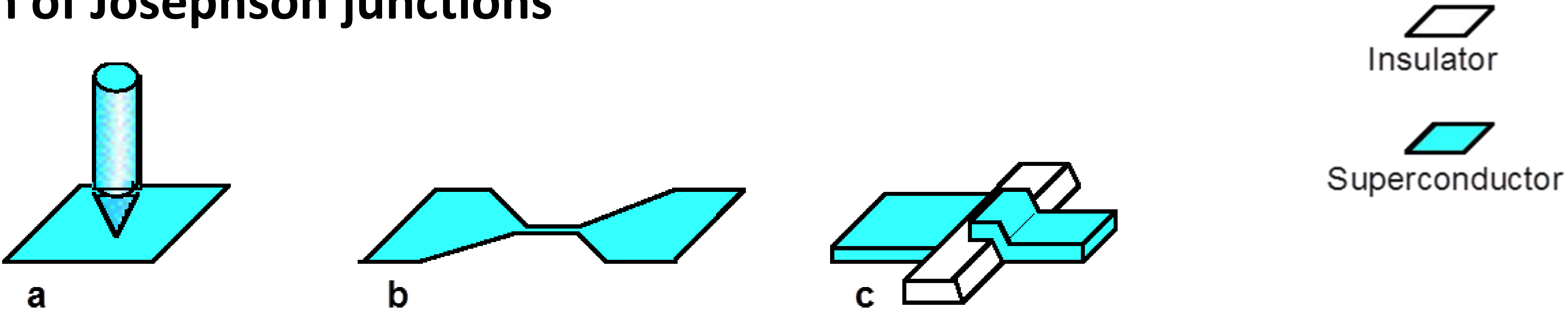


- double loop SQUIDs (often in multi-loop SQUIDs - Drung),
- single resistor shunting (SIEMENS),
- …

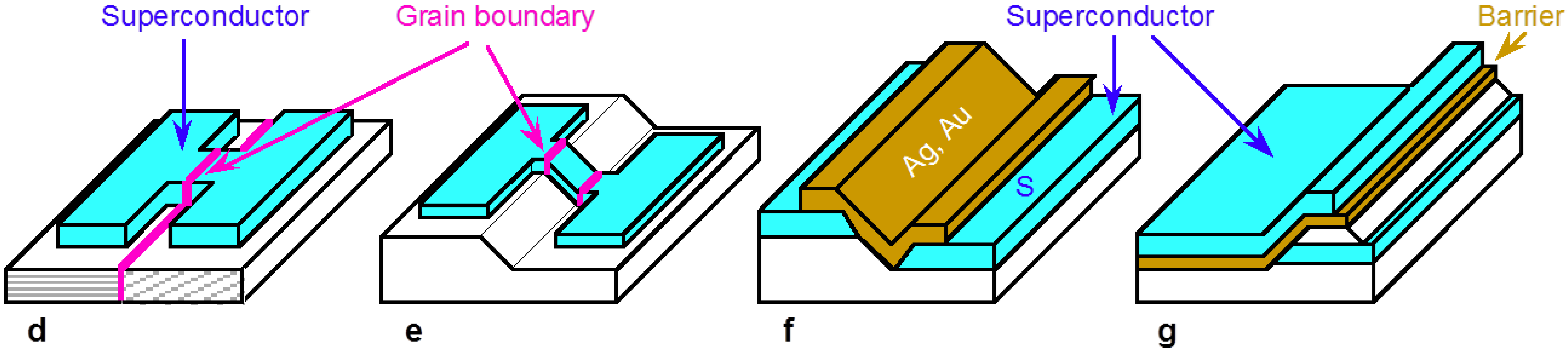


Technology

Fabrication of Josephson junctions



(a) point contact (b) microbridge (c) thin-film tunnel junction



(d) bicrystal, (e) step-edge, (f) step barrier, (g) ramp edge

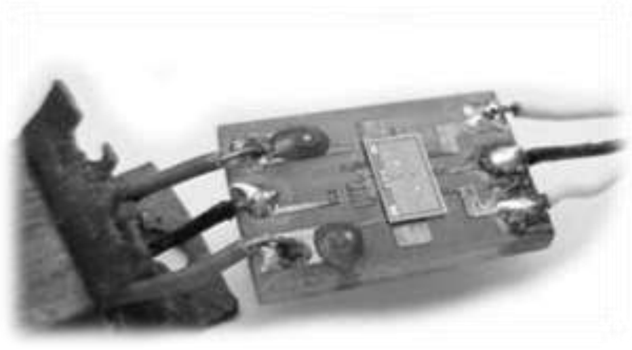
With courtesy of B. Fagaly

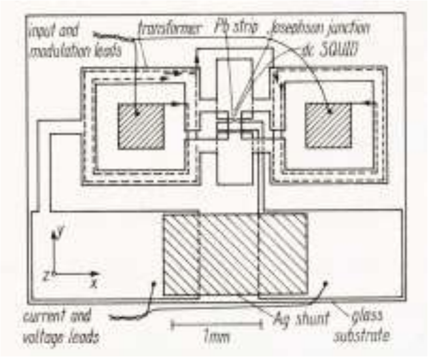
Evolution

~1965 Zimmermann type SQUIDs, bulk niobium

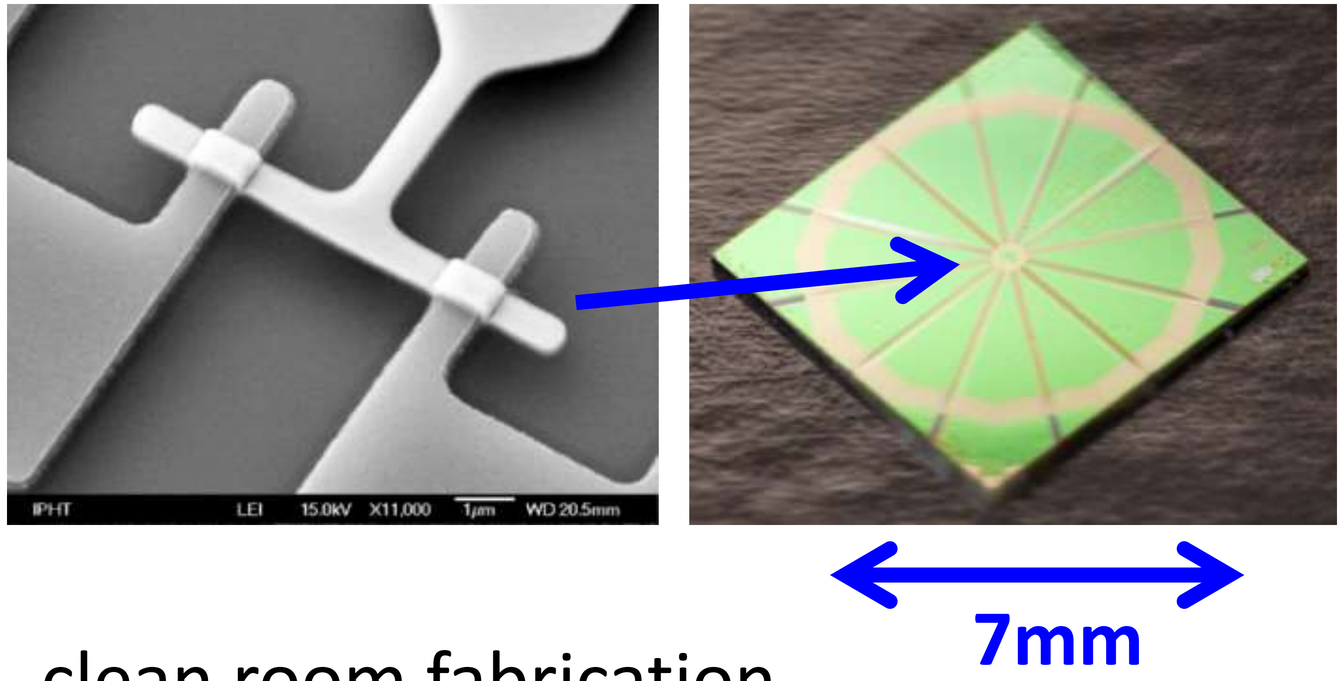
~1975 Bulk-thin film hybrids

1977 J. Richter, K. Blüthner, H.-J. Köhler, G. Albrecht
first fully on-chip integrated thin-film DC SQUID in Jena





Todays LTS SQUIDs…



- clean room fabrication,
- full wafer-scale & multi-layer process,
- standard photolithography down to sub-µm (nm) sized junctions,
- with suitable readout electronics:
  - flux noise $< 1\,\mu\Phi_0/\sqrt{Hz}$ at $4.2K$ and $> 1Hz$,
  - quantum limited at mK temperatures.

SQUID types by material

- Low temperature superconductors (LTS, e.g. liquid Helium cooled):
  - niobium so far best material ($T_C \approx 9.2K$, for $4.2K$ at $\approx \frac{1}{2} T_C$)
  - only LTS device commercially available,
  - fabrication with reliable parameters ▶ standardization measures on the way,
  - lab demonstration of NbN devices ($T_C \approx 20K$ e.g. Villigier),
  - carbon nanotube based SQUIDs at mK (Cleuziou et al. Nat. Nanotech. 1 53 (2006)),
- High temperature superconductors (HTS, e.g. liquid Nitrogen cooled or cryo-cooler implemented):
  - YBCO has $T_C \approx 93K$ (for $77K$ at $\approx \frac{5}{6} T_C$),
  - much larger parameter fluctuations,
  - commercially available devices only based on YBCO,
  - BSCCO ($T_C \approx 110K$) and lab demo of Thallium HTS SQUIDs ($T_C \approx 125K$),
  - MgB_2 (Brinkman et al. APL 79 2420 (2001))
    not yet available but may be in future.

SQUID suppliers and manufacturers

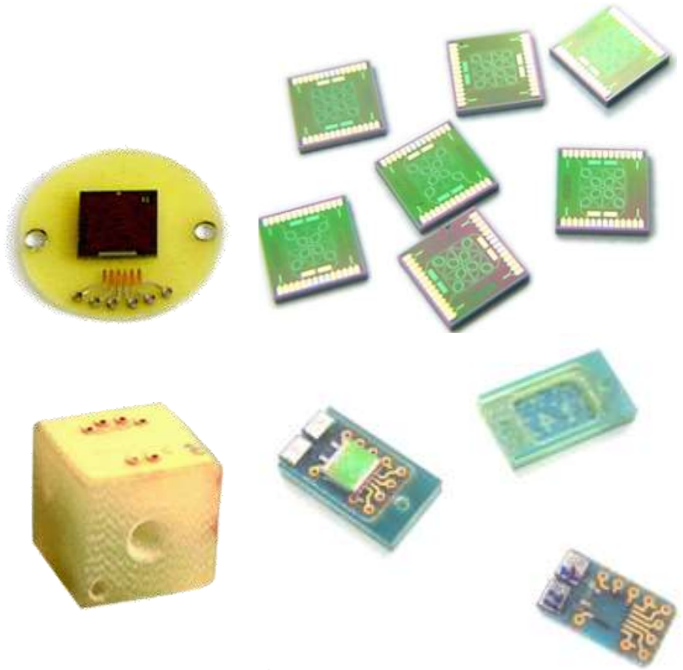
- Jülicher SQUID GmbH (Germany)
- Magnicon GmbH (Germany)
- Quantum Design (USA)
- Starcryo Ltd. (USA)
- Supracon AG (Germany)
- Tristan Technologies (USA)

- AIST (Japan)
- Chalmers Uni (Sweden)
- CSIRO (Australia)
- KRISS (Korea)
- PTB (Germany)
- Leibniz-IPHT (Germany)
- National Taiwan Uni

- NIST (USA)
- SIMIT (China)
- Sustera (Japan)
- Thales (France)
- UC Riverside (USA)
- VTT (Finnland)

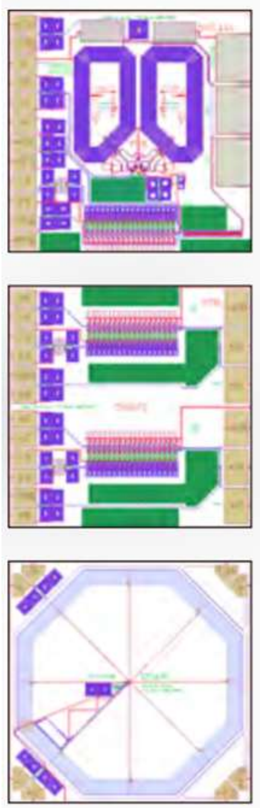
- *MIT, HYPRESS, SEE QC…*

and many more
(sorry and please let me know if I forgot you…)



Example LTS SQUIDs
Leibniz-IPHT / Supracon AG

Example Starcryo SQUIDs



Example Magnicon SQUIDs

Example HTS SQUIDs
FZ Jülich

LTS vs. HTS SQUIDs

- LTS isotropic, $\xi \sim 300 \text{Å}$; HTS anisotropic $\xi_{a,b} \sim 15 \text{Å}$ and $\xi_c \sim 6 \text{Å}$,
  - crossovers with larger dimensions than coherence length of YBCO in c-direction (MgB$_2$ is isotropic, but smaller: $\xi_{a,b} \sim 7 \text{Å}$ and $\xi_c \sim 2.5 \text{Å}$,)
    ▶ HTS crossovers with good performance have not been successfully fabricated,
- LTS metallic, malleable; HTS ceramic ▶ LTS technology mature
  - *multi-layer vs. single/dual superconducting layers technology* for LTS vs. HTS,
  - LTS can be wound in coils; HTS cannot,
  - LTS coils can be remote from the SQUID sensor,
  - HTS coils are often implemented adjacent to the SQUID,
- LTS coils can be operated in fields up to H$_c$ ($9T$ with NbTi, $20T$ with Nb$_3$Sn),
- HTS device performance often degrades in “non-zero” magnetic field amplitudes
  - changing working parameters (I_c, R_N, $I_c \cdot R_N$, V_{pp}),
  - higher white ($\propto \sqrt{H}$) and (more dramatic) low frequency noise,
  - reduced slew rate,
  - some older devices hysteretic in ac fields (μT-amplitude).

LTS vs. HTS SQUID technology continued…

D. Drung, Review on SQUIDs , KRYO 2014

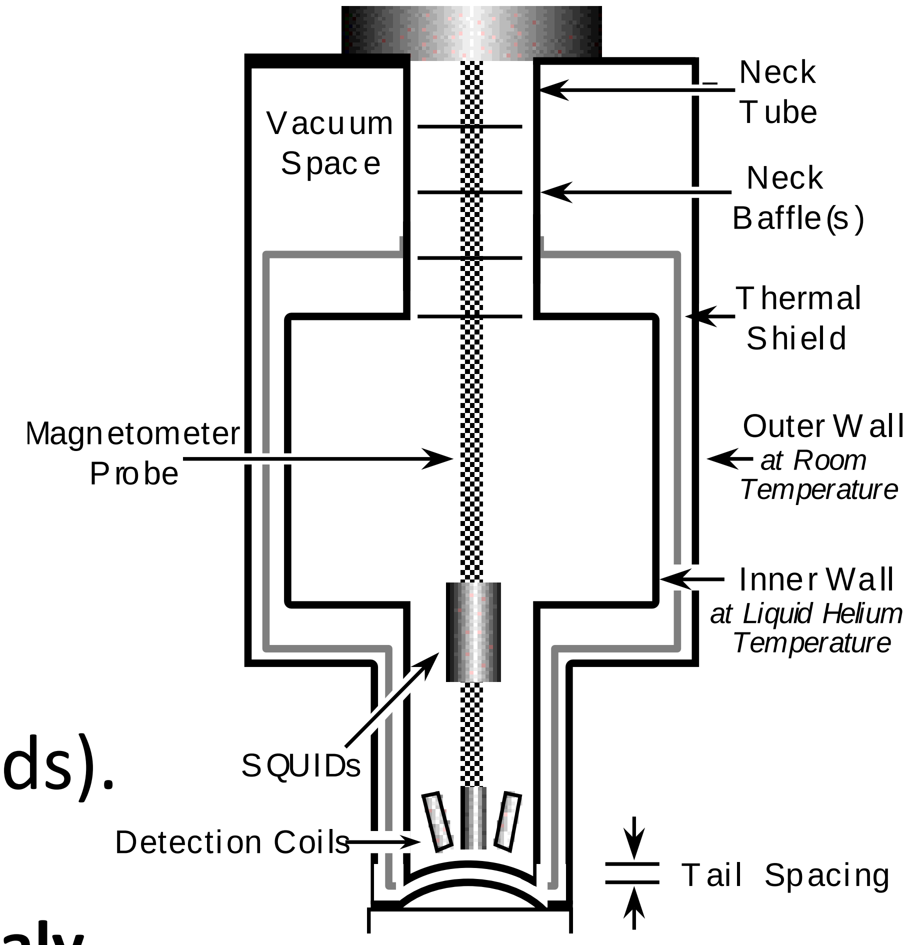
Parameter	LTS SQUID	HTS SQUID
Noise	Very low (++)	Low (+)
Fabrication costs per chip	Low (+)	Very high (--)
Reliability / producibility	Very high (++)	Low (-), eg. JJ degradation
Design flexibility	Very high (++)	Low (-)
Cooling costs & time	Very high (--)	High (-)

Cooling is still the main drawback of SQUID sensors!

- HTS is more acceptable; more simple cooling at lower cost,
- cryogen-free cooling will enable many applications,
- cryogenics accepted when performance required
  (CT or MRI maschines; see application lectures).

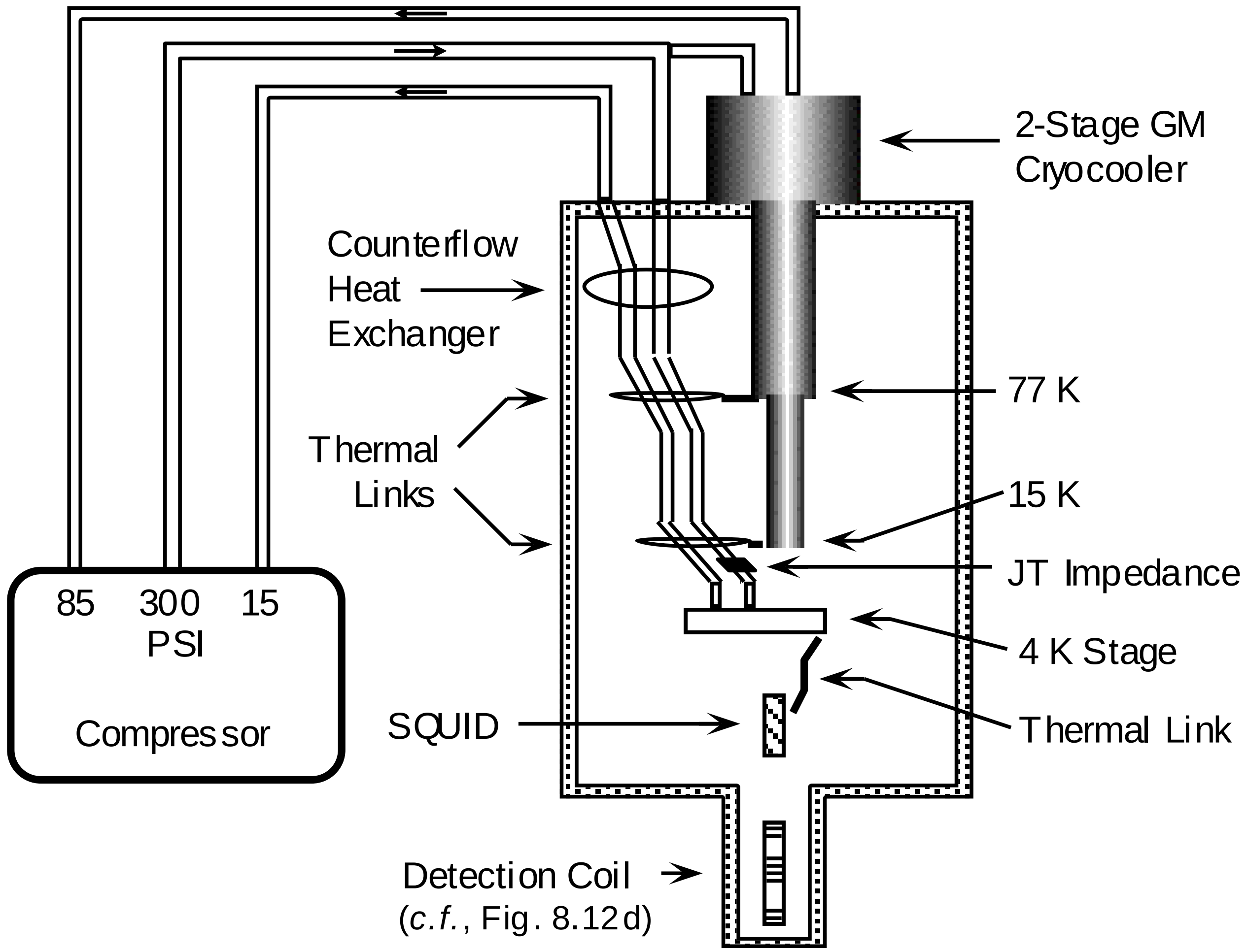
Cooling variants: Dewar vs. Cryo cooler

- consumption of cryogenic liquids
  - ▶ costs and availability
- shielding: magnetic and EM noise (metallic vs. magnetic transparent),
- warm-to-cold distances (tail gap),
- dewar vs. closed cycle operation,
- only a few suppliers,
- adds significantly to instruments costs,
- servicing (e.g. vacuum) and reliability,
- safety (handling of liquids).



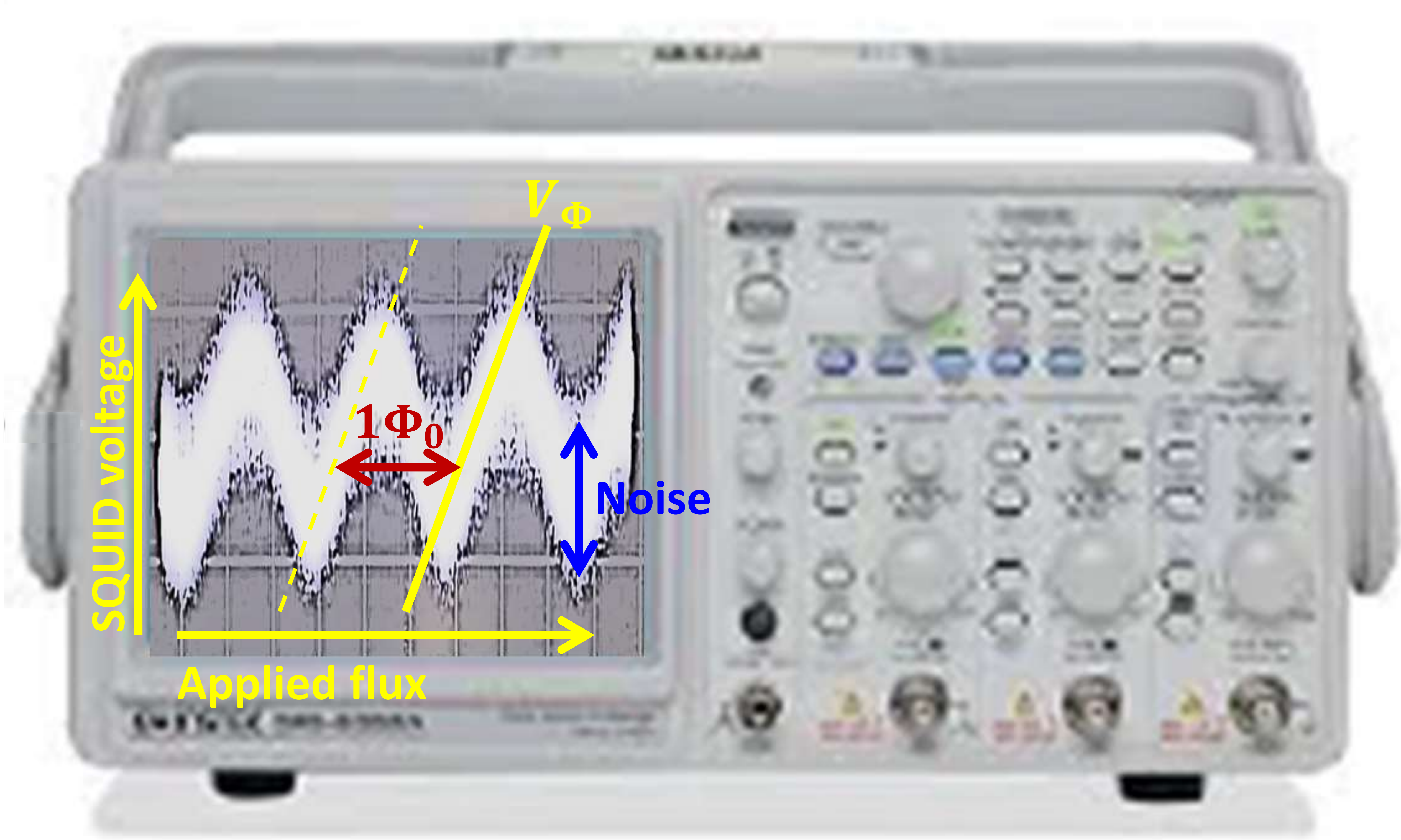
Pictures with courtesy of B. Fagaly

- standard for HTS and more coming to LTS,
- cool down time,
- shielding,
- reliability / safety.

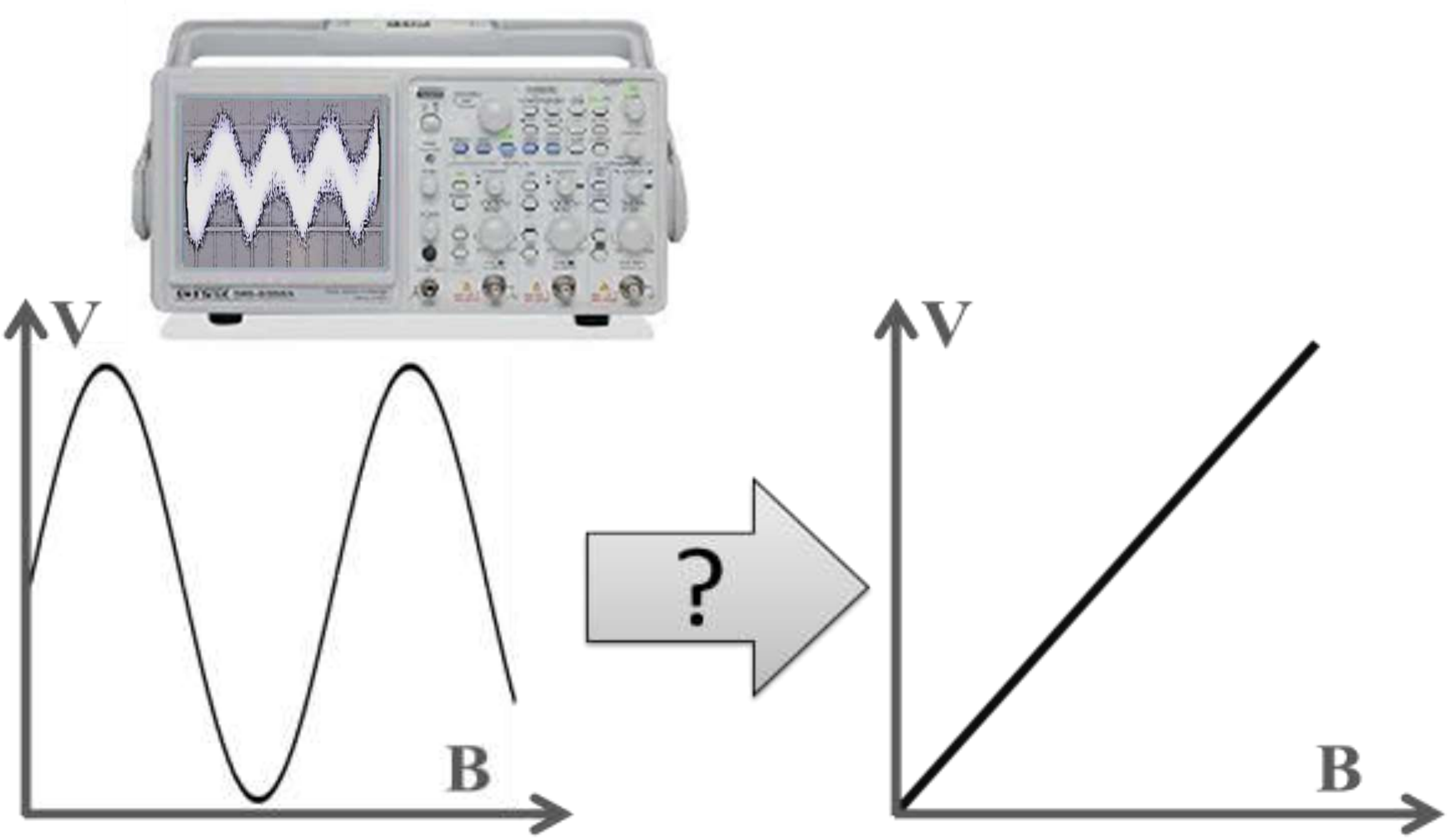


Electronics and noise

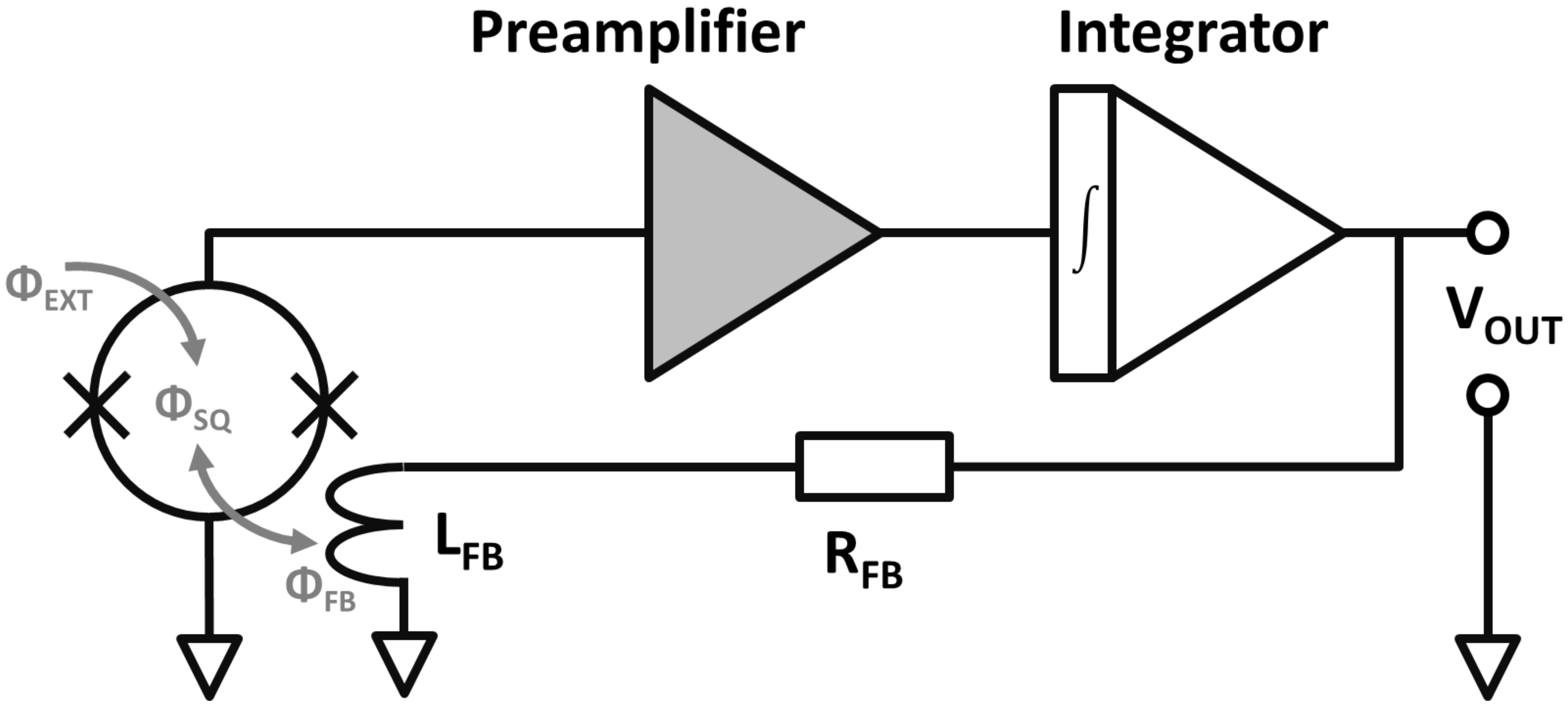
What do you encounter by measuring a SQUID signal?



Question: how to linearize SQUID characteristics?



General scheme – Flux locked loop (FLL) circuit

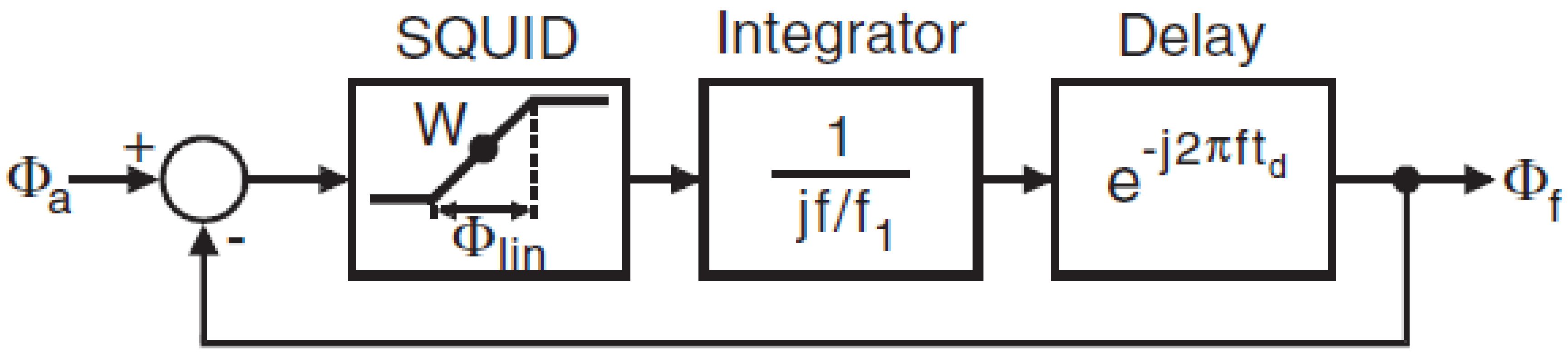


$$S_{\Phi eff}(f) = S_{\Phi}(f) + \left[S_{V,AMP}(f) + S_{I,AMP}(f) \cdot R_{DYN}{}^{2}\right] / V_{\Phi}{}^{2}$$

Example:	SQUID	$1\,\mu\Phi_0/\sqrt{Hz}$	$50\mu V_{pp}$ ▶ $200\,\mu V/\Phi_0$	$R_{DYN} = 50\Omega$
	electronics	$0.3\,nV/\sqrt{Hz}$	$1\,pA/\sqrt{Hz}$	

➲$1.8\,\mu\Phi_0/\sqrt{Hz}$

Important parameters for SQUID electronics – dynamics



Simplified FLL model

D. Drung, SUST 16, 1320, 2003

- max. output signal: $\Phi_{FB,MAX} = V_{OUT,MAX} \cdot M_{FB}/R_{FB}$,
- bandwidth: $f_{3\mathrm{dB}} = f_{GBP} \cdot G_{SQ} = f_{GBP} \cdot V_{\Phi} \cdot M_{FB}/R_{FB}$

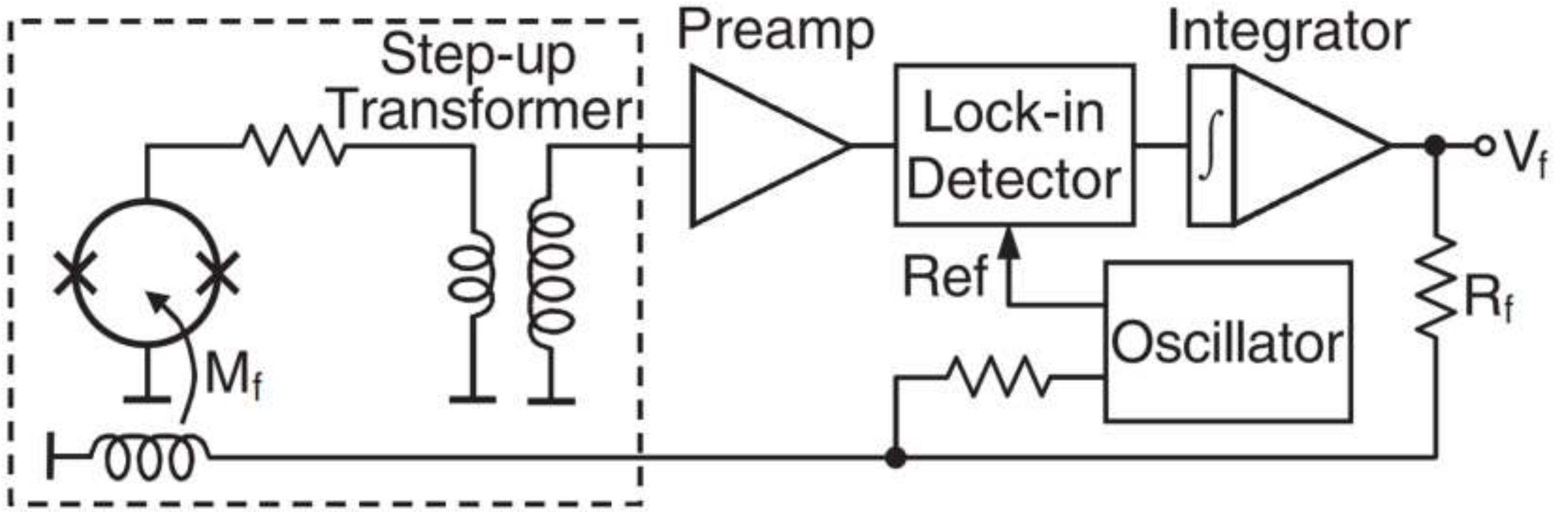
  f_{GBP} forward Gain-Bandwidth-Product of FLL (≈ gain· f_1),

- other bandwidth limitations:
  - bandwidth of FLL ▶ $f_{3\mathrm{dB}} \cong 0.8 f_{3\mathrm{dB,AMP}}$
  - input voltage noise $S_{\mathrm{V,AMP}}$ ▶ $f_{3\mathrm{dB}} \cong 0.0044\,(2 \cdot \delta V)^2 / S_{\mathrm{V,AMP}}$
  - dead-time t_d ▶ $f_{3\mathrm{dB}} \cong 0.18/t_d$ (5.8 ns/m CAT5e cable)
- slew rate of FLL: $\dot{\Phi}_{MAX} = |\partial\Phi_{FB}/\partial t| = 2\pi f_{GBP} \cdot \delta V \cdot M_{FB}/R_{FB}$

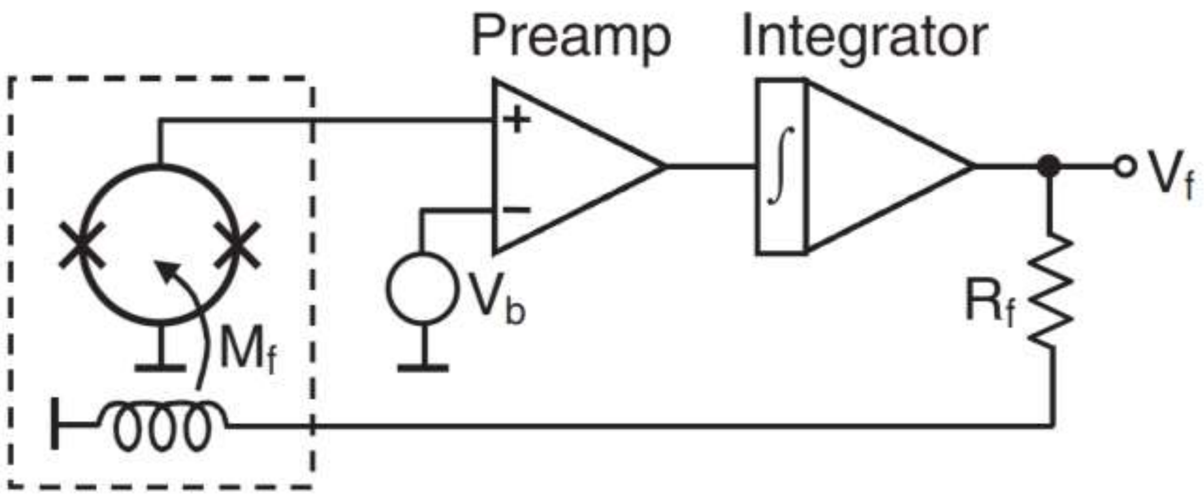
  and thus, $\dot{\mathrm{B}}_{MAX} = \dot{\Phi}_{MAX}/A_{eff}$

Analogue FLLs

- ***flux modulated electronics***
  - 1st implementation: Forgacs & Warnick Rev. Sci. Instrum. 38 214 (1967),



- ***directly coupled electronics***
  - often use bipolar, JFET or SiGe transistors,
  - cryogenic amplifiers:
    Mück et al. Rev. Sci Instr. 76 074701 (2005),
    Robinson et al. Rev. Sci Instr. 75 3169 (2004),
    Drung et al. (*300MHz*) IEEE Trans. Magn. 17(2) 699 (2007),
    Kiviranta et al. SUST 19 1297 (2006),

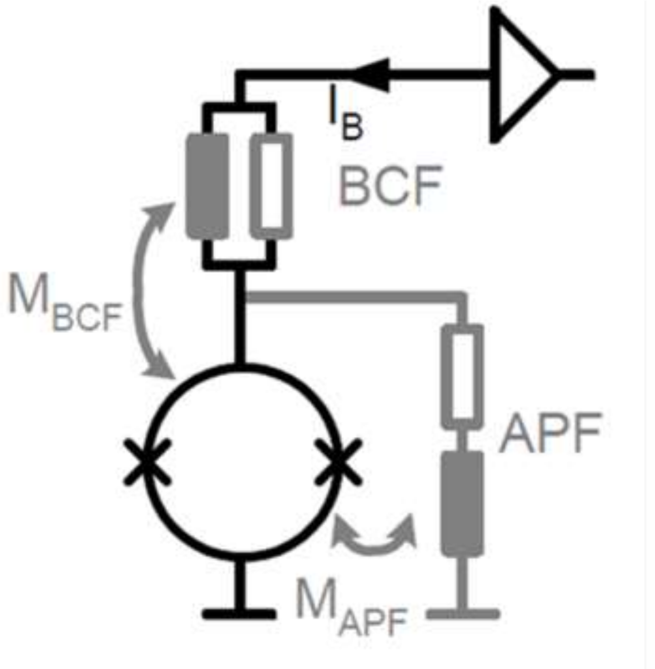


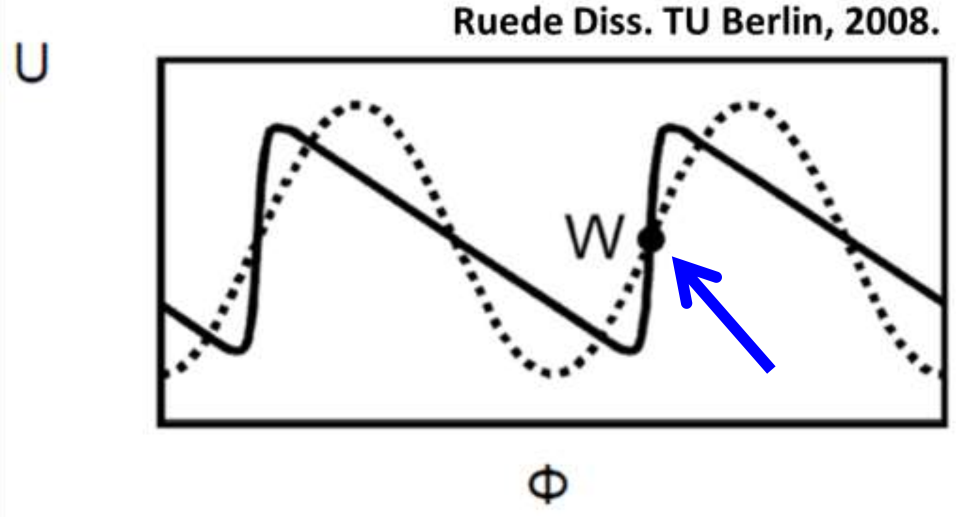
Drung et al. SUST 16 1320 (2003)

- **system performance limits set by FLL:** (e.g. by Supracon AG):
  - slew rate $\approx 30mT/sec$,
  - bandwidth $\approx 8MHz$,
    dynamic range $\approx \mathbf{165dB}$ $[\boldsymbol{DNR = 20log_{10}(B_{max}/B_{noise})}]$
  - ***adds on to sensor noise floor*** (e.g. < 10 vs. $20\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ for 2.5mm multi-loop magnetometer),
  - system noise often limited by ***digitizers noise (24bit ADC)*** ▶ digital or hybrid readout schemes.

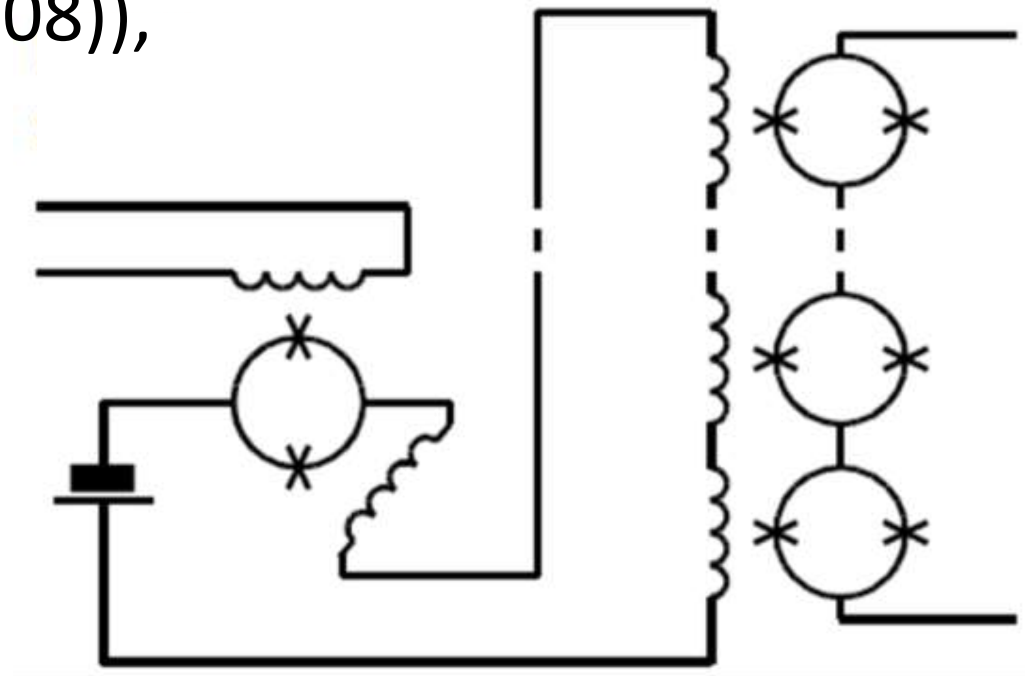
Analogue FLLs, continued

- ***other amplification / feedback schemes:***
  - APF / BCF
    Drung et al. APL 57 406 (1990),

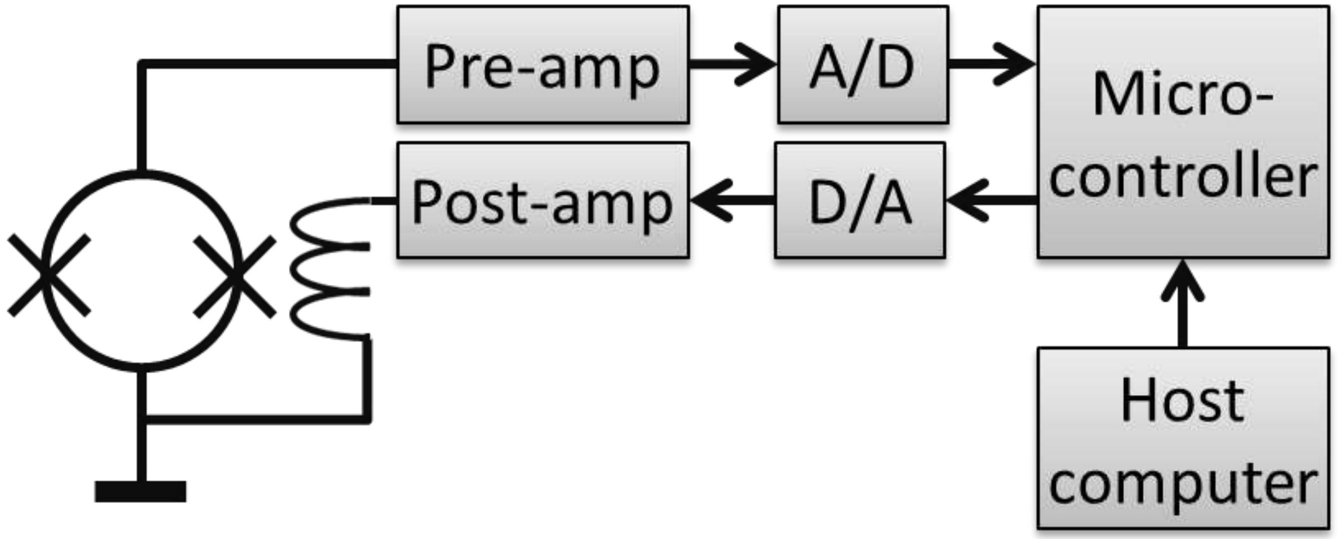



Ruede Diss. TU Berlin, 2008.

  - bootstrap circuit Y. Zhang et al. SUST 25(12) 125007 (2012),
  - noise cancellation Seppä et al. IEEE Trans. Magn. 27 2488 (1991),
  - local feedback schemes (e.g. Kiviranta et al. SUST 21(4) (2008)),
  - small signal readout without FLL (e.g. OCF – Drung et al. IEEE Trans. Appl. Supercond.19, pp. 772(2009)),
  - SQUID array readout (higher voltage but larger dynamic resistance),
  - SQIF amplified readout (unique single peak).



Digital or flux counting circuits



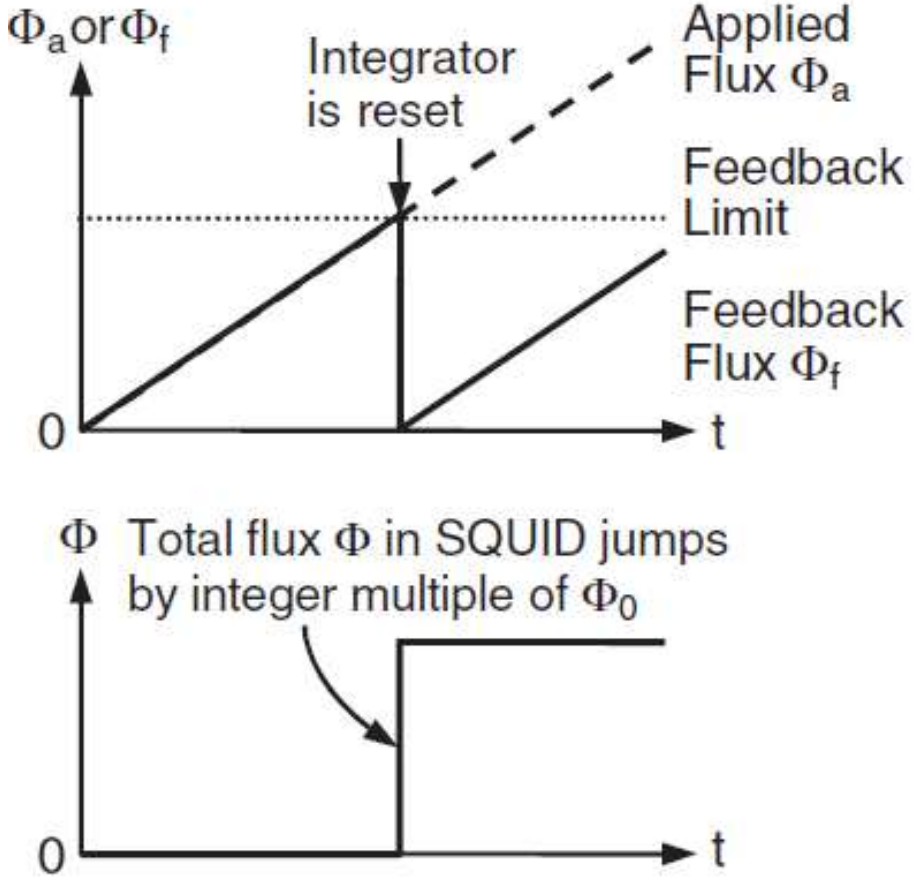
Digital FLLs:

1) Flux counting electronics
McKay et al. Proc. Canadian Conf. on Electrical & Computer Engineering 1090 (1993)
Zimmermann et al. Rev. of Progr. in Quant. NDE 16A 2129 (1997)
Vrba et al. Biomag 96, Springer 138 (2000)
Ludwig et al. IEEE Trans. Appl. Supercond. 11 1122 (2001)

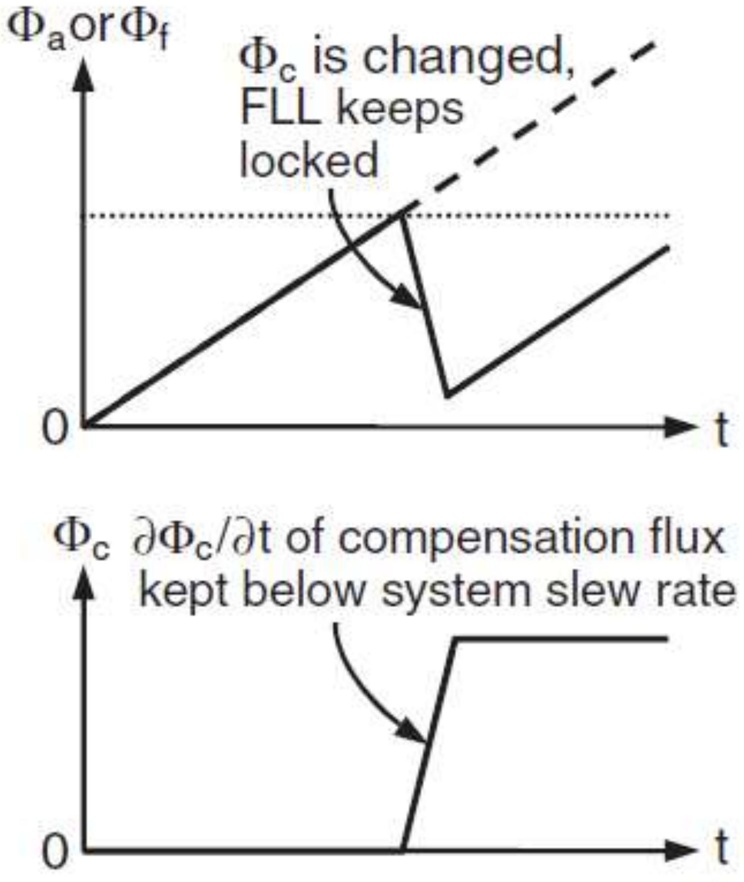
2) Dynamic field compensation (DFC),

3) pure digital FLLs – digital readout of single SQUID, ROS or DROS
Drung et al. (1989), Igarashi et al. (1990), Matz et al. (1991), Eschner et al. (1993), Podt et al. (2001), Myoren et al. (2012)

next step digital SQUIDs...
but this is another talk...



Flux counting electronics



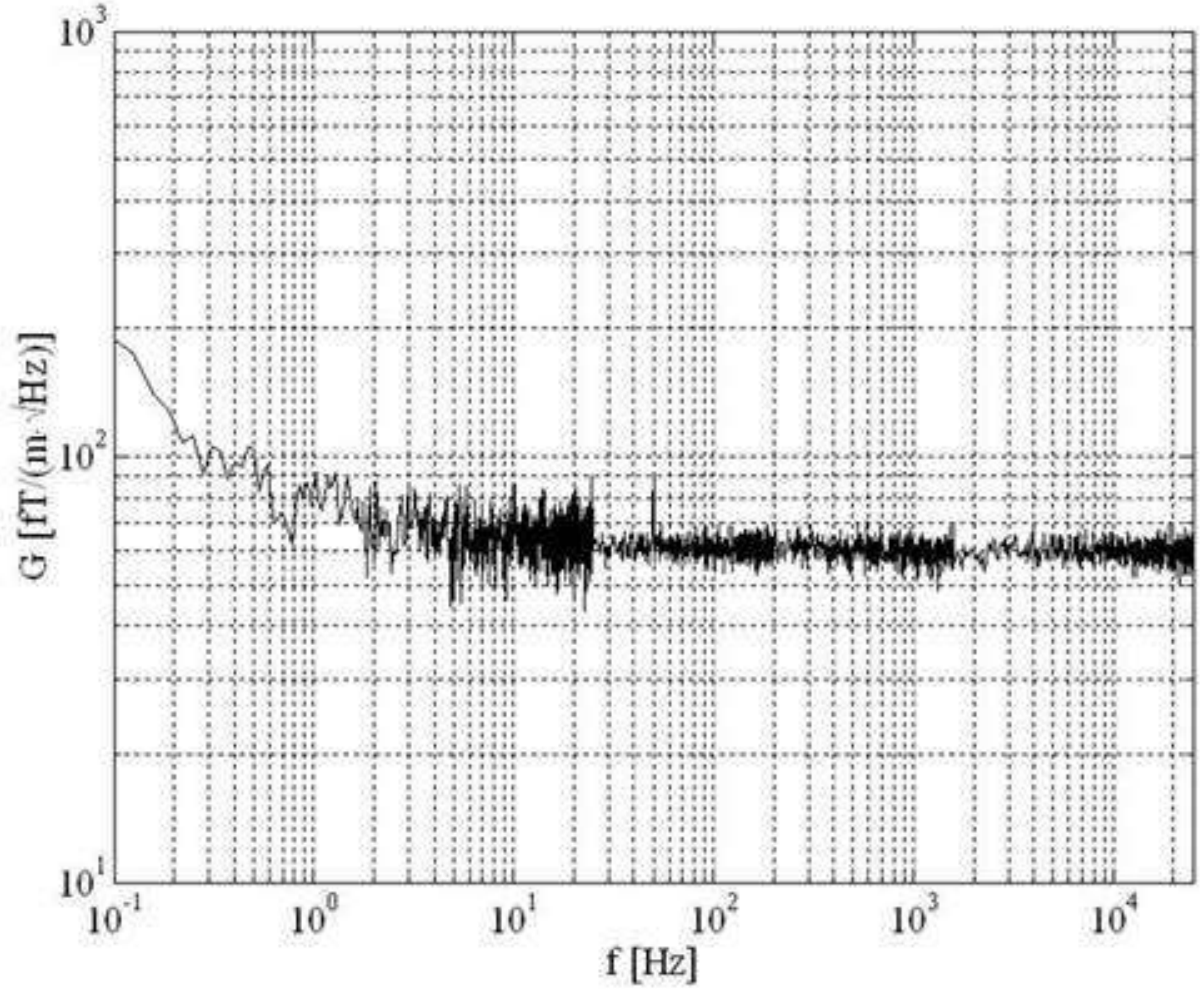
Dynamic field comp.

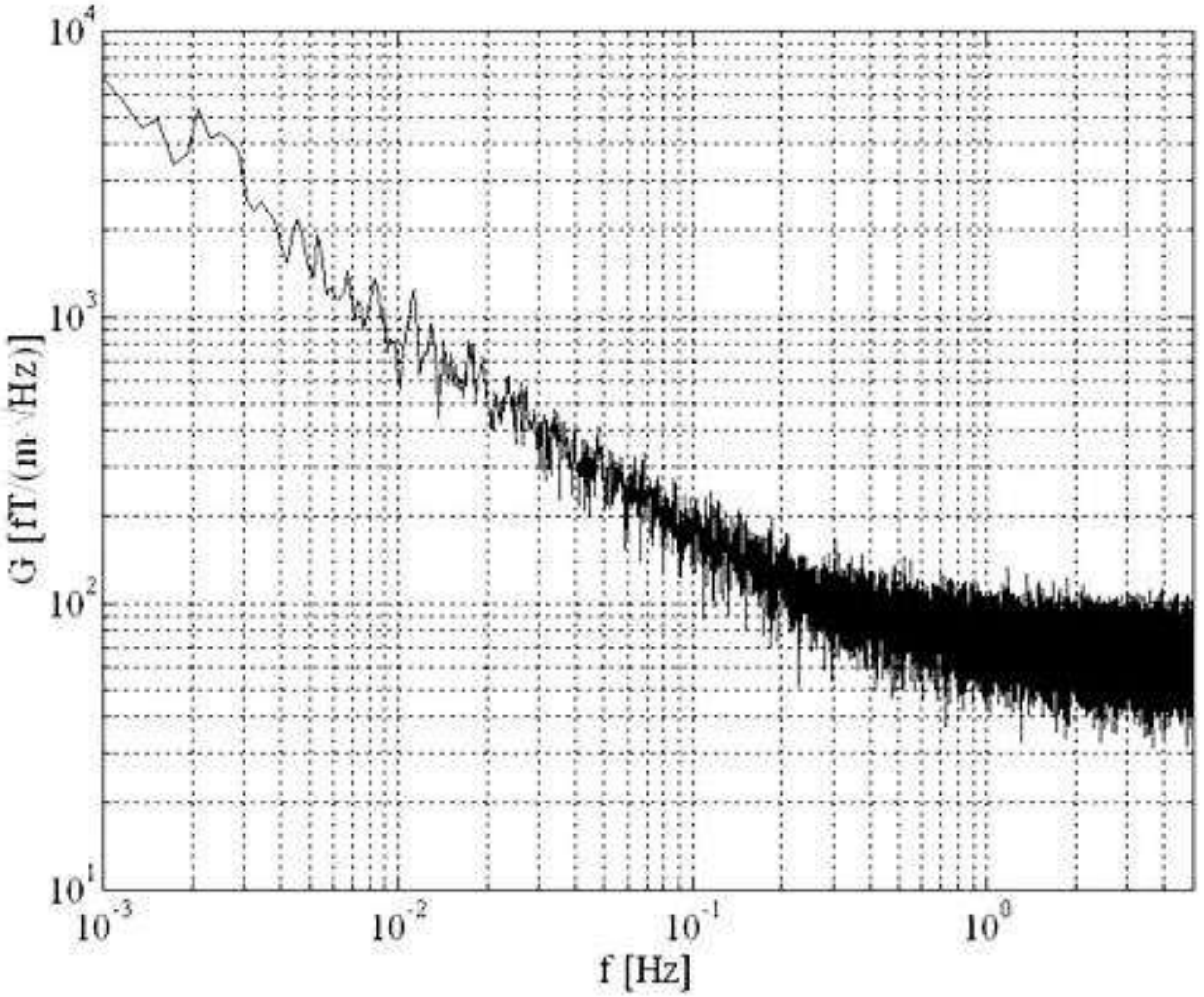
D. Drung et al. SUST 16 1320 (2003)

Other readout schemes

- ROS electronics,
- RF SQUID electronics,
- MHz and GHz detection,
- Flux ramp modulated readout with large dynamic range
  ▶ S. Kempf et al. at this conference.

Noise of SQUIDs

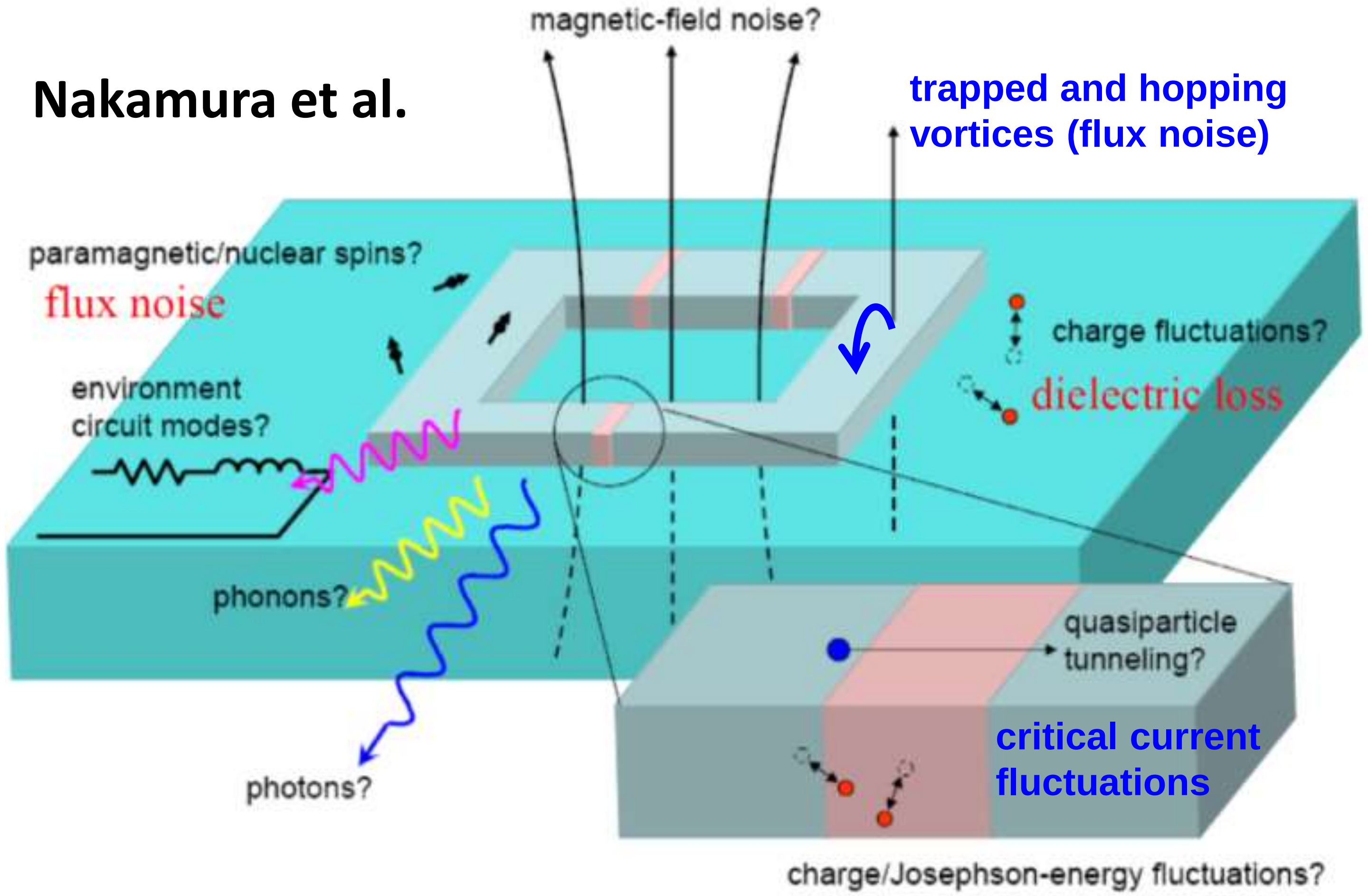




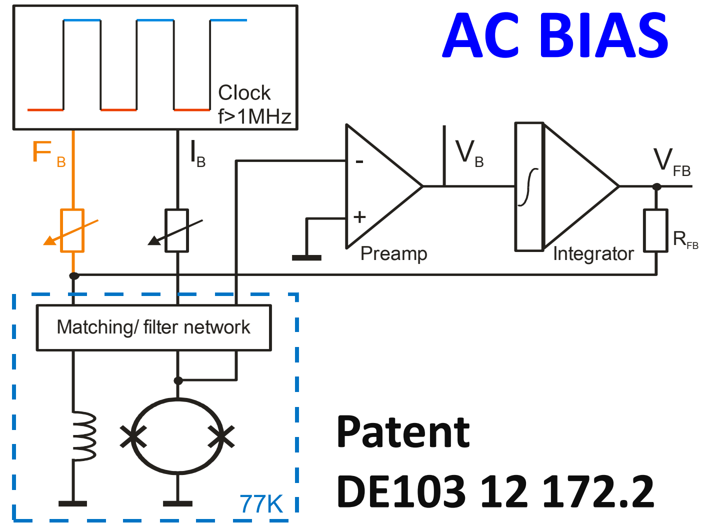
- for optimal case $\beta_L \approx 1$ and $\beta_C \approx 1$, numerical simulations resulted in $\boldsymbol{\varepsilon \approx S_\Phi / 2L_{SQ}}$ $\boldsymbol{\varepsilon \approx 9\, k_B T L_{SQ}/R_0}$ **or** $\boldsymbol{\varepsilon \approx 16 k_B T \sqrt{L_{SQ} C_0}}$ [**Tesche & Clarke J. Low Temp. Phys. 29 pp. 301 (1977)**] for a "bare" SQUID without any parasitic capacitances / resonances in SQUID layout,
- often significant increase of noise $S_\Phi \propto 1/f^{\alpha}$ at low frequencies.

Low frequency noise in SQUIDs

Nakamura et al.

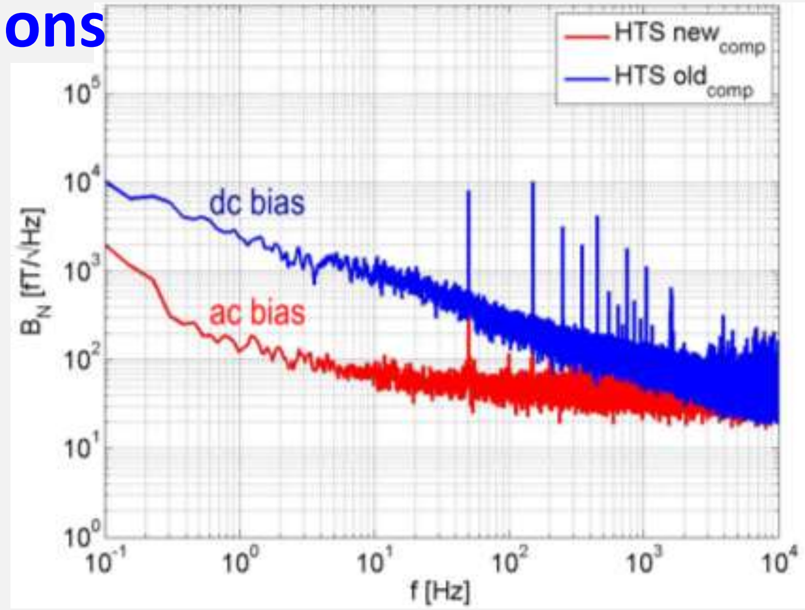


Reduction current fluctuations



AC BIAS

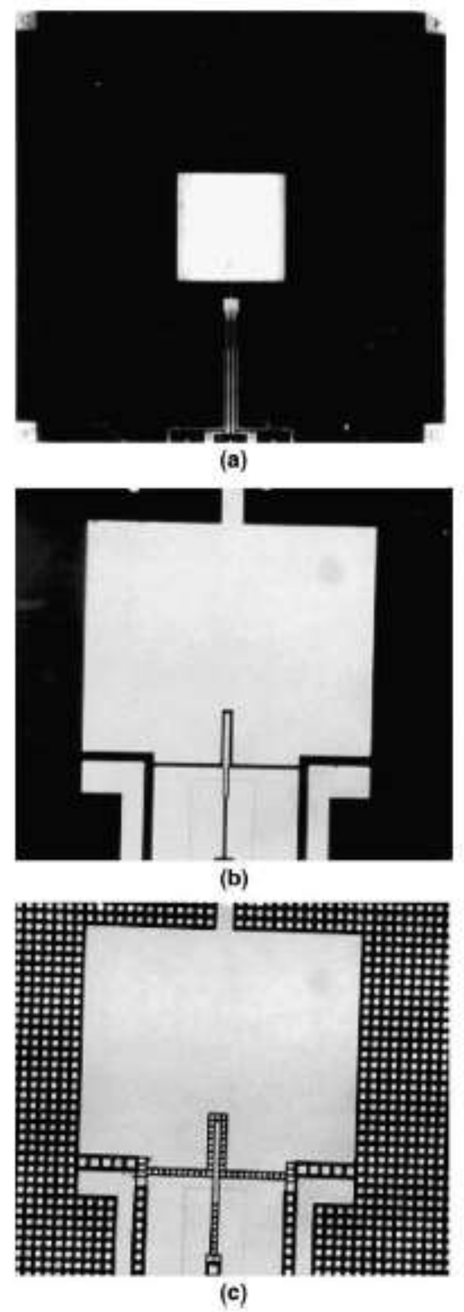
Patent
DE103 12 172.2



Prevent flux hopping

- reduction of width of superconducting wiring $B_C \sim 1/w^2$ **(Stan et. al. PRL 2004, Kuit et al. PRB 2008)**,
- moats - slotted structures,

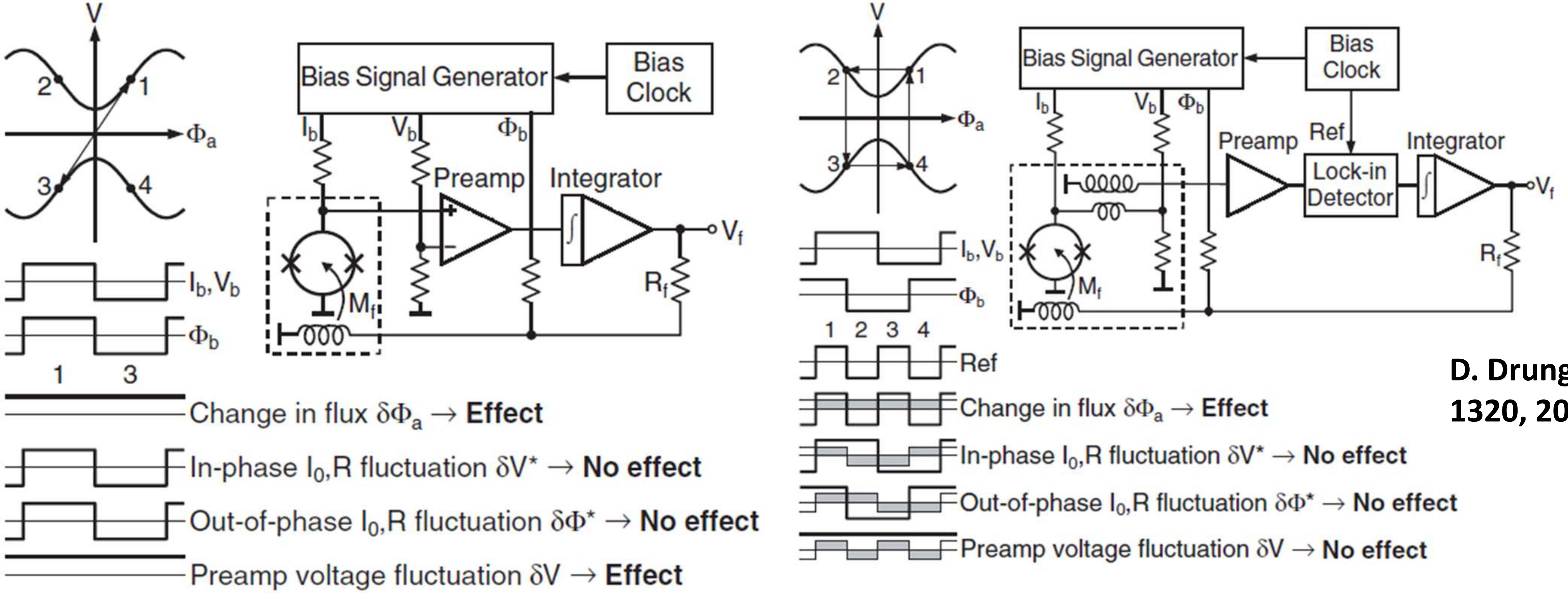
Du et al.
Physica C 400(3)
143 (2004)



- holes or implanted vortex pinning centers,
- nanoparticles as pinning centers.

AC bias techniques

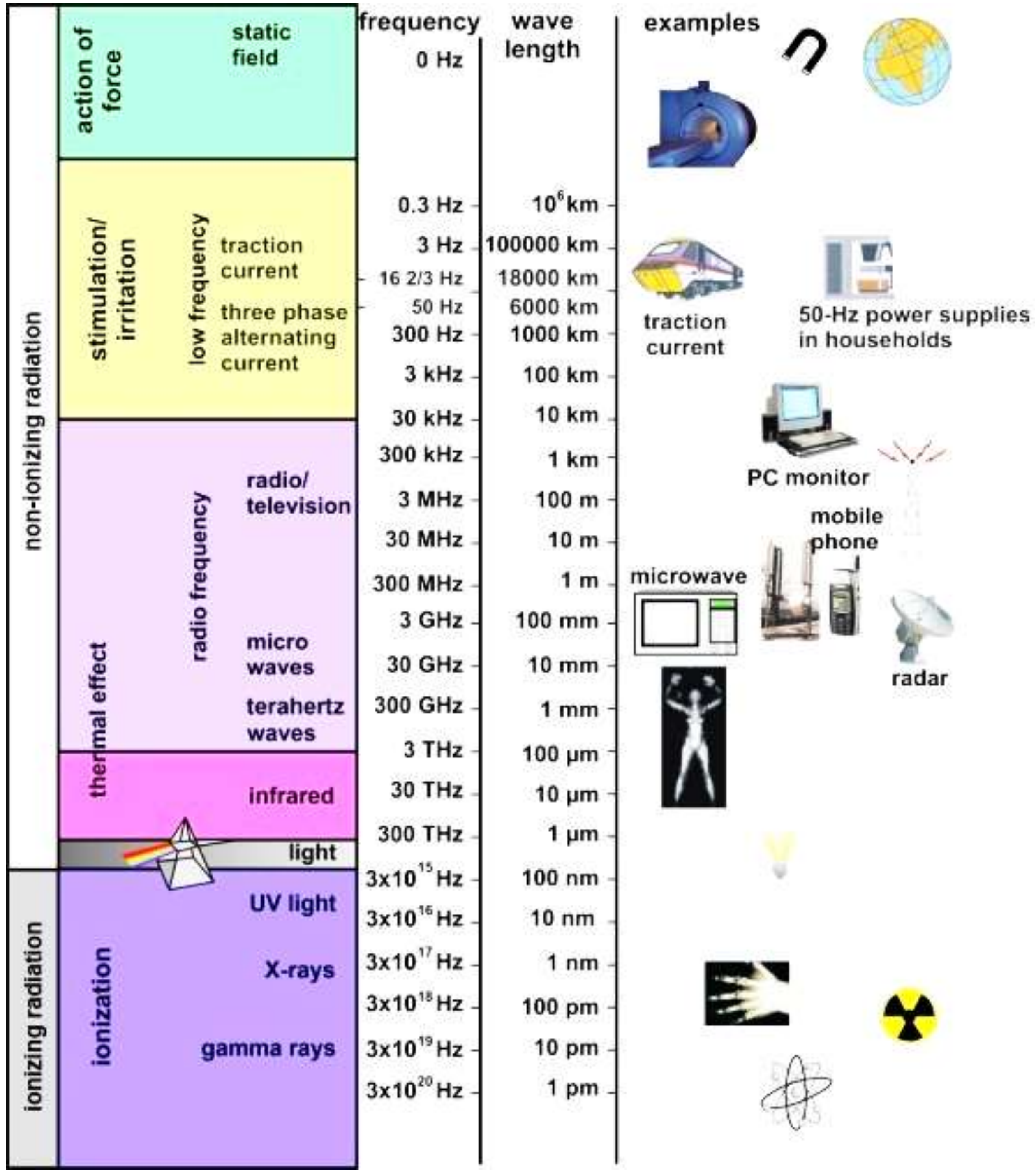
- important in HTS SQUIDs; may be important also for SQUIDs with sub-µm junctions,
- main cause: critical current fluctuations of JJs
  → can be mitigated by bias modulation (often combined with flux modulation),
- another mechanism: real flux noise,
  in patricular at sub-kelvin temperatures; cause not completely understood;
  influence of fabrication and SQUID materials → bias modulation does not help.



D. Drung, SUST 16, 1320, 2003

So, what are SQUIDs good for?

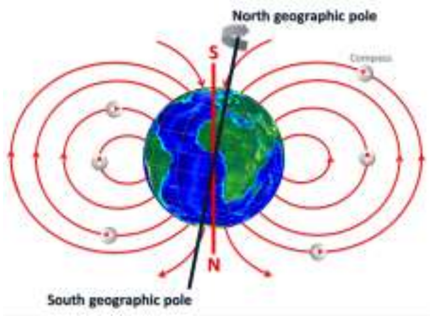
Radiation



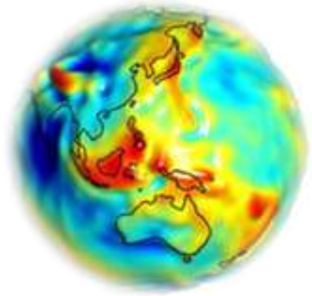
SQUIDs

Particle detection

Current and voltage,
Impedance



Magnetic field and
Gradients (Flux)



Gravity and gravity gradients

Temperature

emerging & enabling technologies

- „noise-free“ preamplifier
- multiplexers
- superconducting electronics

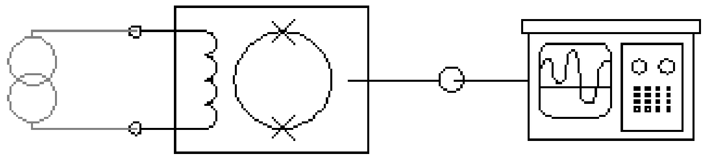
and many more.

Leibniz ipht Leibniz Association jenaphotonics 39

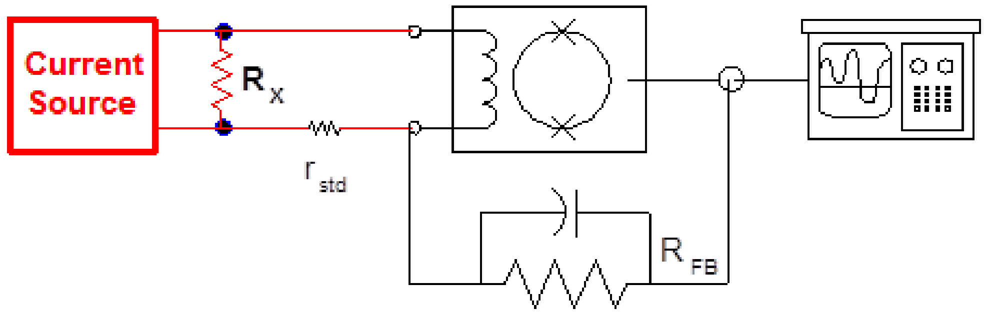
SQUID based Lab instruments

Probe configurations

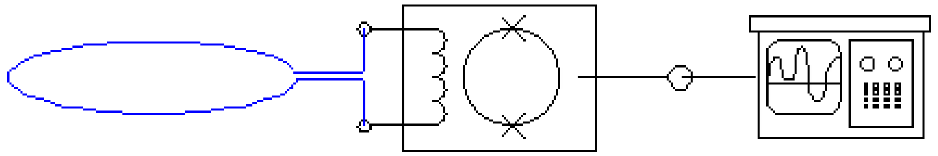
current



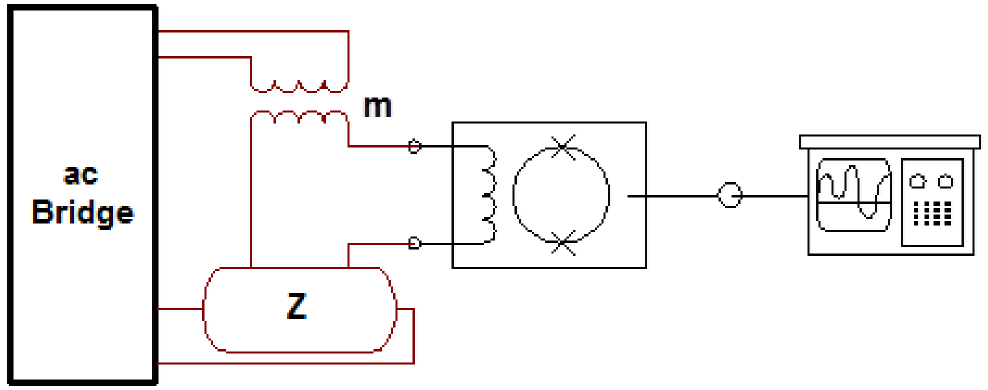
resistance



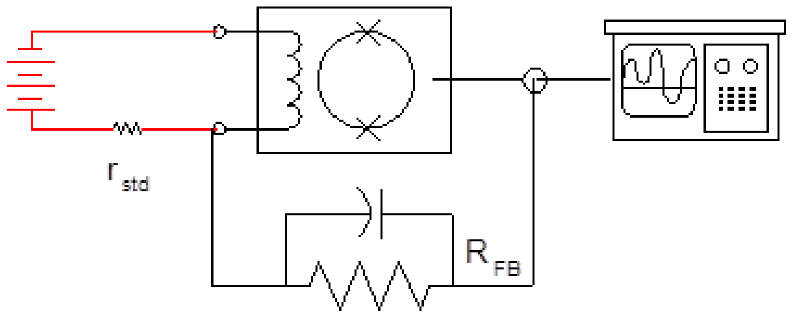
field



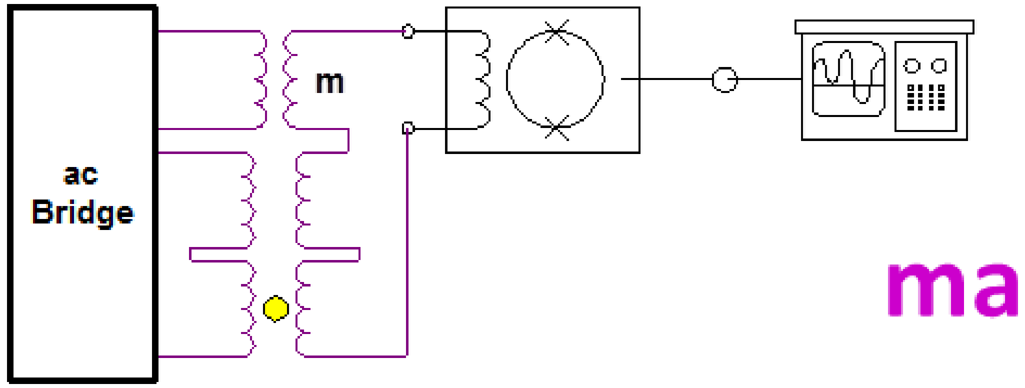
impedance



voltage



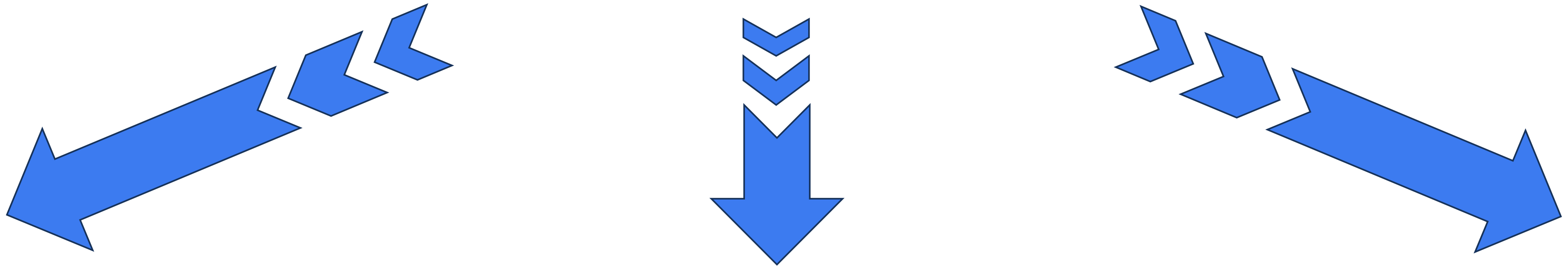
magnetization



Pictures with courtesy of B. Fagaly

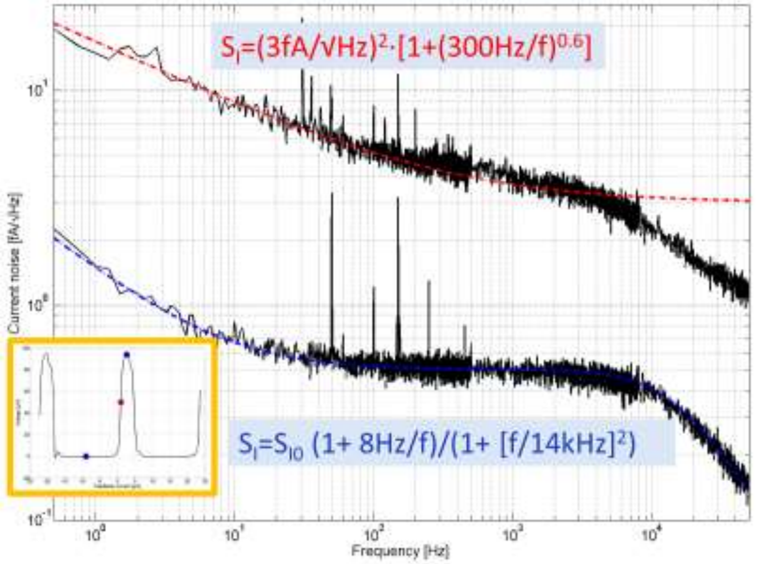
Current sensors and amplifiers

Gradiometric SQUID and signal coupling via integrated thin-film coil



Current sensors

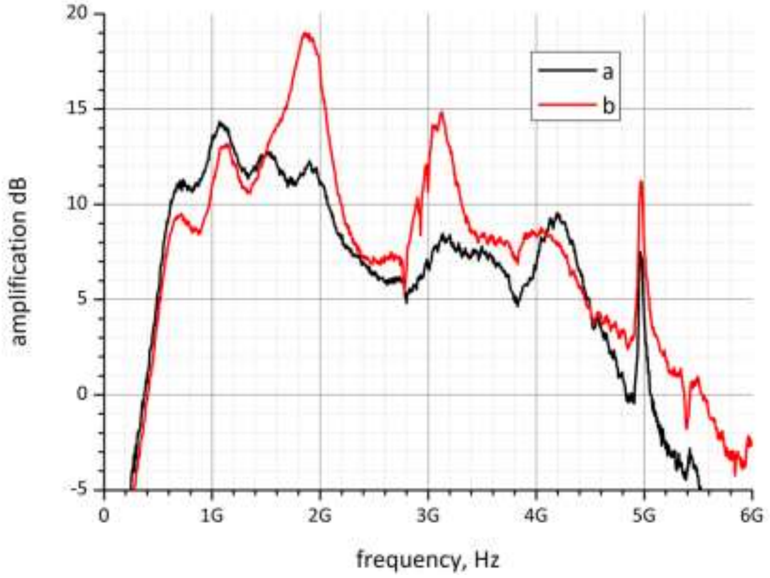
- readout of radiation detectors,
- measurement of beam profiles, etc.,
- $\sqrt{S_I}$ few $fA/\sqrt{Hz}$,…



V. Zakosarenko et al., SUST 25, 2012.

Single SQUID amplifiers

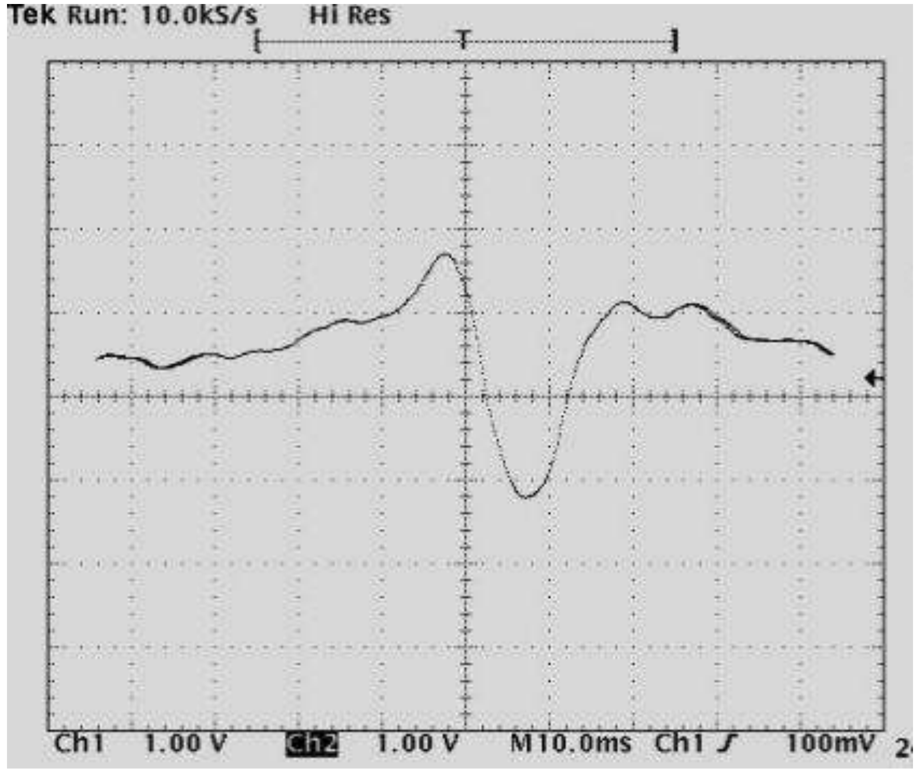
- RF-amplifier - quantum limited sensitivity (e.g. Axion and dark matter research - AMORE), 100 MHz … 10 GHz
- voltmeter, displacement sensors,…



Matlashov et al. Cryogenics 91 125 (2018)

SQUID amplifiers

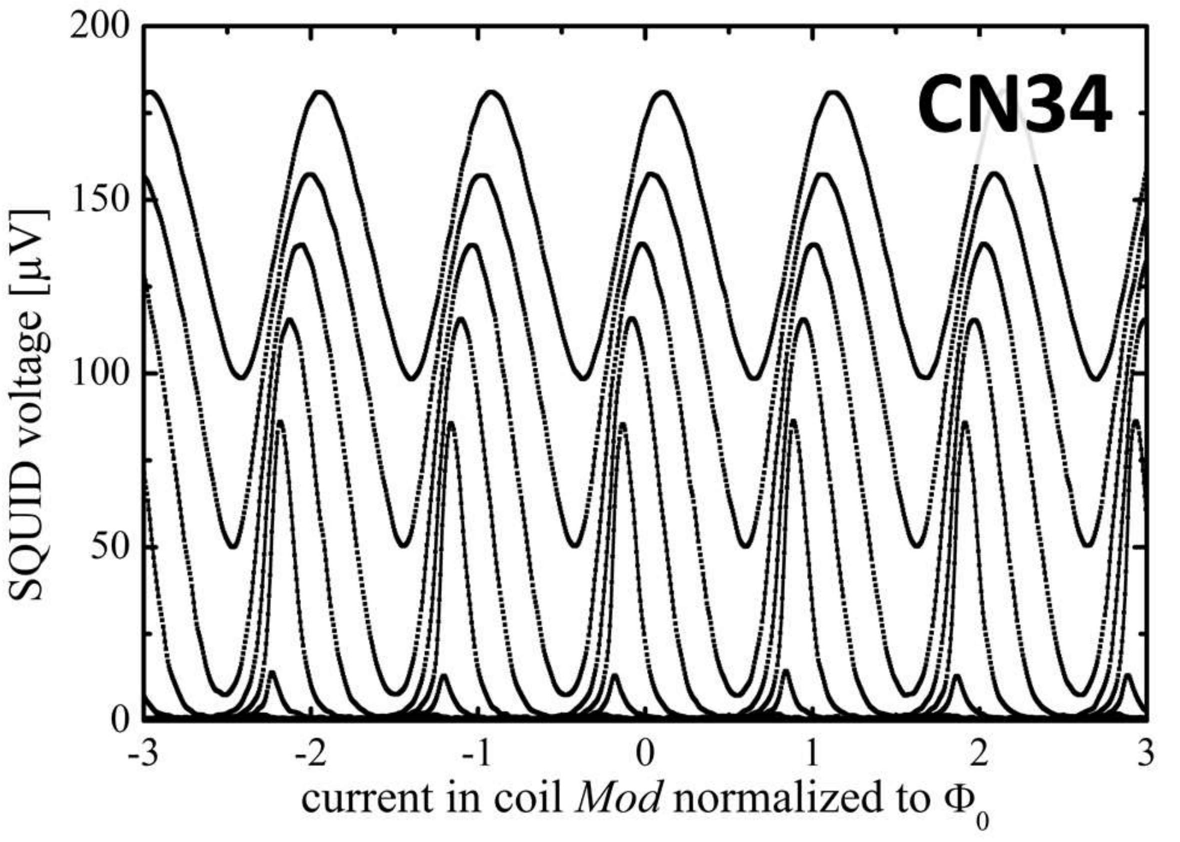
- SQUID arrays
- SQIFs as amp e.g. for MUXes, …

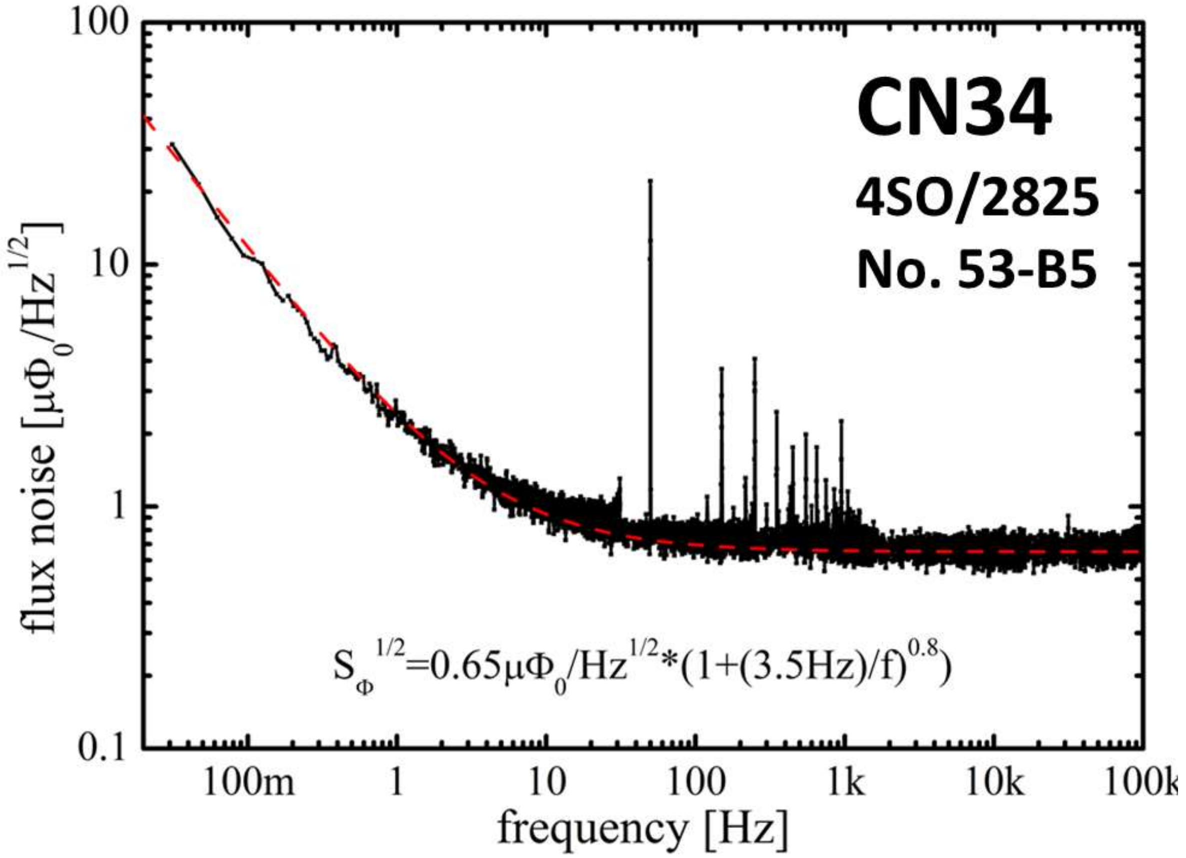


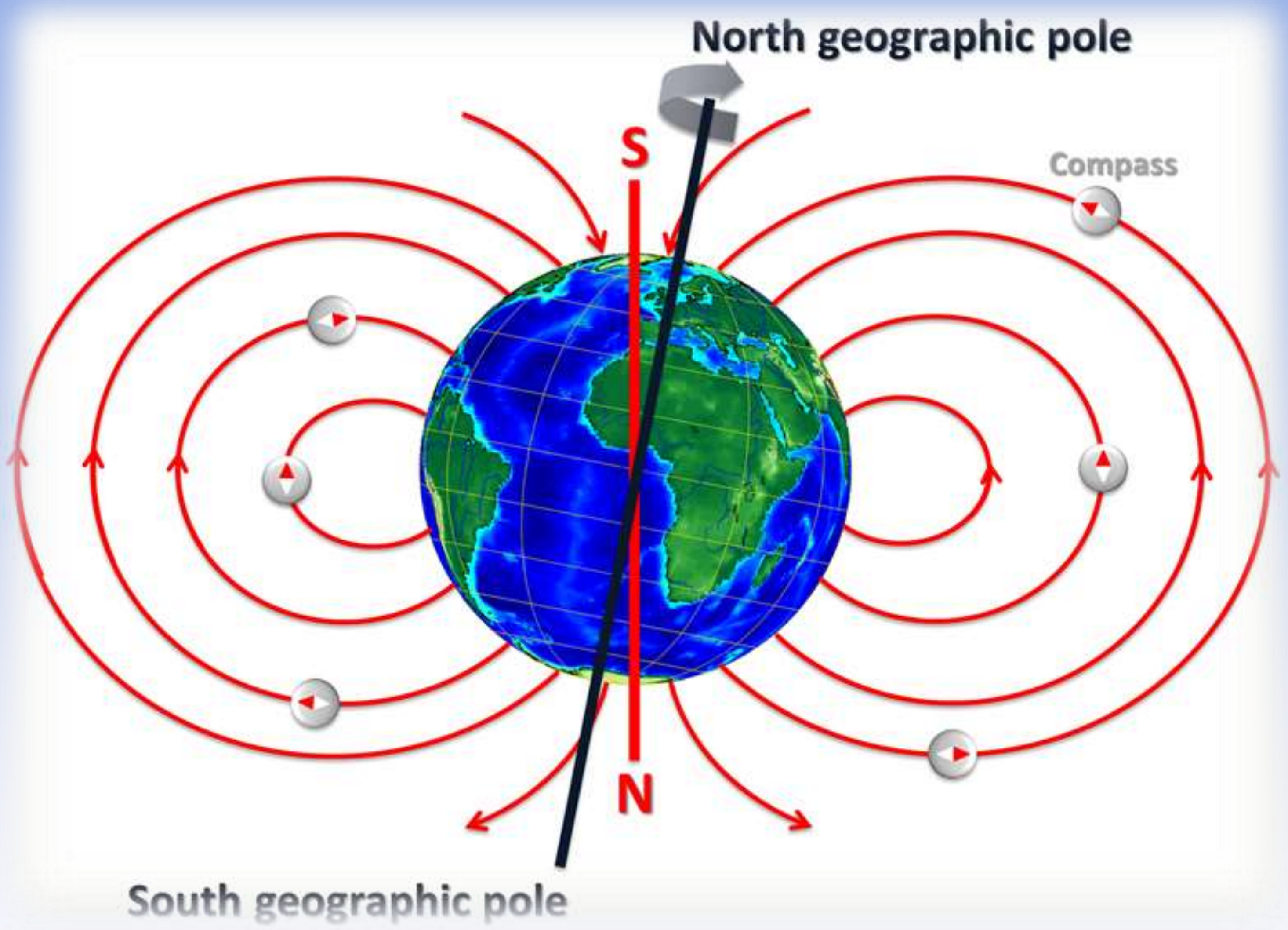
One example of current sensors

Device name	**CN2**	**CN4**	**CN8**	**CN17**	**CN34**
No. of input coil turns N	2	4	8	17	34
L_W [pH]	650	650	650	610	610
L_{SQ} [pH]	170	170	170	160	160
L_{in} [nH]	10.7	44	174	723	2860
$1/M_{in}$ [μA/ Φ_0]					
design	1.60	0.80	0.40	0.20	0.10
measured	1.57	0.79	0.40	0.20	0.10
M_{Fb} [nH]	1.5	2.2	4.5	9.8	20.3
k_{in}	0.98	0.96	0.95	0.96	0.97
Intrinsic flux noise $S_\Phi^{1/2}$ [$\mu\Phi_0$/Hz$^{1/2}$]	0.55	0.55	0.55	0.58	0.65
Input current noise $S_I^{1/2}$ [pA/Hz$^{1/2}$]	**0.86**	**0.43**	**0.21**	**0.12**	**0.065**
Energy resolution:					
ε, uncoupled [h]	5.8	5.8	5.8	6.8	8.5
ε_C, coupled [h]	6.0	6.3	6.4	7.3	9.1

SQUID sensor family with sub-µm cross-type Josephson junctions







Magnetic field detection

Magnetic field sensors

spatial resolution ⟸ **optimization** ⟹ **field resolution**

$\approx 0.1\mu m$ **typ. loop diameter** **several mm…cm**

Nano-SQUIDs

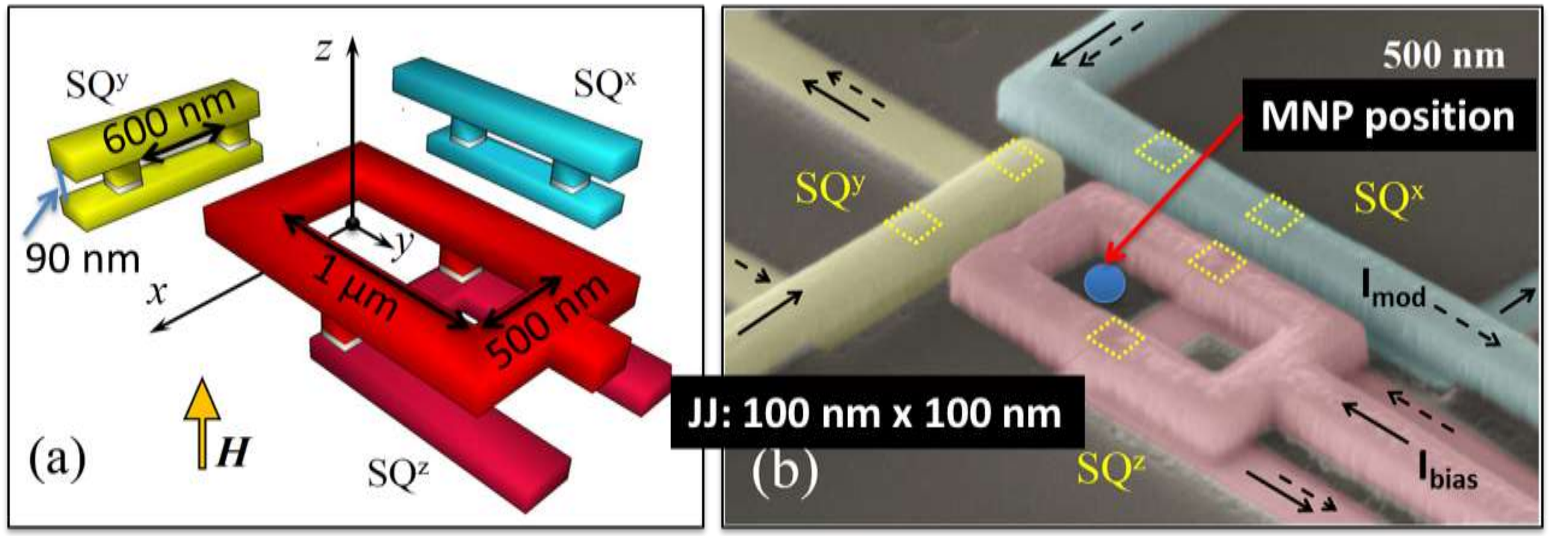
- investigation of small spin systems,
- single electron spin flip detection,
- magnetization on small scales,

Magnetic properties

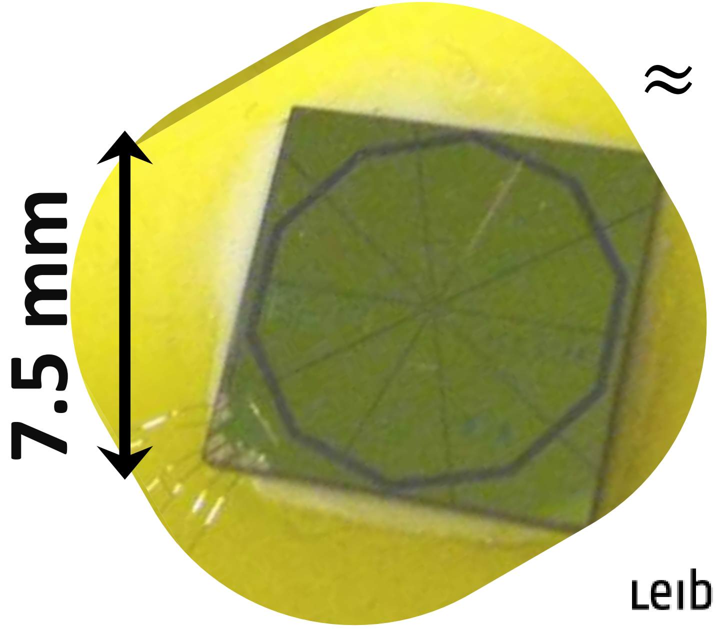
- biomagnetism,
- SQUID microscopy,
- susceptometry,
- …,

Magnetometry

- geophysics,
- biomagnetism,
- $\sqrt{S_B}$ down to $\approx 0.09 fT/\sqrt{Hz}$.

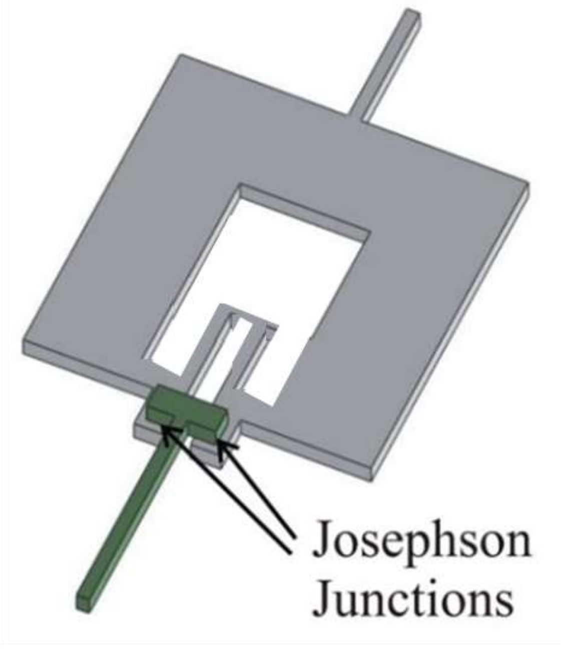


Pictures with courtesy of D. Kölle and O. Kieler

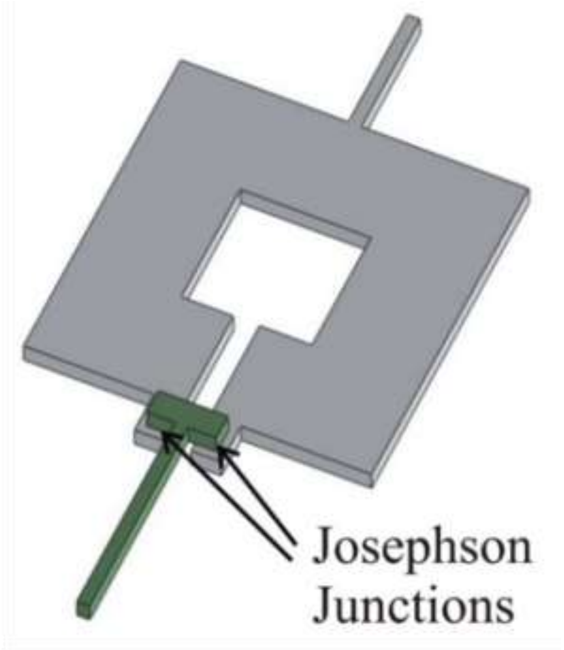


Magnetometers

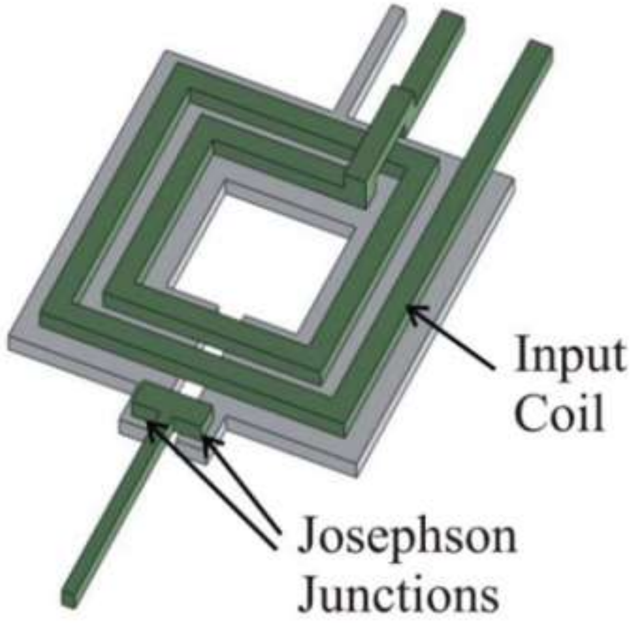
Parameter	Galvanometer SQUID	Washer-SQUID	Flux transformer SQUID	Multi-loop SQUID



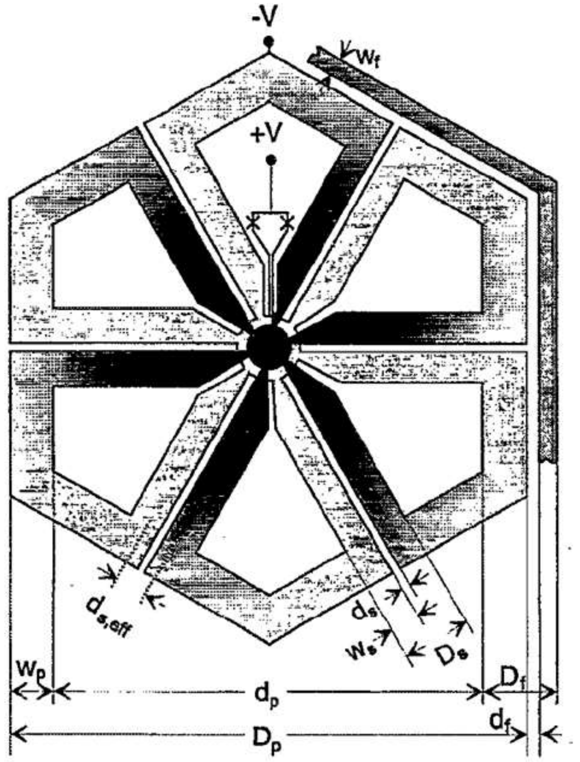
Ketchen et al.
J. Appl. Phys. 49
4111 (1978).



Ketchen et al.
IEEE Trans. Magn.
MAG23 1650
(1987).



Jaycox & Ketchen
IEEETrans. Magn. 17 400
(1981).
planar coupling scheme



fractional turn structure
by Zimmermann (1971),
thin film devices by Drung
at PTB since 1989,
review by Drung (1995).

How to derive maximum sensitivity $\left[A_{eff} = {}^{\partial\Phi}/_{\partial B}\right]_{MAX}$**?**

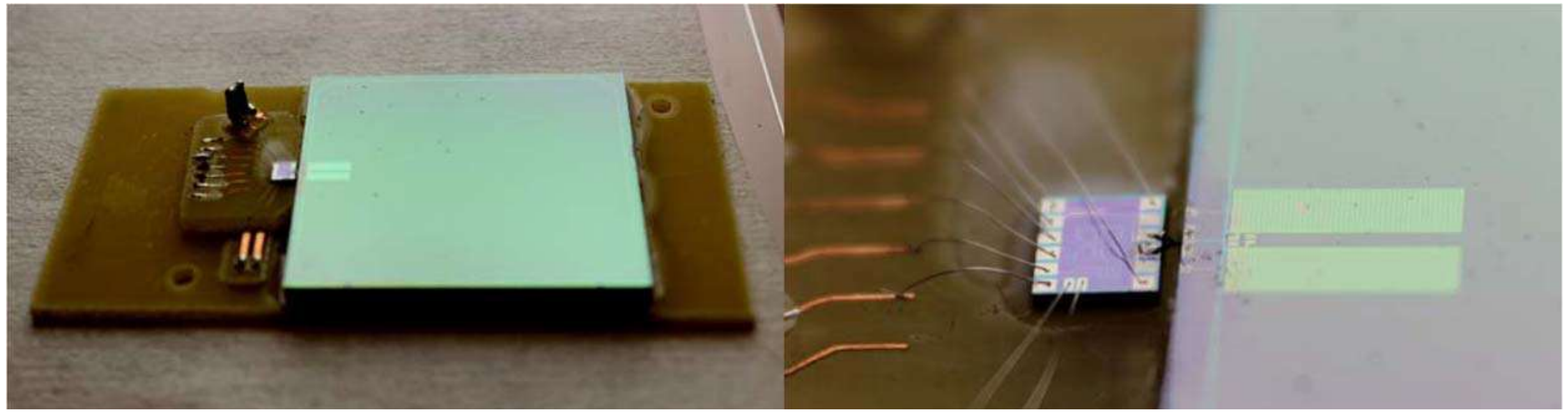
Example

best magnetic field to flux transfer coefficient →

Parameter	Galvanometer SQUID	Washer-SQUID	Flux transformer SQUID	Multiloop SQUID
effective area $[mm^2]$	0.071	0.14	0.23	0.305
effective area $[x \cdot A_A]$	$L_{SQ}/(L_A + L_{SQ})$	$1.1\, d/D$	$k_{12}/2\sqrt{L_{SQ}/L_A}$	$\frac{1}{N} - \frac{A_S}{A_A}$
resolution $[fT/\sqrt{Hz}]$	58	30	18	13.5
Advantages	single layer HTS SQUIDs	simple SQUID design, good for single layer HTS structures,	good matched coupling, low SQUID inductance, RF input filter enabled,	
Disadvantages	more design flexibility than washer SQUID	flux trapping and hopping, not suited for large chips,	resonances, HTS: often flip-chip,	large chip size with low inductance, HTS: difficult to implement.

Chip size: $2.5mm\ x\ 2.5mm$
SQUID noise: $2\,\mu\Phi_0/\sqrt{Hz}$

Record sensitivity of flip-chip flux-transforming magnetometers



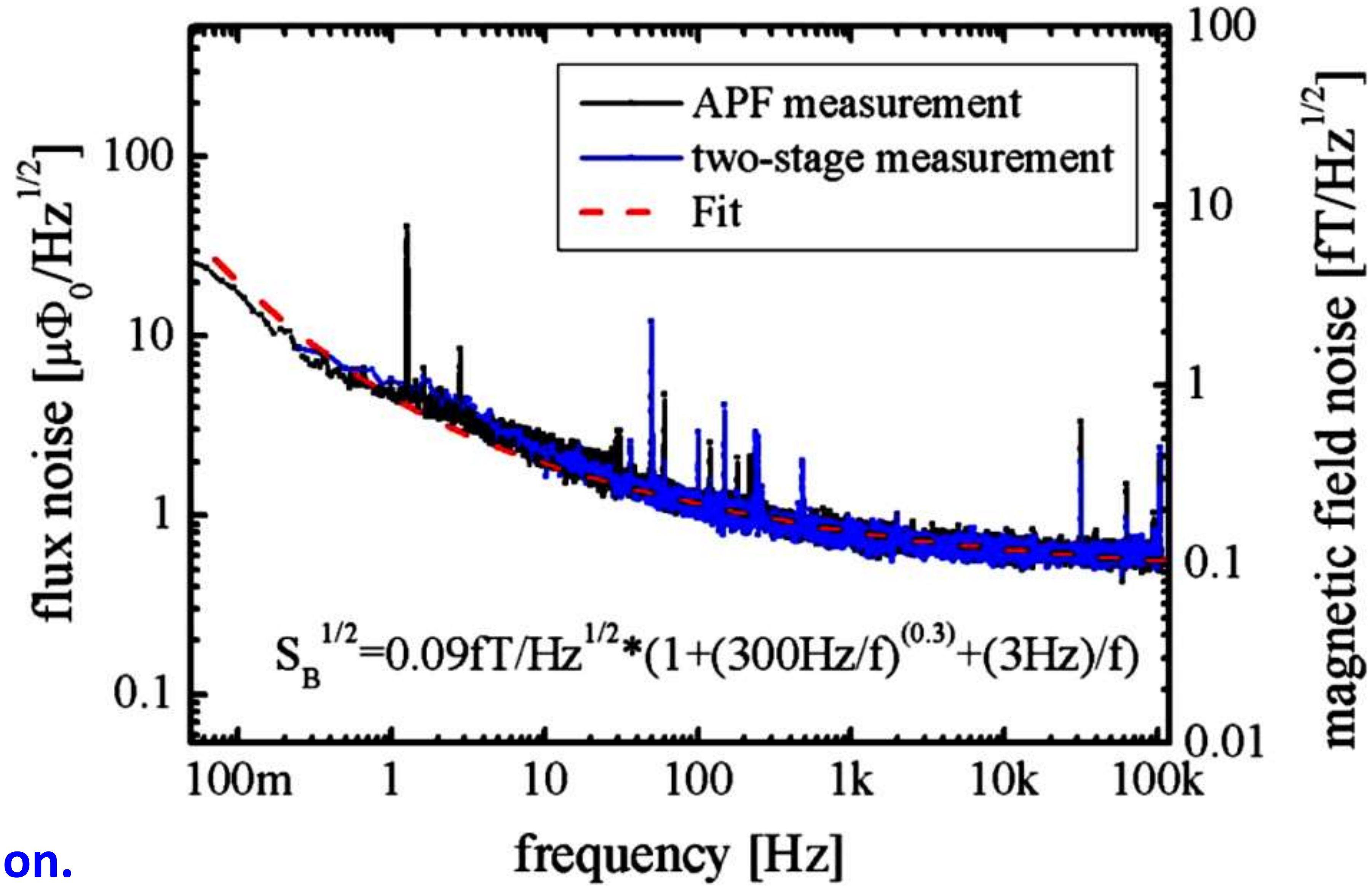
Chip and antenna size:

2.5mm x 2.5mm

2.5cm x 2.5cm

Limits:

- chip size limited only by wafer size,
- dynamic range of electronics
  ▶environmental signal amplitudes,
- practicability.

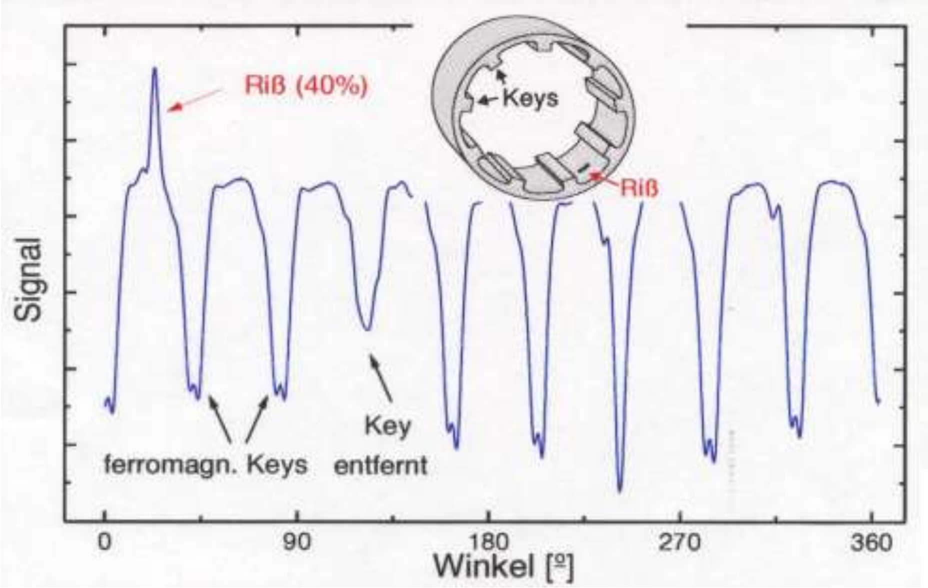


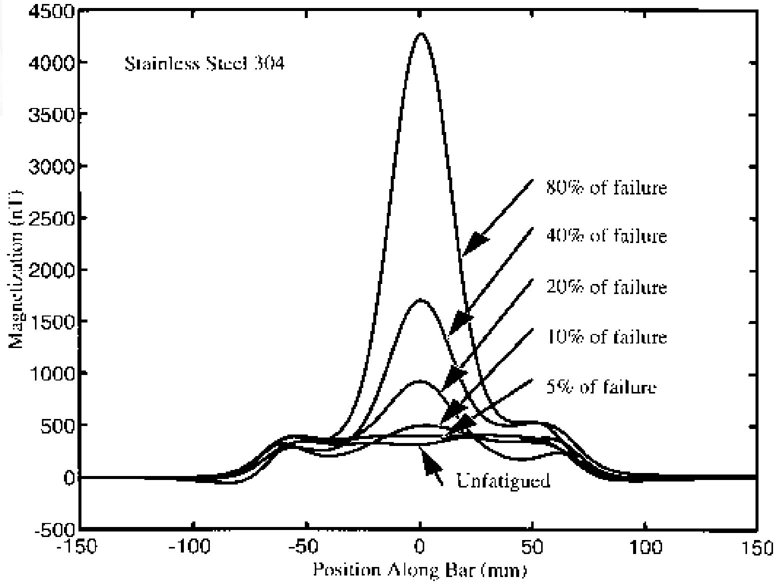
**News on wire wound sensors
in the talk of R. Körber (PTB Berlin) in this session.**

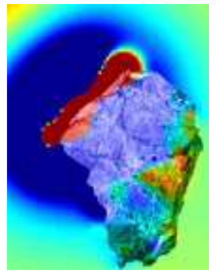
Nondestructive Evaluation

Non-Destructive Test & Evaluation

- **Defect Detection in Ferrous and Non-Ferrous Metals**
  - Cracks, Voids, Weld inspection
  - Stress, Strain, Corrosion
- **Insulating Material Analysis**
  - Flaw features < 150 µm
  - Bridges, Runways, Buildings
  - corrosion in reinforcing rods
  - Embedded sensors
- **Aerospace**
  - Cracks in wheels and turbine blades
  - Skin corrosion
  - Embedded sensors in composite structures
- **Biotech related**
  - Food Processing Nanoparticle Detection
  - Pharmaceutical Manufacturing
  - Magnetoimmunoassay (MIA)
- **Paleoarcheology**



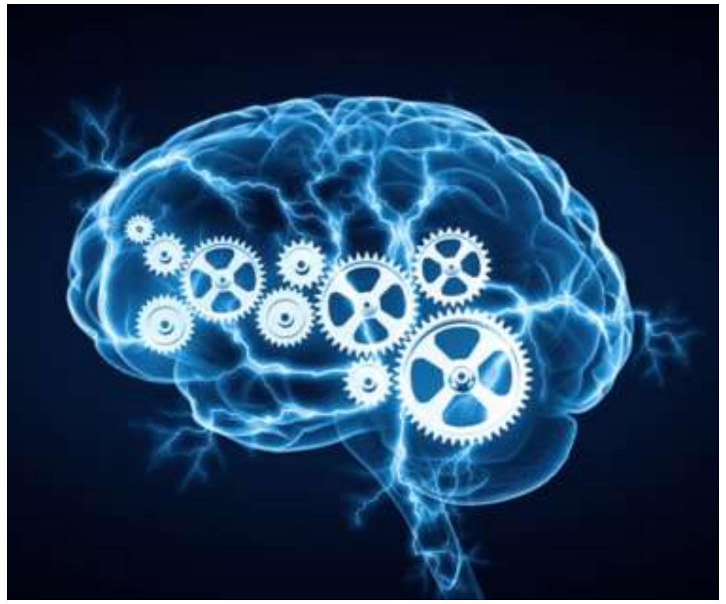




Pictures with courtesy of B. Fagaly

Biomagnetism

Novel magnetic field sensors for biophotonic applications



Biomagnetism: studies the magnetic field generated in biological tissues of specimens caused by bioelectric currents

Magnetoencephalography (MEG) ▶ talk of D. Winkler
Magnetocardiography (MCG, fetal version - fMCG)

nerve stimuli / conduction, plant responses, bacteria, etc.

Biosusceptometry

Paramagnetic substances concentration in specific organs (liver, heart) measured in applied magnetic field

Ultra- and low-field-MRI

Nuclear magnetic resonance in (relatively) low or zero field

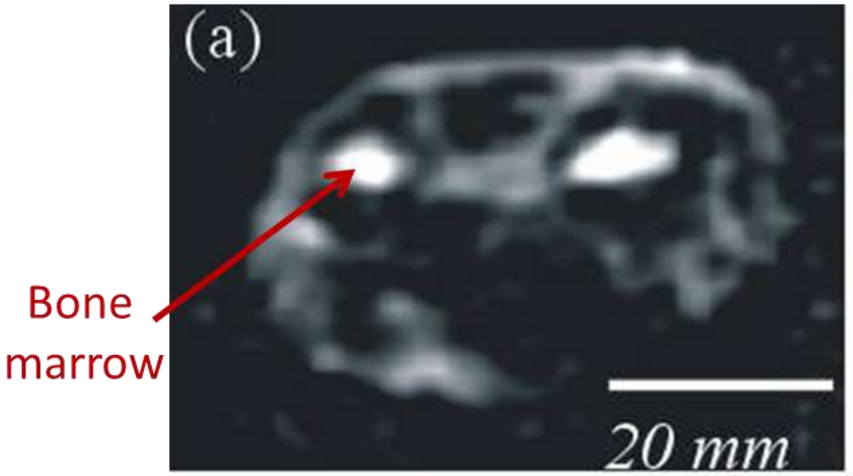
Measurement of Magnetism and Magnetic Matter

Magnetorelaxometry (MRX)
Superparamagnetic relaxation (SPMR)
Magnetic marker monitoring and detection (MMM)
Immuno assay detection or mapping, Scanning microscopy, etc.

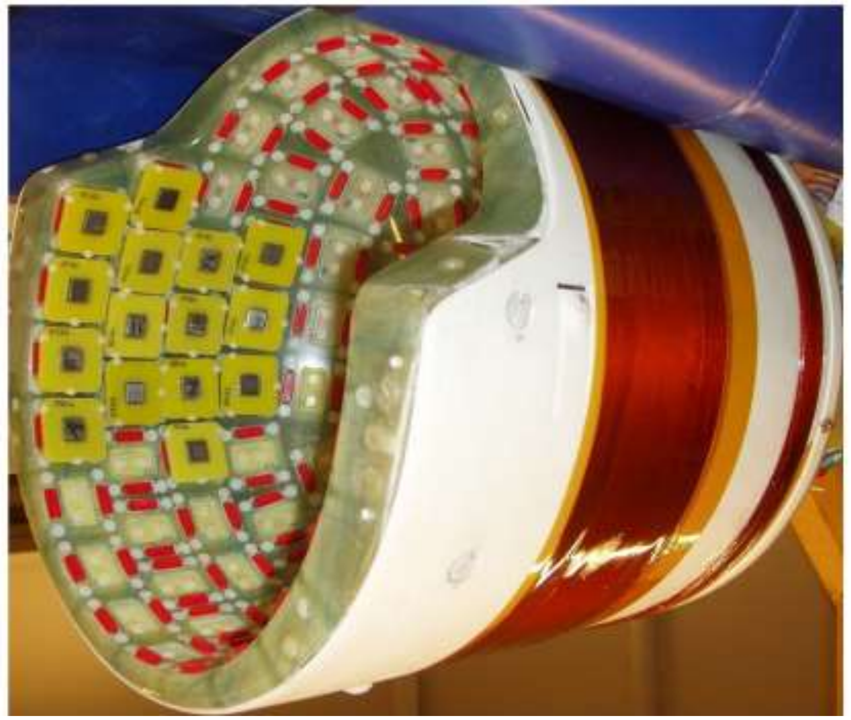
Potential for *In Vivo* ULF MRI Applications

- Imaging cancer: for example, prostate and breast tumors, without the need for a contrast agent,
- Imaging traumatic brain injury (TBI): caused by, e.g. stroke, traffic accidents, high impact sports, combat-related explosions – and monitoring progression of these injuries,
- Integration of MEG and ULF MRI to the benefit of both
  - higher resolution for pre-surgical mapping (e.g. EU project BREAKBEN),
  - MEG and ULF MRI in one sequence (LANL),
- Monitoring progression of Alzheimer’s and Parkinson’s diseases,
- Measuring elapsed time since stroke (U. of Eastern Finland, UCB),
- Neuronal current imaging in the brain with ULF MRI (PTB Berlin).

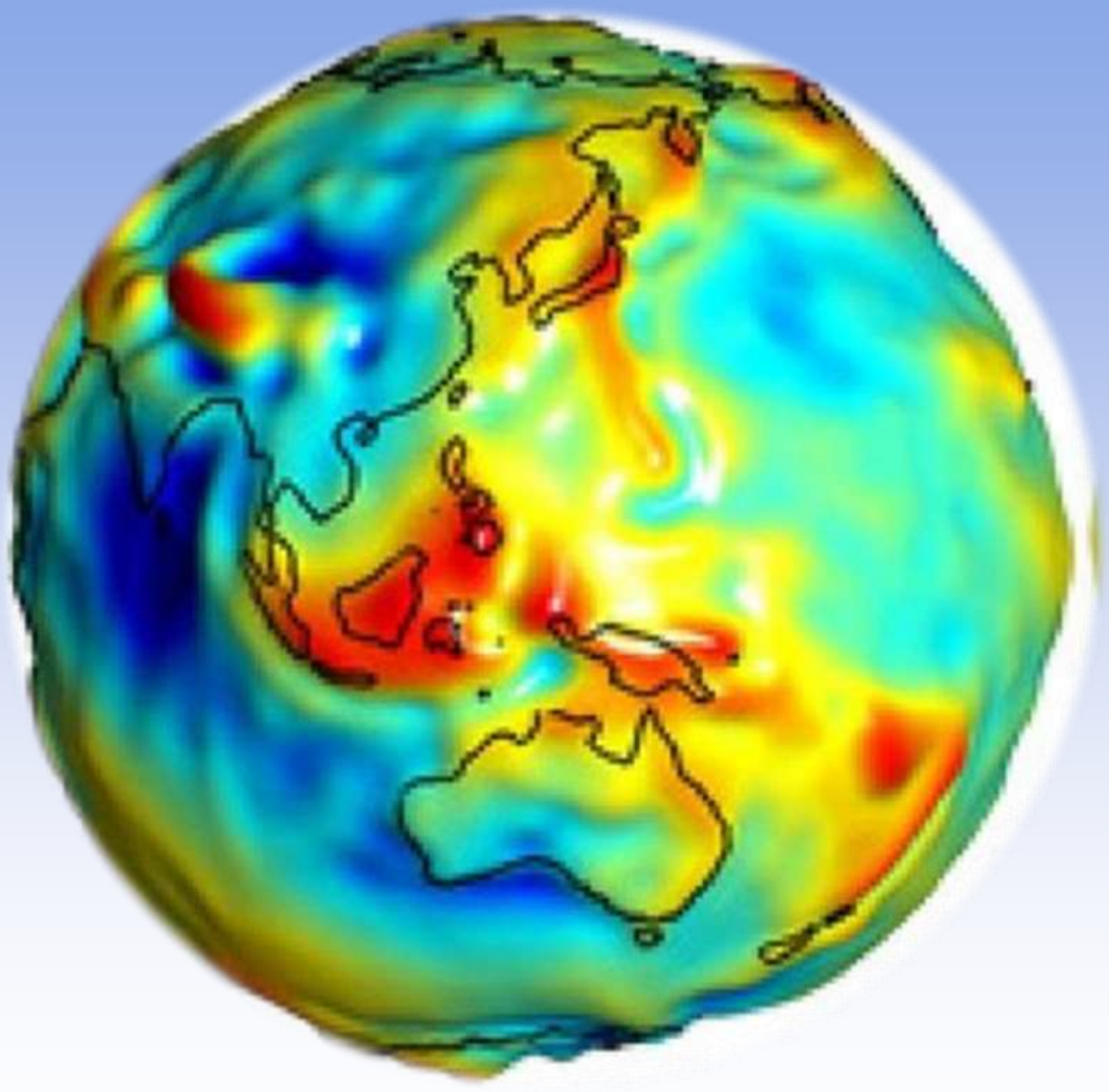
3-D *In Vivo* Image of the Arm



JC, Hatridge, Moessle (2007)



Pictures with courtesy of J. Clarke



Geoscientific applications

Motivation: Task of mineral exploration – „…all easy targets are discovered…“

- 21st Century: increased consumption of mineral raw materials in industrialized countries and ***emerging industrial nations*** (e.g. Brazil, India, China, Russia)
  ► human society faces new challenges to meet rising demand in longer term,
  ► secure, affordable and sustainable mineral supply for industry,
- new character of resources to be discovered:
  often small size and/or very deeply situated,
  location in hazardous areas (e.g. sub-arctics, swamp…),
  disseminated minerals,
- new demands: low impact exploration and exploitation,
  ► **need new tailored instruments with fast sensors with high resolution**
  as well as new exploration methods
  for exploration of mineral resources and natural oil/gas.

Exploration methods…

Magnetics
3D magnetometry,
Gradiometry

Magnetic Properties

Palaeomagnetics

Magnetotellurics
MT, AMT, CsAMT,
AFMAG,
RMS or RMT

Electromagnetics
TEM, LOTEM,
NanoTEM™,
FEM or FDEM,
TURAM, VLF

Induced Polarization
IP /MIP

Nuclear Resonance
SNMR

Radar
GPR

Gravity
Gravimeters,
Gravity gradiometry

Geoelectrics
Standard 1D or 2D,
3D, SP, IP, SIP etc.

Imaging
IR
Thermometry
THz
Hyperspectral

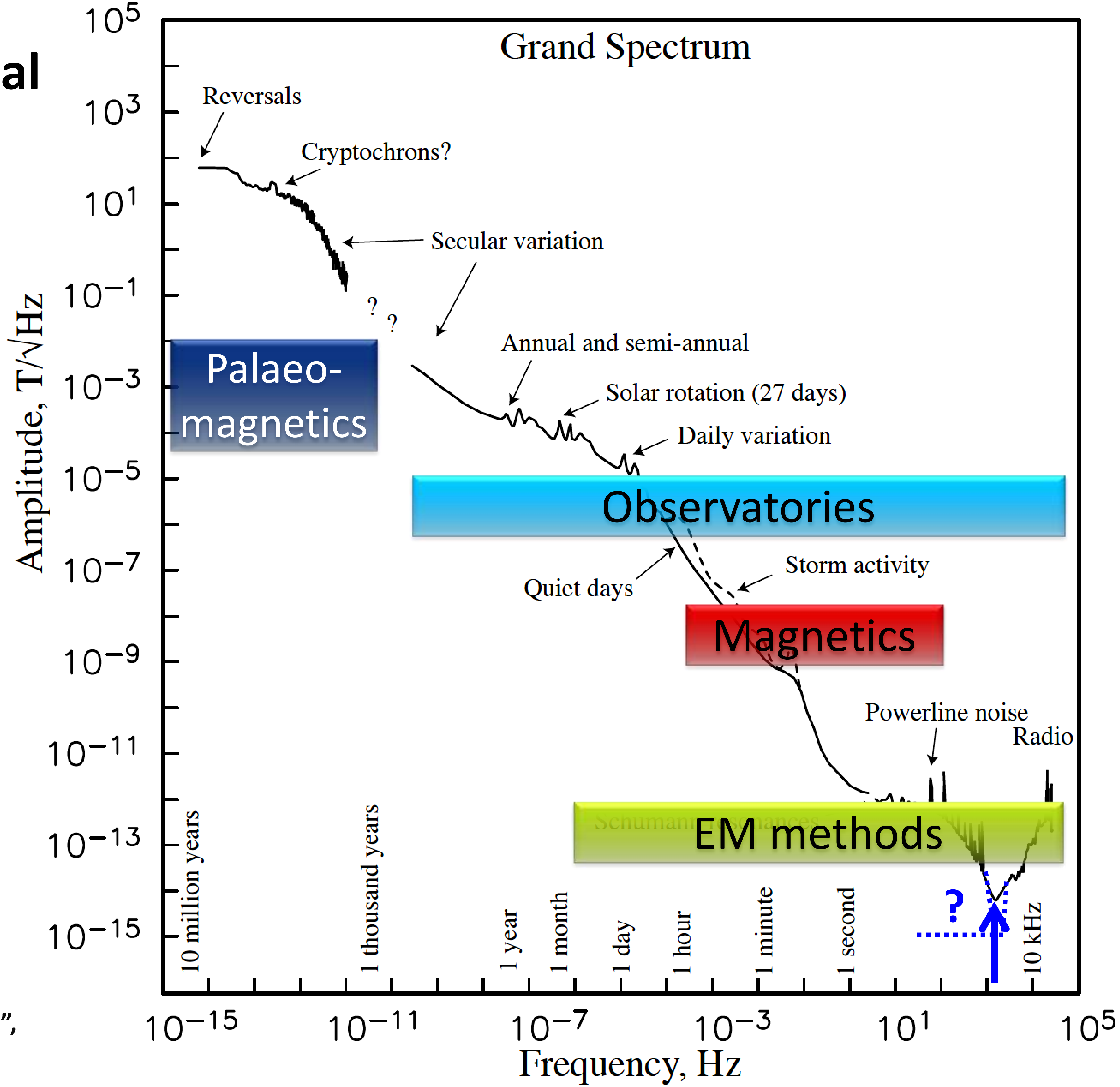
Thermometry

Radioactivity

and many more…

Today’s Noise is Tomorrow’s Signal

- passive magnetic methods:
  - ▶ ***signal***, but sensor resolution should be sufficient,
- active magnetic methods:
  - ▶ ***noise***,
  - ▶ explore methods to extract weak signals from noise.

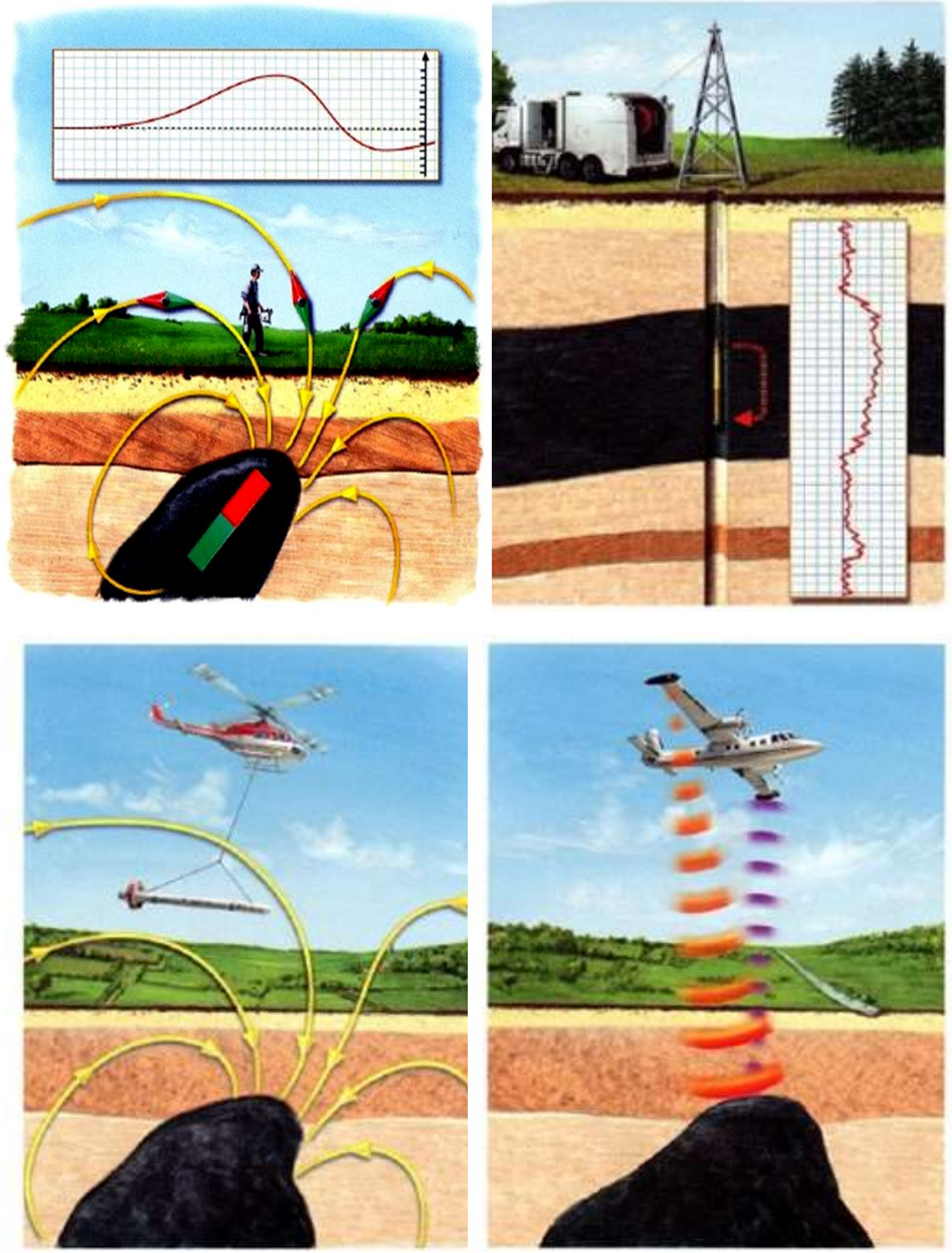


Composite amplitude spectrum of geomagnetic variations vs. frequency and corresponding time scales.

Constable, C.G., & S.C. Constable (2004) in “The State of the Planet: Frontiers and Challenges in Geophysics”, AGU, DOI 10.1029/150GM13, pp. 147–160.

Demands on sensors and electronics

- extremely high sensitivity and ultra-low noise ▶need quantum or quantum limited sensors $(\sim fT/\sqrt{Hz})$ ▶intrinsic vs. ***system noise***,
- low coloured noise (as low as possible),
- high linearity and slew rate $(\sim mT/s)$,
- ultra-high dynamic range (DNR up to $32bit$),
- high bandwidth ▶up to $50kHz$ for EM methods,
- small size and weight,
- simple, robust and stable operation in Earth magnetic field $(\sim 100\mu T)$,
- of course as cheap as possible!

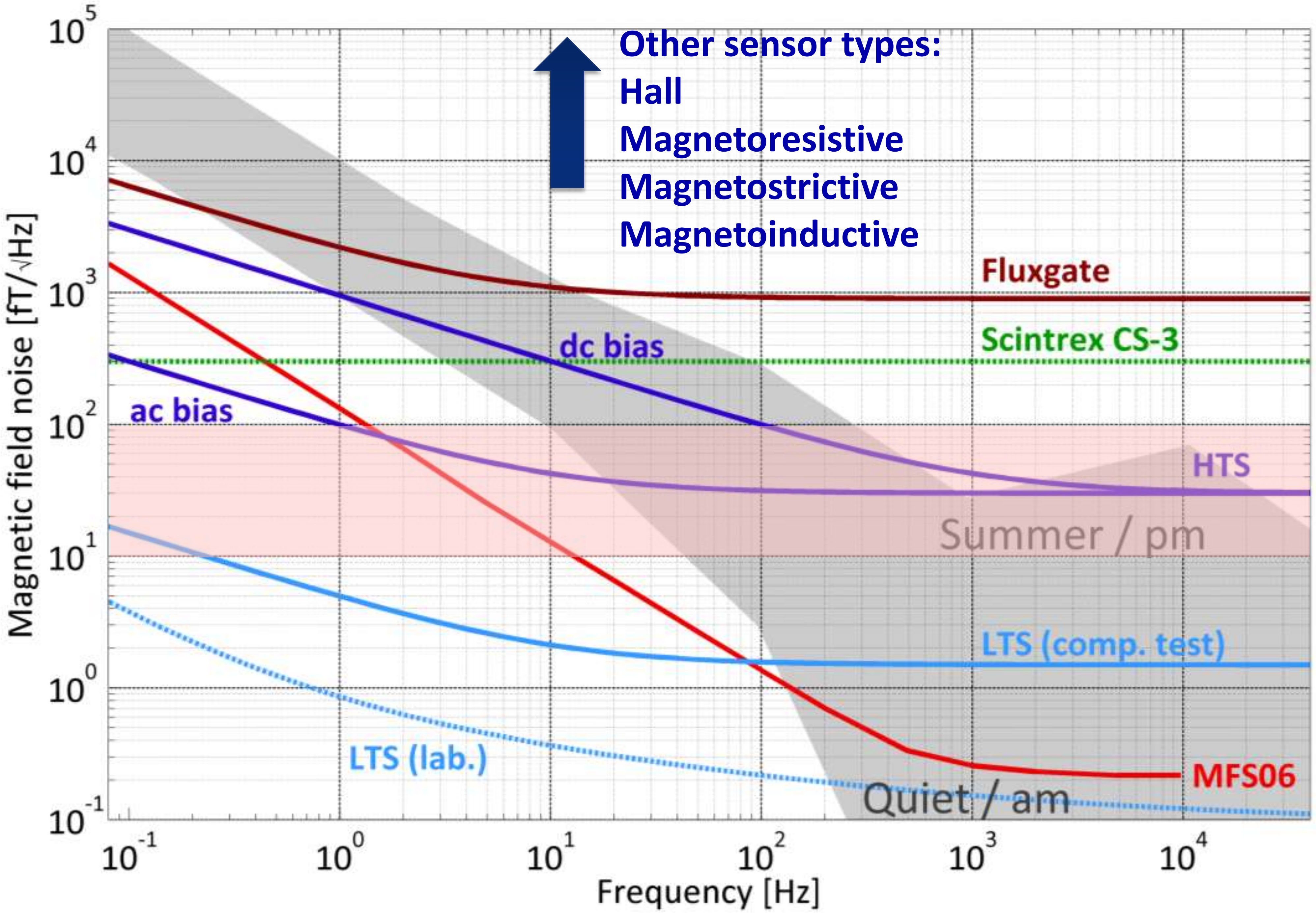


Bergbau: Schätze der Erde, Illustrations by Eberhard Reimann

Noise properties: Quantum-limited magnetometers

SQUIDs

Optically pumped magnetometers (Caesium vapour based, NVCD based or FRM)



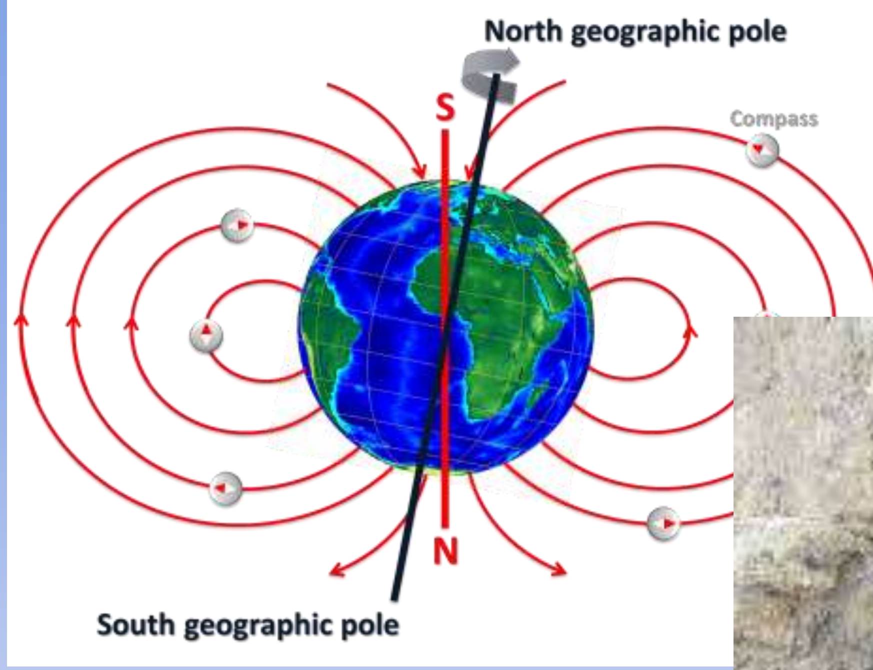
MFS06: induction coil of Metronix GmbH

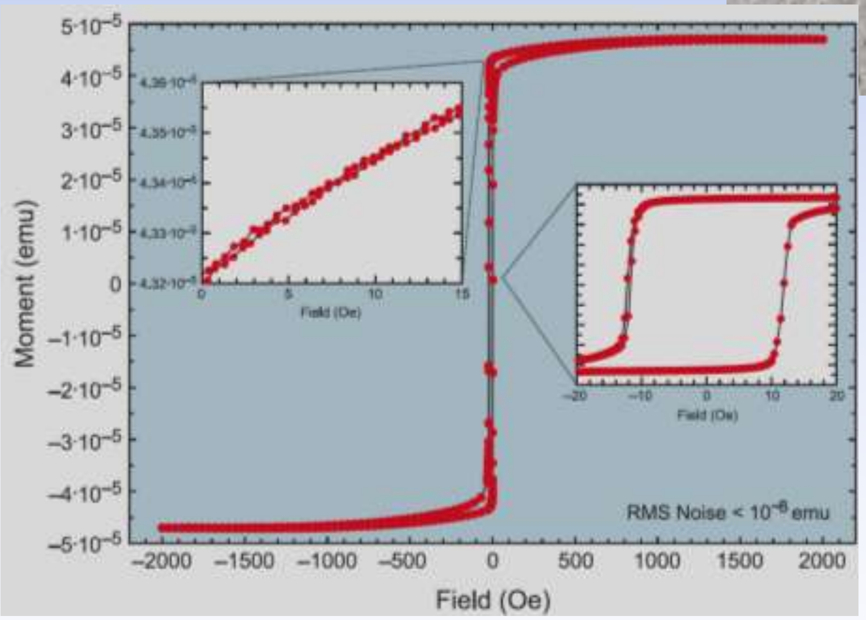
Comparative magnetometer test 2012 (comp. test):
Chwala et al., SUST 26(3), 035017 (2013).

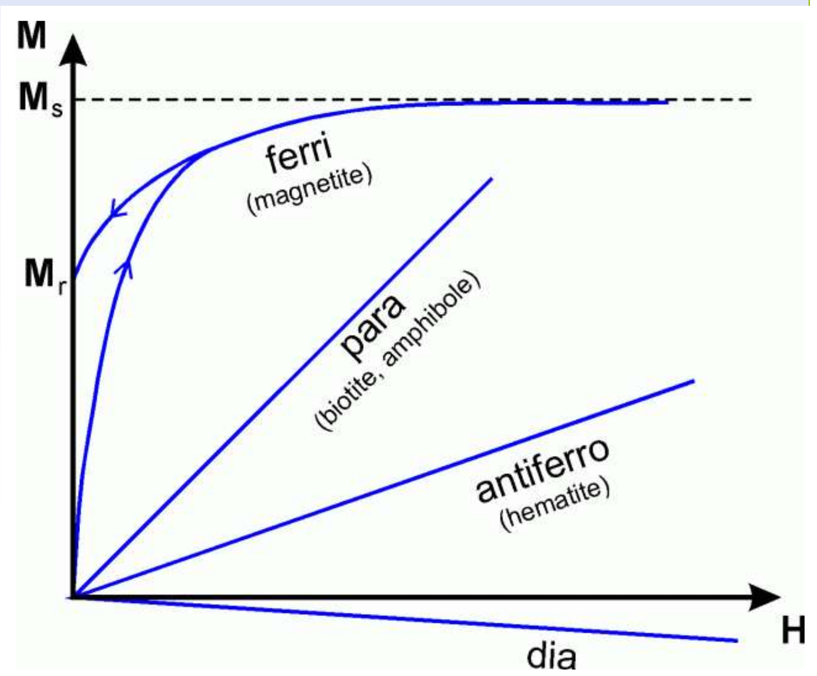
Magnetic Properties

Magnetic properties

Laboratory devices







Laboratory devices

- 1974 start of development of superconducting rock magnetometers (SRMs) using SQUIDs,
- since 1981 first systems available; few hundred systems installed (2G Enterprises more than 135),
- various suppliers: 2G Enterprises, ***Quantum Design***, Cryogenics Ltd., FIT, CSIRO, ***Neocera*** (SQUID Microscope),
- 10^{-12}Am^{-2} magnetic moment with cryo-cooler operation,
- main use Palaeomagnetism - study of record of Earth's magnetic field in rocks, sediments, or archeological materials,
- nano-SQUID instruments to study magnetization on small scale,
- well established with cryo-cooling; not too many improvements possible.

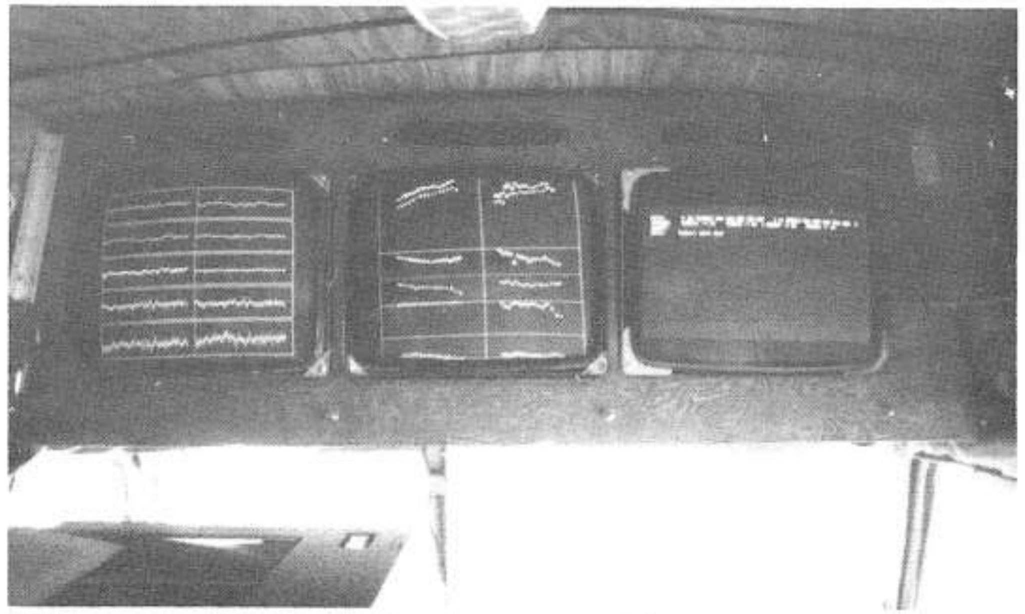
Magnetotellurics

Magnetotellurics
MT, AMT, CsAMT,
AFMAG,
RMS or RMT

Installation of SQUID magnetometer, which involves leveling and partial burial to prevent wind vibration

Equipment for MT station setup: SQUID magnetometer, preamp/filter/ telemetry package, antenna, wire for telluric lines, and battery packs

Woodward-Clyde Consultants
1980‘s



CRT screens in MT-1 van, showing processed data on center screen

THE BETTER THAN EVER MAGNETOMETER

Since 1976, S.H.E. Corporation has been the leading supplier of the most sensitive and easy to use three-axis magnetometers available for ground-based electromagnetic measurements. Now, the world's most experienced manufacturer of superconducting instruments is pleased to announce that the Better Magnetometer is even better:

- Frequency response has been extended beyond 200 Hz while preserving the system's immunity to troublesome spherics and rf interference.
- For use in difficult environments and areas where cultural noise is a problem, the Model GMSX has been further compensated to reduce noise due to low-level mechanical vibrations.
- Field-worthiness has again been improved with the inclusion of our remarkable new HYBRID SQUID amplifier—the lowest noise, most reliable SQUID sensor commercially available.
- Exeptionally low drift, 10^{5} gamma resolution and 134dB dynamic range continue to set the standard for sensitive magnetic measurements.

If your work includes magnetotelluric or controlled-source electromagnetic methods, you'll want to compare the capabilities of the Model GMSX with other vector magnetometers. Please call us or write to discover how S.H.E. Corporation can help make your magnetic measurements easier, faster and Better than Ever!

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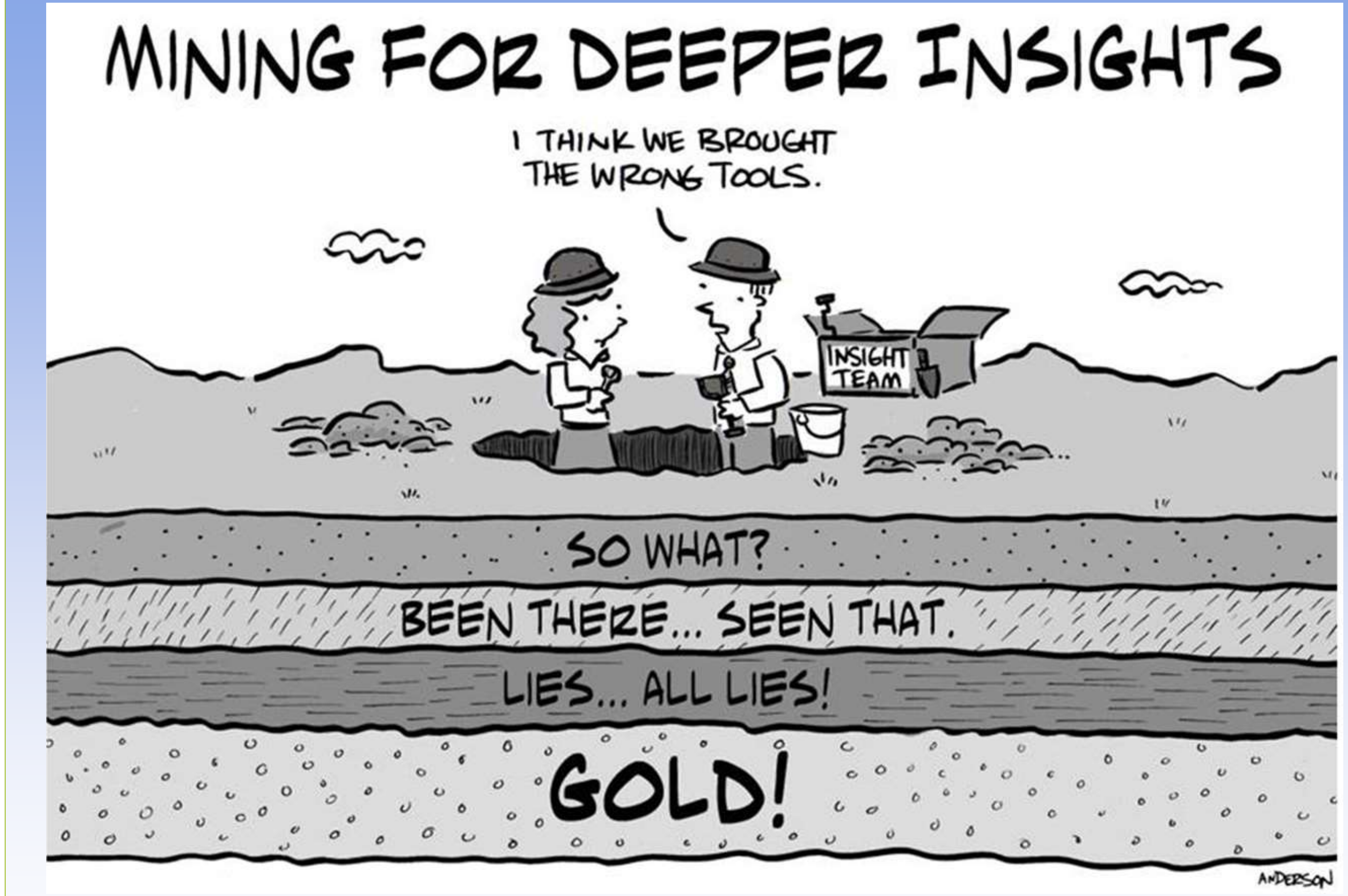
22, ALEXANDRIA AVE.,
EASTWOOD N.S.W. 2122
All Correspondence to:
P.O. BOX 203
EASTWOOD N.S.W. 2122
PH. 85-7761

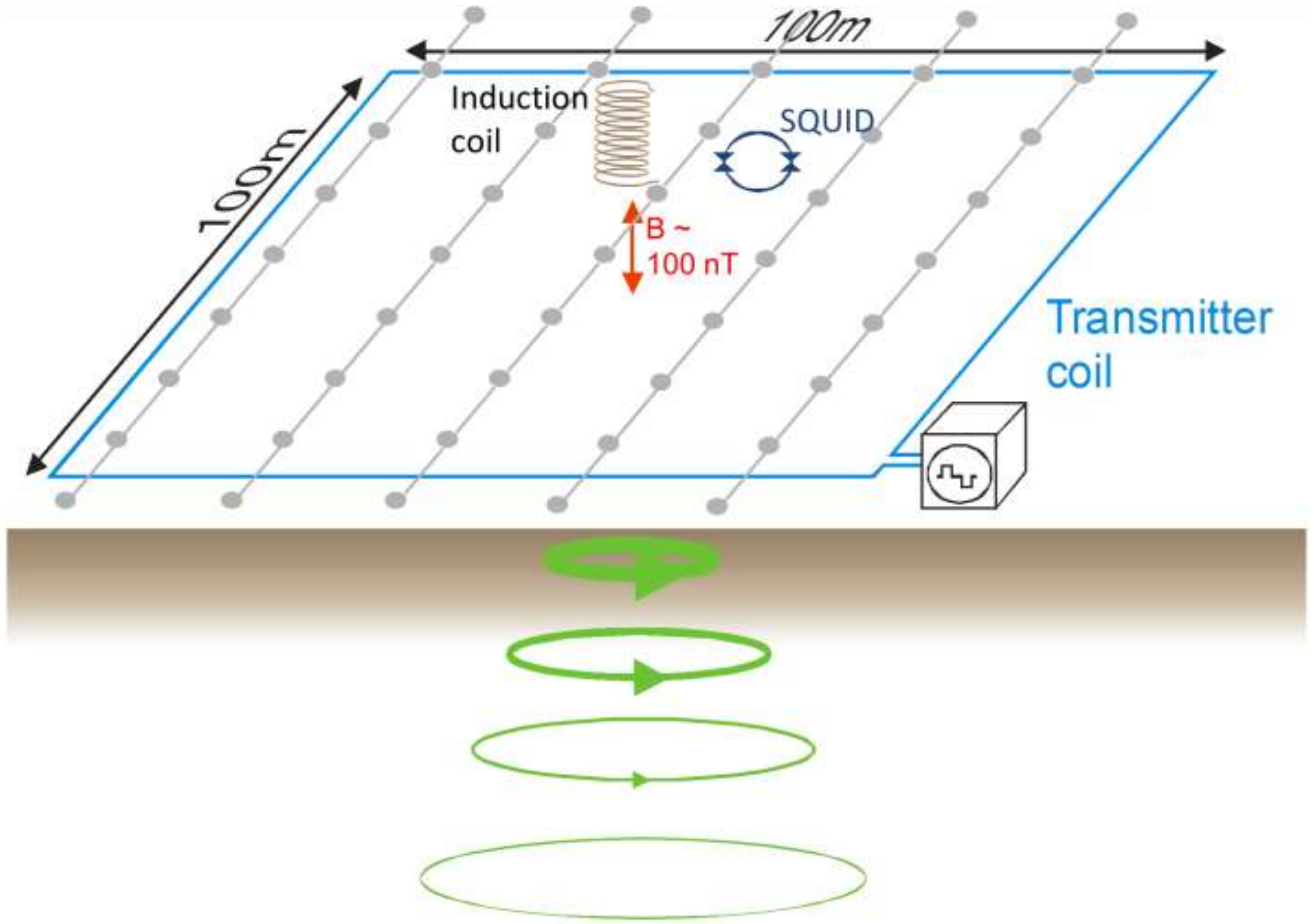
- micro-fluctuations of Earth's magnetic field measured with RF SQUIDs by Forgacs and Warnick (1967),
- Jim Zimmermann was next (Geophysics 1975, 40 pp269-84),
- Gamble, Goubau and Clarke (Geophysics, 1979 p.53-68):
  two simultaneous MT measurements at distance of 4.8km,
  remote referencing already at this time!
- Harold Weinstock's workshop ahead of its time in 1980,
  concepts for geophysical use of SQUIDs:
  EM methods, Rock and Paleomagnetism, Gravimetry,
- Pro SQUID: wideband low-noise receiver with flat characteristics
  Con SQUID: cryogenics & system costs,
- Options: MT networks, CsAMT (SIMIT China, LTS), RMT / VLF - SQUIDs no option so far,
  Magnetic observatories e.g. LSBB [Gaffet, GJI 2003] or for ALF resonances [Kawai, SUST 2017],
  AFMAG: see 3D vector magnetometers for magnetic method.

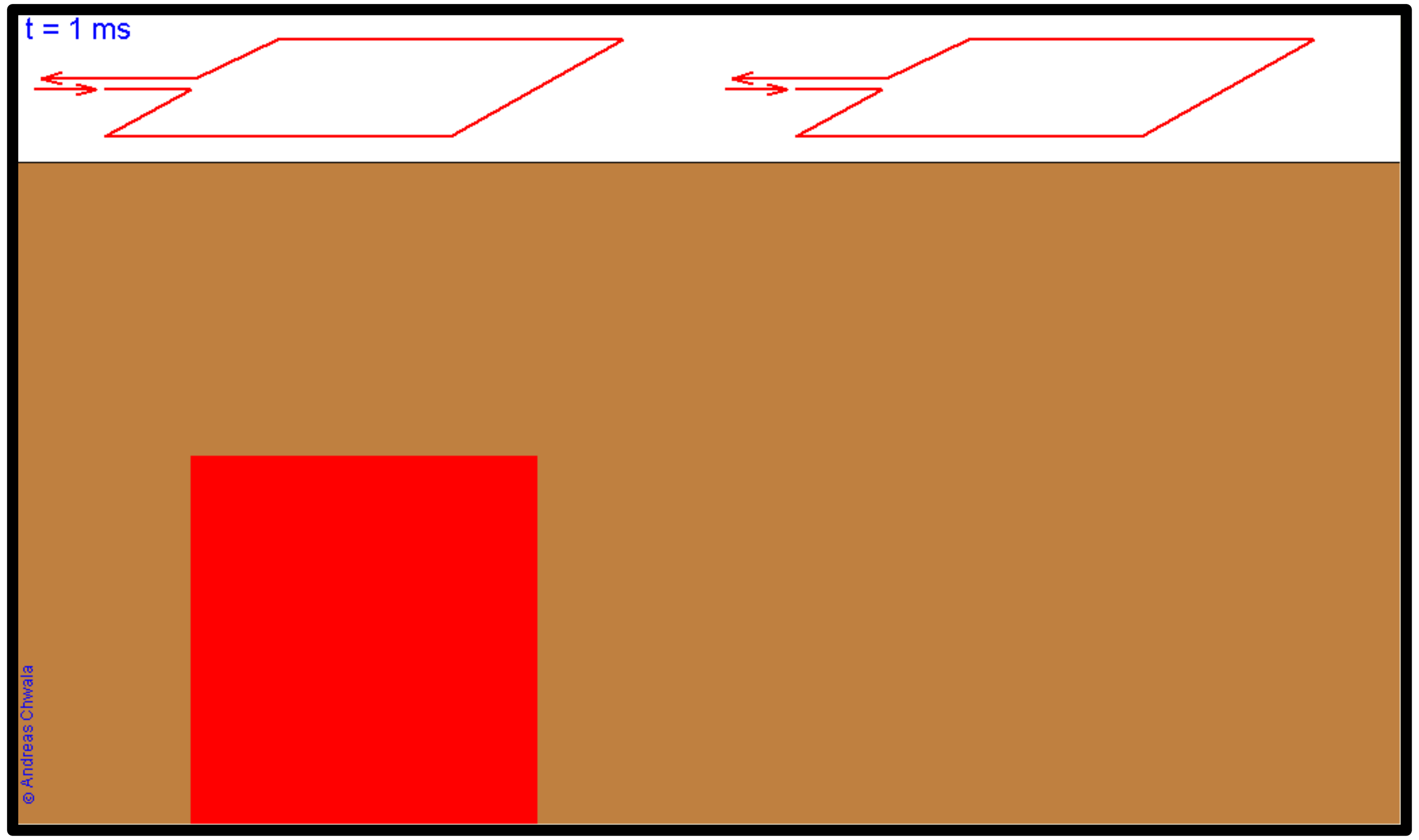

MINING FOR DEEPER INSIGHTS
I THINK WE BROUGHT THE WRONG TOOLS.
INSIGHT TEAM
SO WHAT?
BEEN THERE... SEEN THAT.
LIES... ALL LIES!
GOLD!
ANDERSON

TEM (active)

Transient electromagnetics (TEM)

- demand: wideband low-noise receiver with (a) vectorial characteristsics, (b) flat transfer function [$T(f) = const.$],
- replace conv. induction coils by SQUID,
- robust / semi-automatic operation,
- shield for vibrations and wind noise.

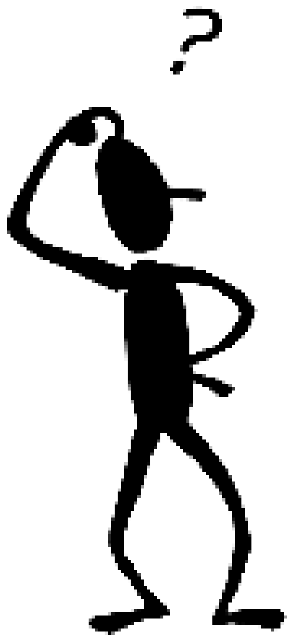




- high signal slew rate: high-power transmitter (TX), fast TX off,
- limitation: dynamic range of available 24bit ADCs,
- imaging of conductivity via inversion of signal amplitude vs. decay time profiles
  ▸ **spatio-temporal sounding with exploration depth in km range!**

State of TEM receivers

- mature technology already provided by industry,
- ***why do still R&D on TEM receivers?***



- deeper and smaller size targets
  - ► high sensitivity and low frequencies,
- need less demanding / cheaper technology,
  - ► ***LTS*** and ***HTS SQUIDs*** or novel induction coils or in future ***optically pumped magnetometers (OPMs),***
  - ► need reliable SQUID technology and Josephson junctions,
  - ► transfer technology to industry (e.g. Supracon AG).

Supracon: JESSY DEEP LTS

TRISTAN Technologies

CSIRO: LandTEM

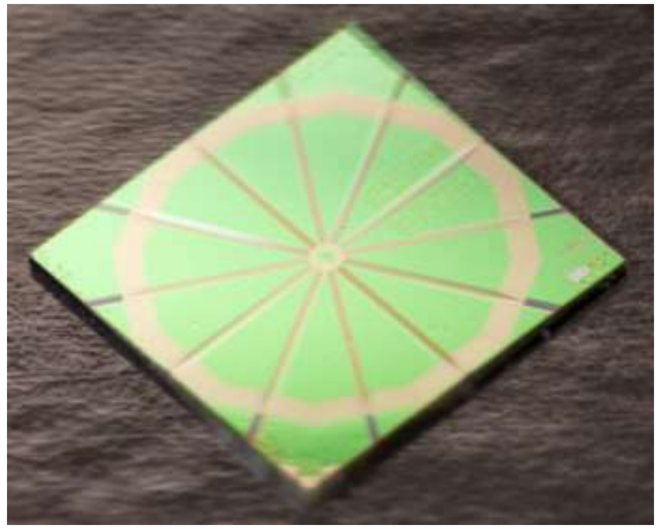
Jülicher SQUID GmbH

SUSTERA: SQUITEM-3

Hato, SUST 26 (2013) 115003

SIMIT and Jilin Univ.

SQUID based instruments for active or passive methods



- LTS multi-loop SQUIDs with scalable sensitivity,
- LTS system noise: 15 / 1.3 $fT/\sqrt{Hz}$ configurable, HTS system noise 30 $fT/\sqrt{Hz}$ (talk L. Kaczmarek),
- slew rate 85 mT/s, dynamic range 165dB,
- robust with full automatic control.

Idea: Zimmermann, J. Appl. Phys. 42 (1971) for bulk SQUIDs

Schmelz et al. SUST 24-6 (2011)

	ML2A	ML4.5	ML7	ML12
Outer pickup dimension [mm]	2.0	4.5	7.0	12.2
Loop number	8	8	10	12
A_{eff}^{-1}, meas [nT/Φ_0]	5.55	1.09	0.57	0.25
Noise [fT/Hz$^{1/2}$]	3.0	1.0	0.7	0.33

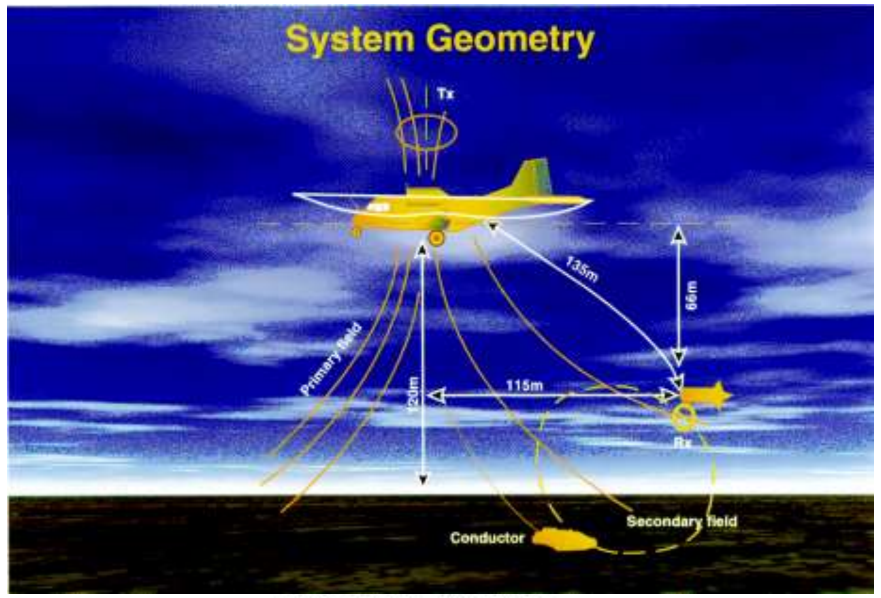
Former approaches to airborne TEM with SQUIDs

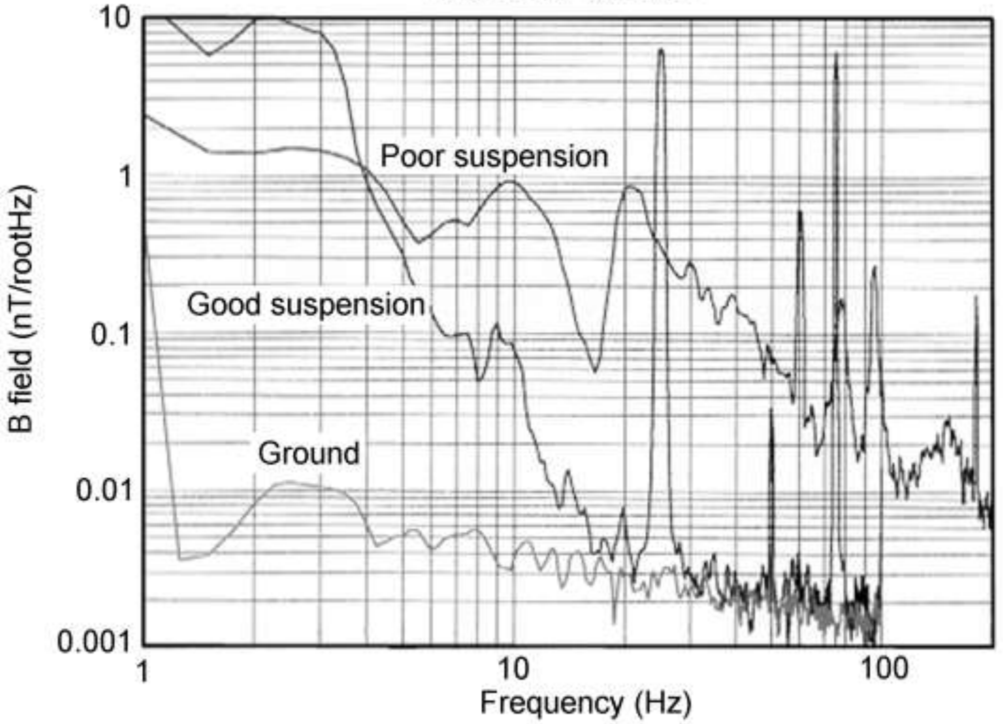
Leibniz IPHT's Airborne TEM approach

The elusive flying SQUIDs
LeRoux et al., SAGA2009

- motion noise: dynamic range and dynamic/post-processing compensation?
- technical issues: TX quality, bucking, and slew rate,
- need a new approach.

CSIRO's and BHP's approach





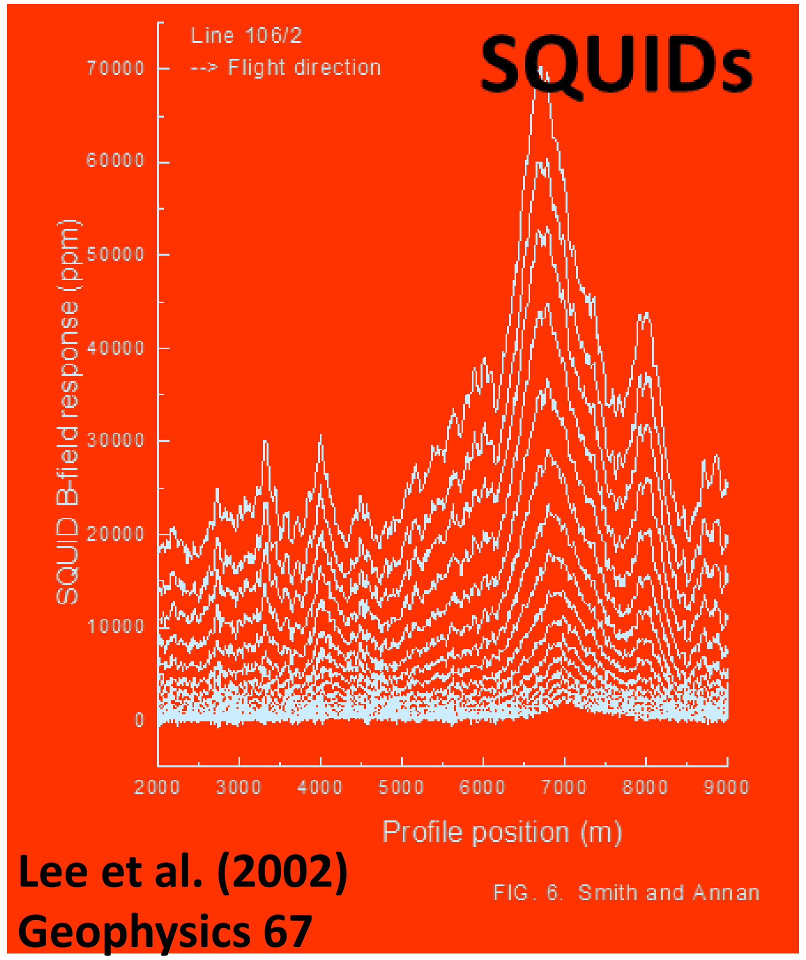


FIG. 6. Smith and Annan

Lee et al. (2002)
Geophysics 67

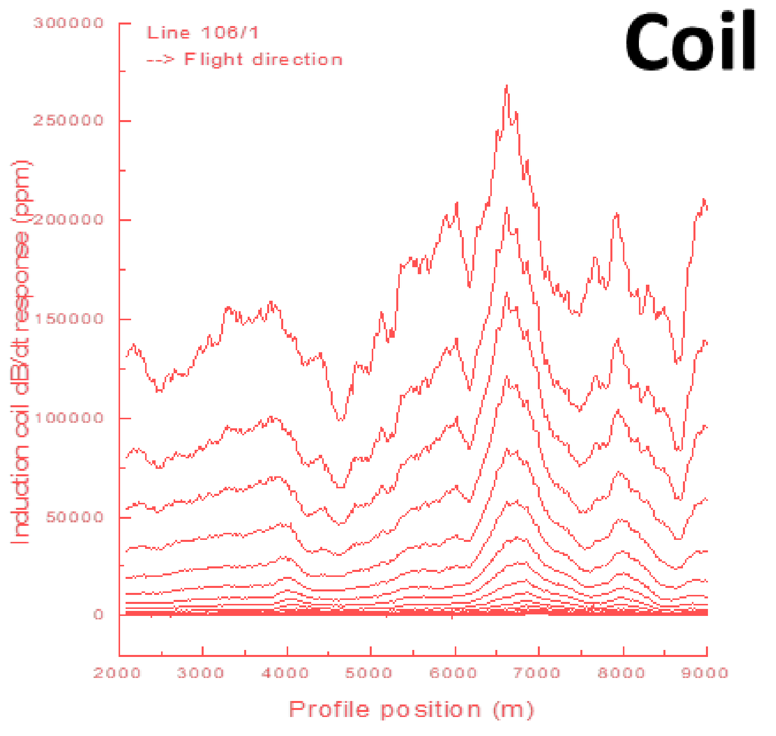
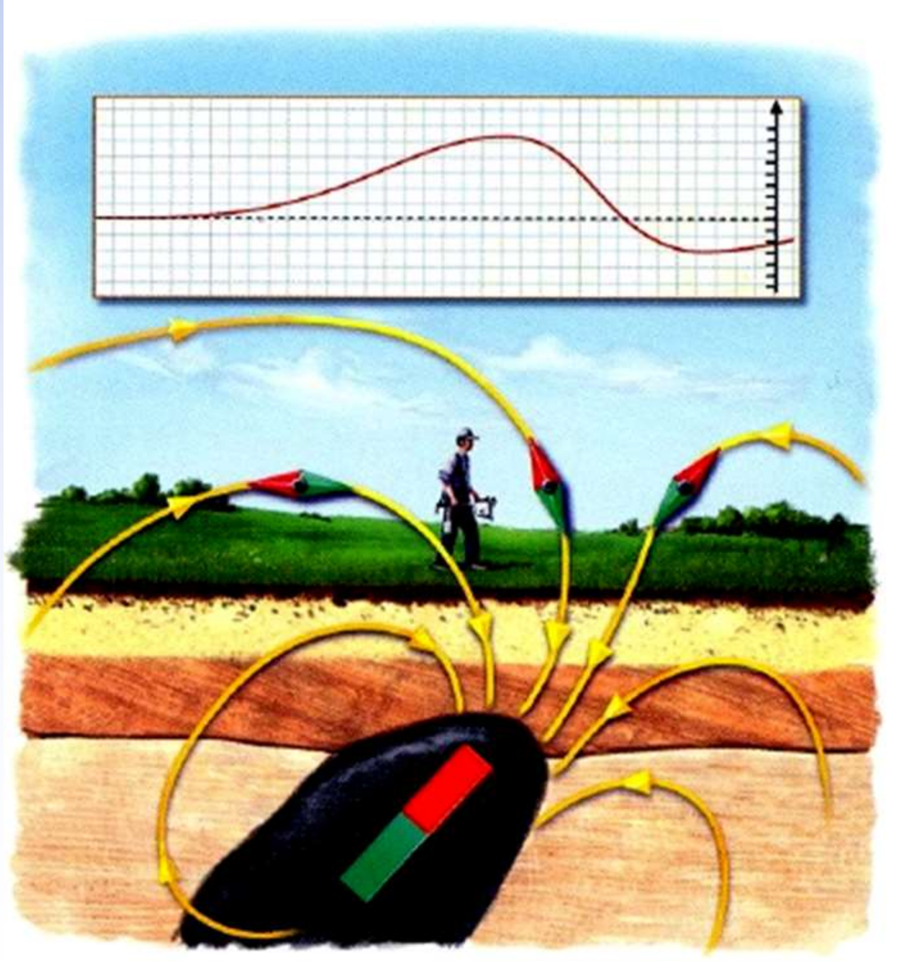


FIG. 4. Smith and Annan

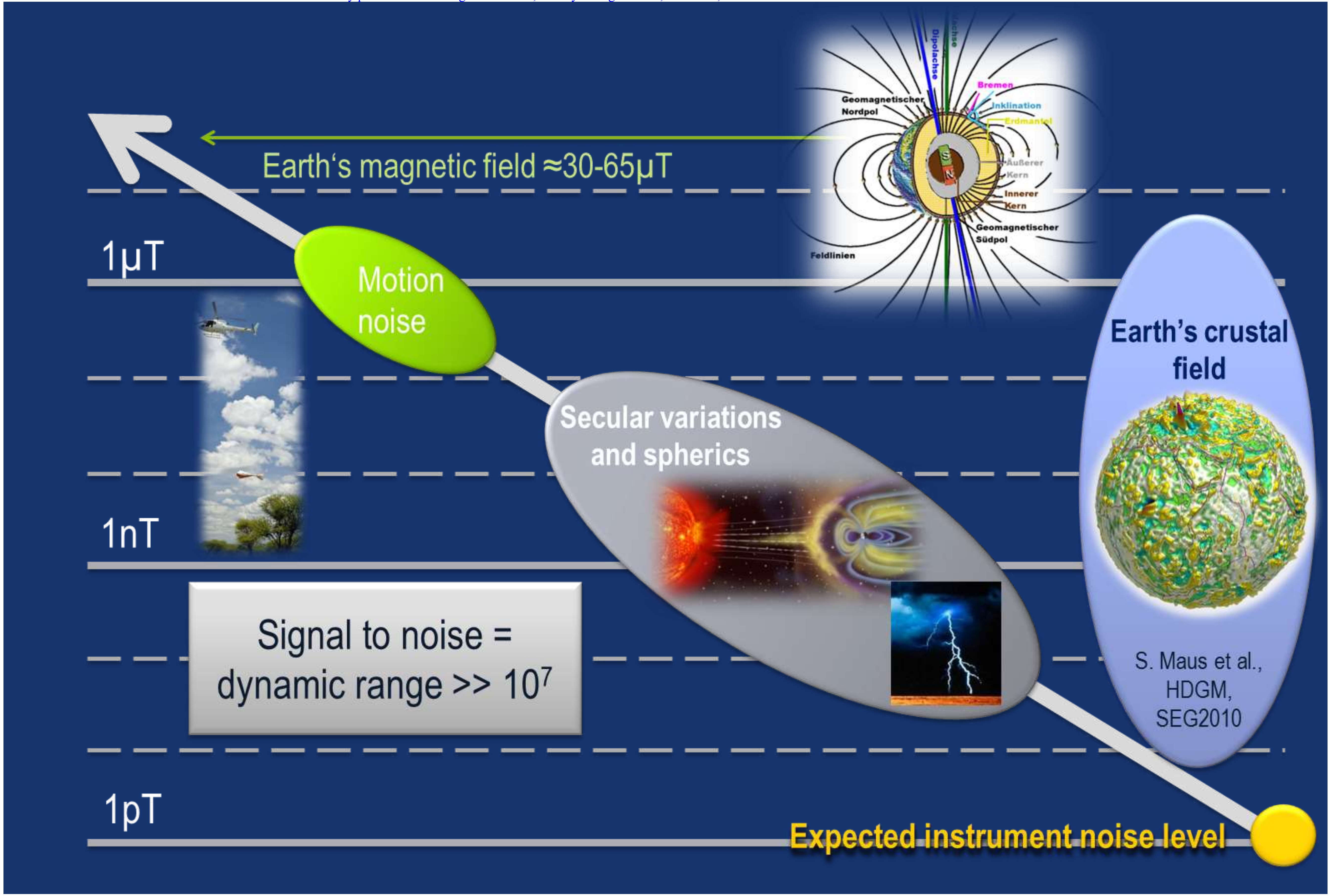
The past and present…



Geomagnetics
3D magnetometry,
Gradiometry

Magnetic (passive) method

Task of magnetic method:
Magnetic field and dynamic range



Earth‘s magnetic field ≈30-65µT

1µT

Motion noise

Secular variations and spherics

Earth’s crustal field

S. Maus et al., HDGM, SEG2010

1nT

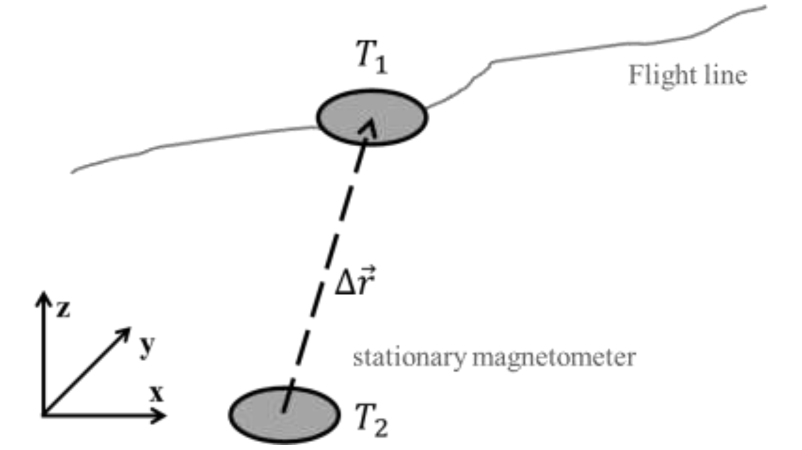
Signal to noise = dynamic range >> 10^7

1pT

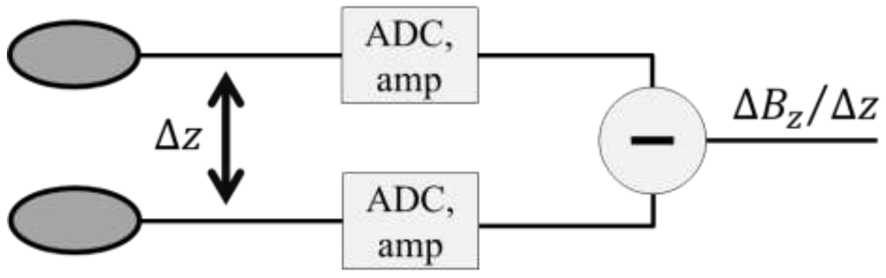
Expected instrument noise level

How to extract signal from noise in Geophysics?

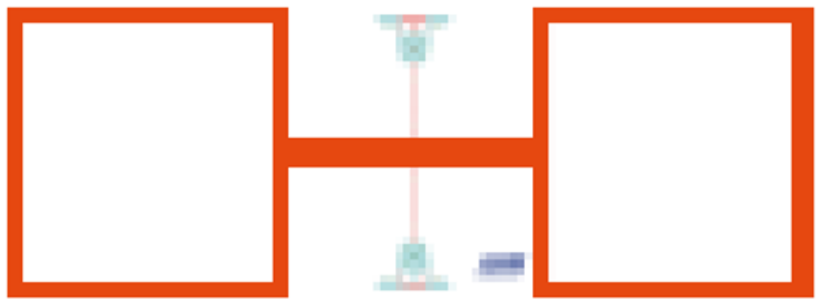
- filter in time or frequency domain (TD, FD),
- filter by ideal signal representation,
- geo-referencing,
- scalar (total field) magnetometry,
- gradiometry
  ▶ intrinsic, hardware, or software gradiometers.



Geo-referencing

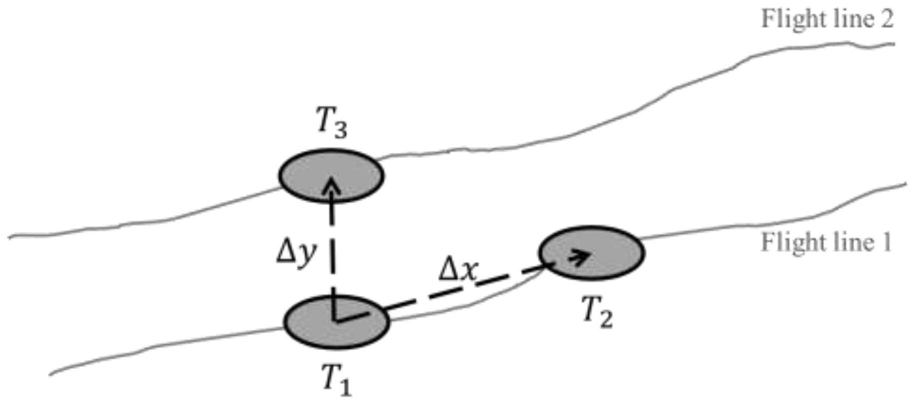


Electronic gradiometer



Intrinsic gradiometer

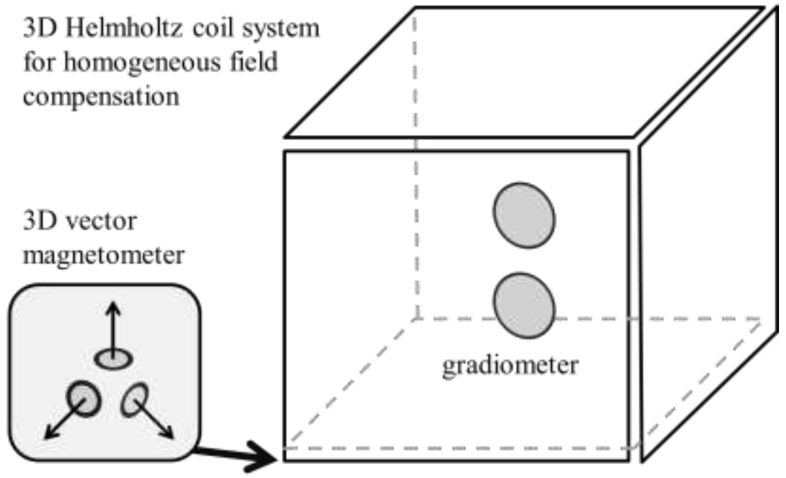
Stolz, Diss. 2006, FSU Jena

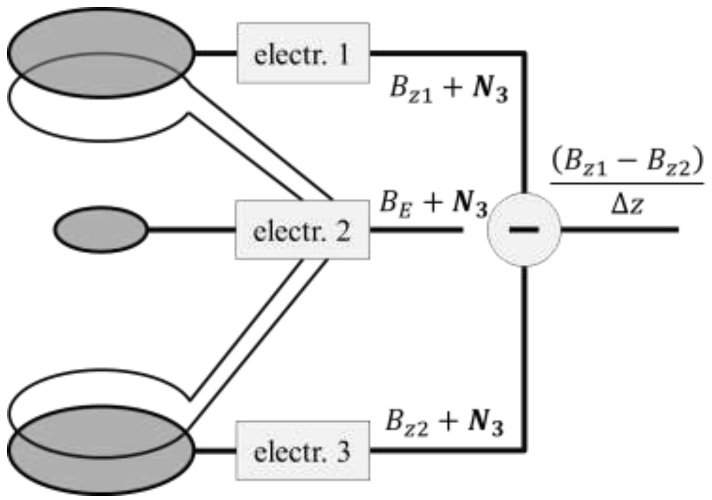


Along and cross line gradiometry

Global feedback systems With electronic or intrinsic gradiometers

K.P. Humphrey et al. [TAS 15, 753 (2005)]





Three SQUID gradiometer

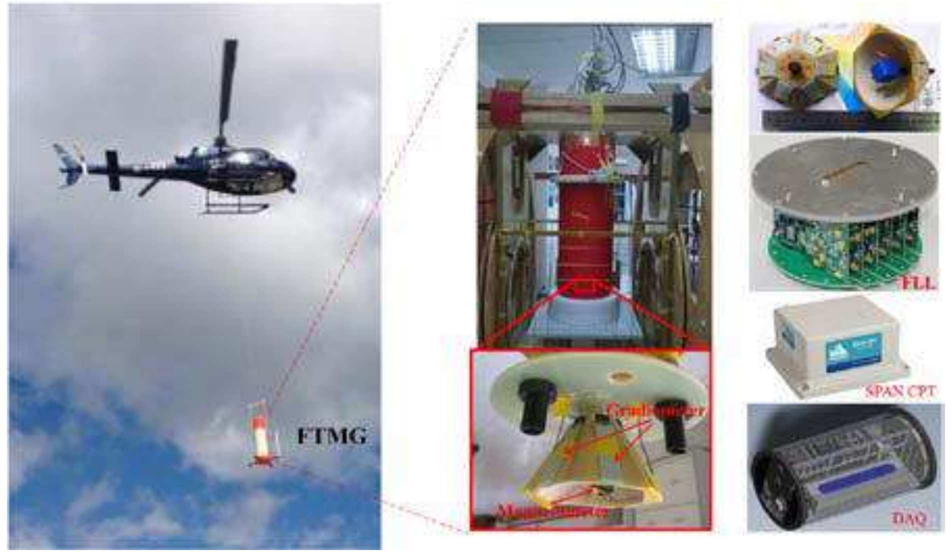
R.H. Koch et al. [APL 63, 403 (1993)]

Available FTMG instruments

Supracon AG (Germany, LTS) – JESSY STAR

SIMIT (China, LTS) FTMG instrument prototype finished 2015; still in test phase,

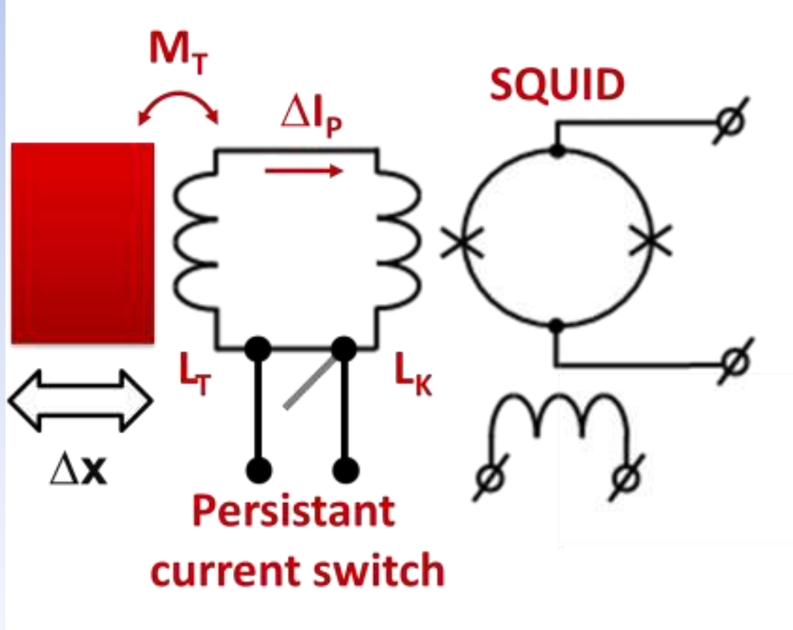
Wu et al., SEG 2016



CSIRO (Australia, HTS):
HTSTG (HTS Tensor Gradiometer) – OCEANMAG
rotating planar-type gradiometer – GETMAG

Tristan Technologies (USA, HTS) – T877

Thanks to D. Hatch, Gedex Systems Inc. Validating the Gedex HD-AGG™ Airborne Gravity Gradiometer, AEGC2018



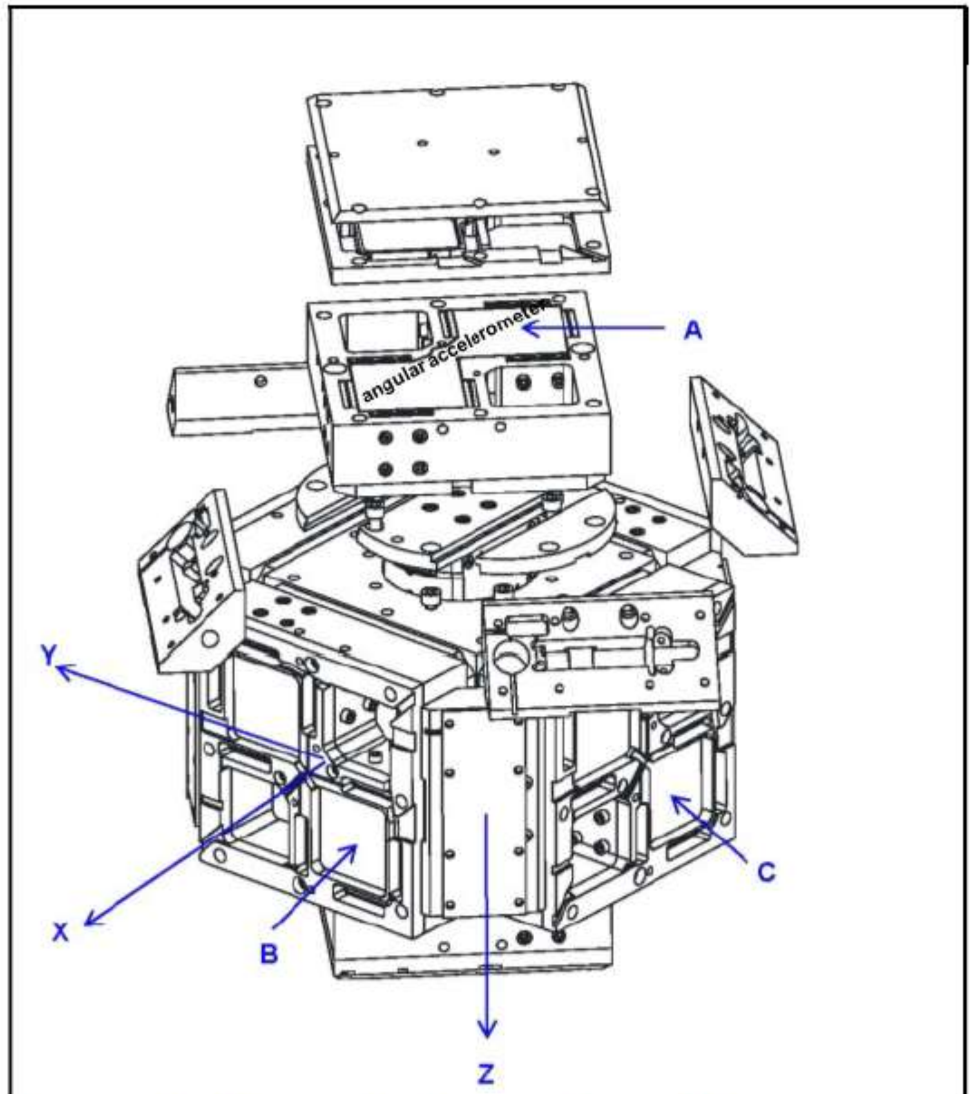


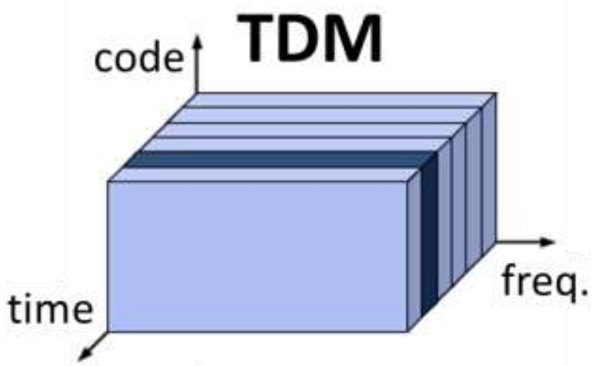
Figure 1: Originally designed as a three component gradiometer (A, B and C) the current implementation consists of two pairs (B and C) of angular accelerometers oriented vertically, perpendicular to one another. One balance beam-type accelerometer is labelled.

Gravity
Gravimeters,
Gravity gradiometry

Gravimetry

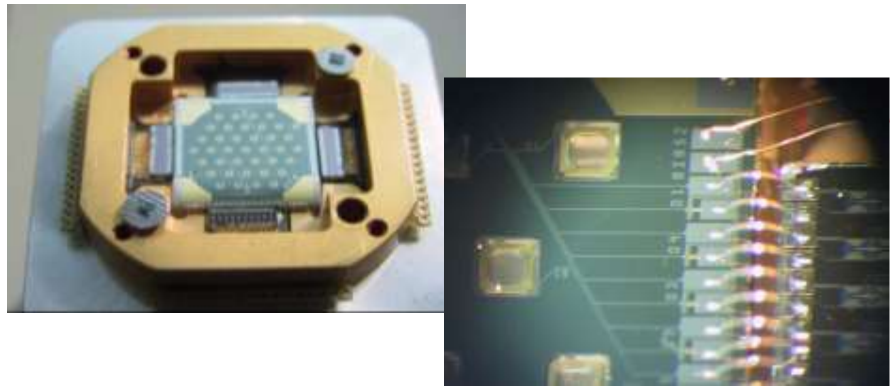
Enabling and emerging technologies

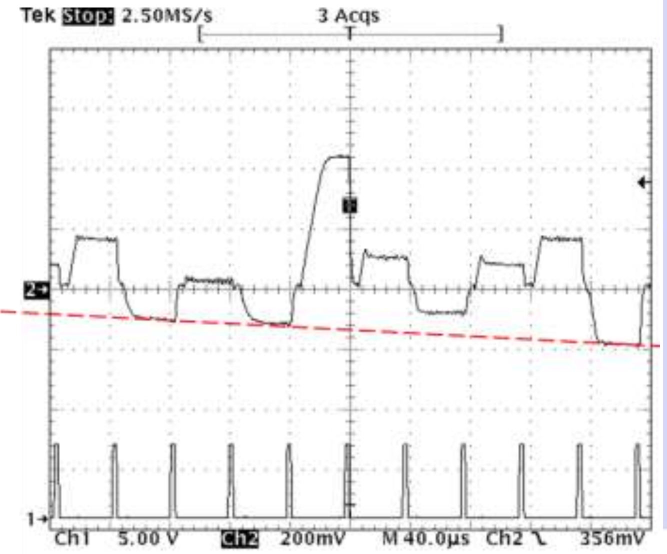
Multiplexers using SQUIDs as preamplifier

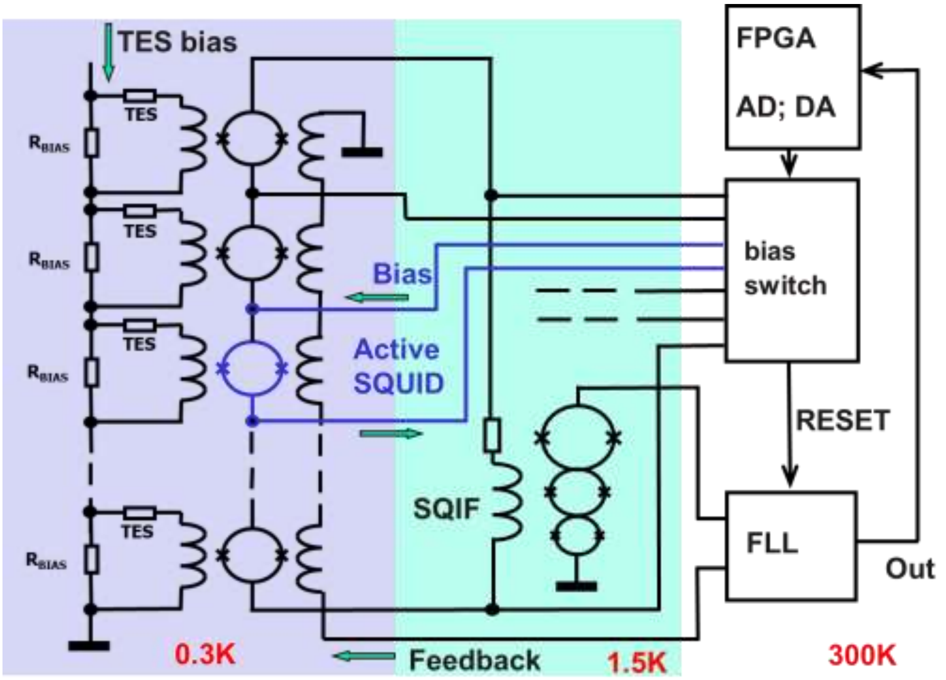


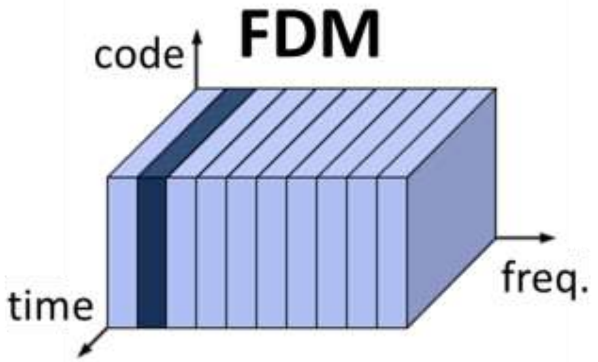
Time-Division Multiplexing (TDM)

- low technical complexity,
- increased noise (aliasing),





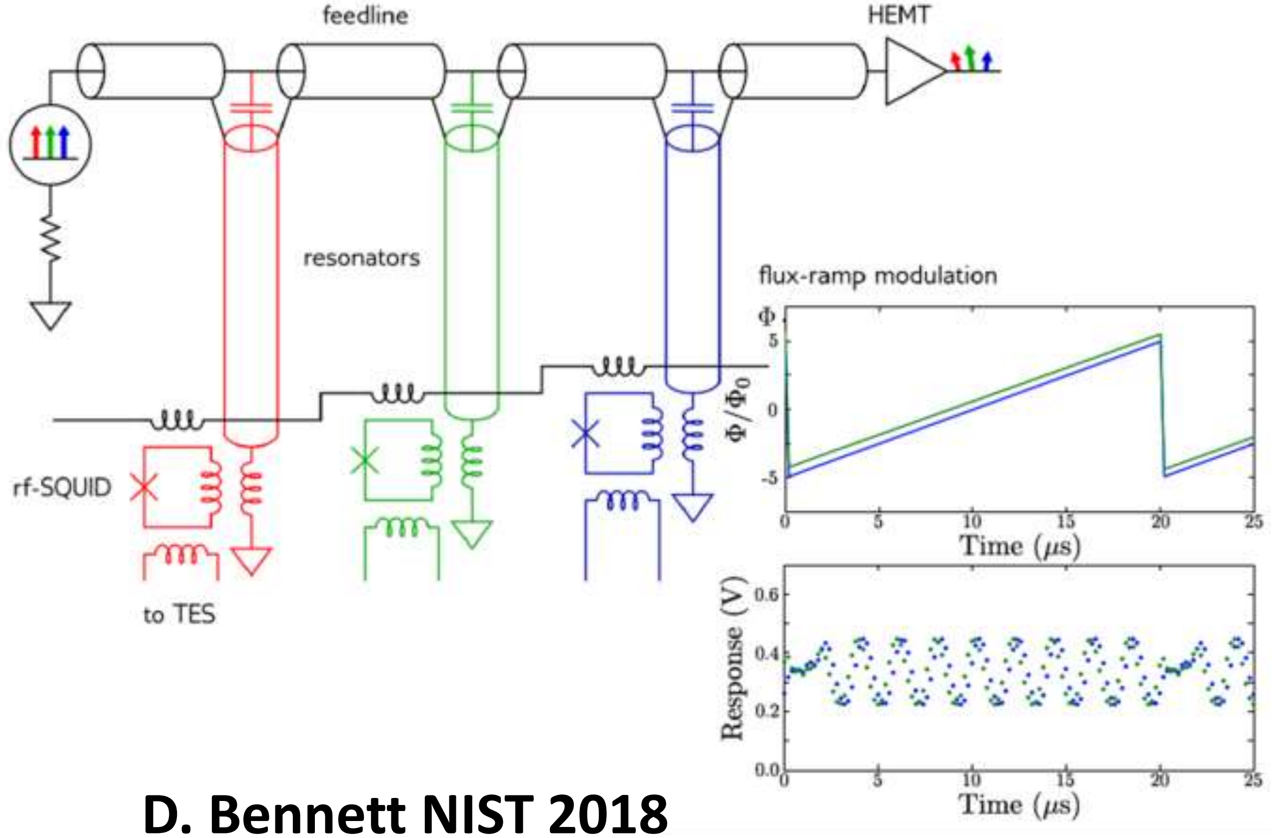


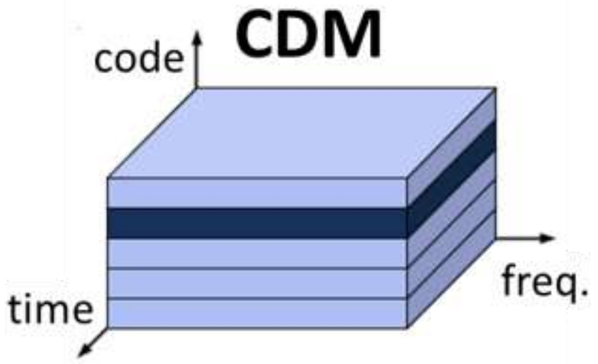


Frequency-Division Multiplexing (FDM)

- high efficiency, complex frequency generators and filters,

News e.g. in the talk of S. Kempf (Uni Heidelberg) in this session





Code-Division Multiplexing (CDM)

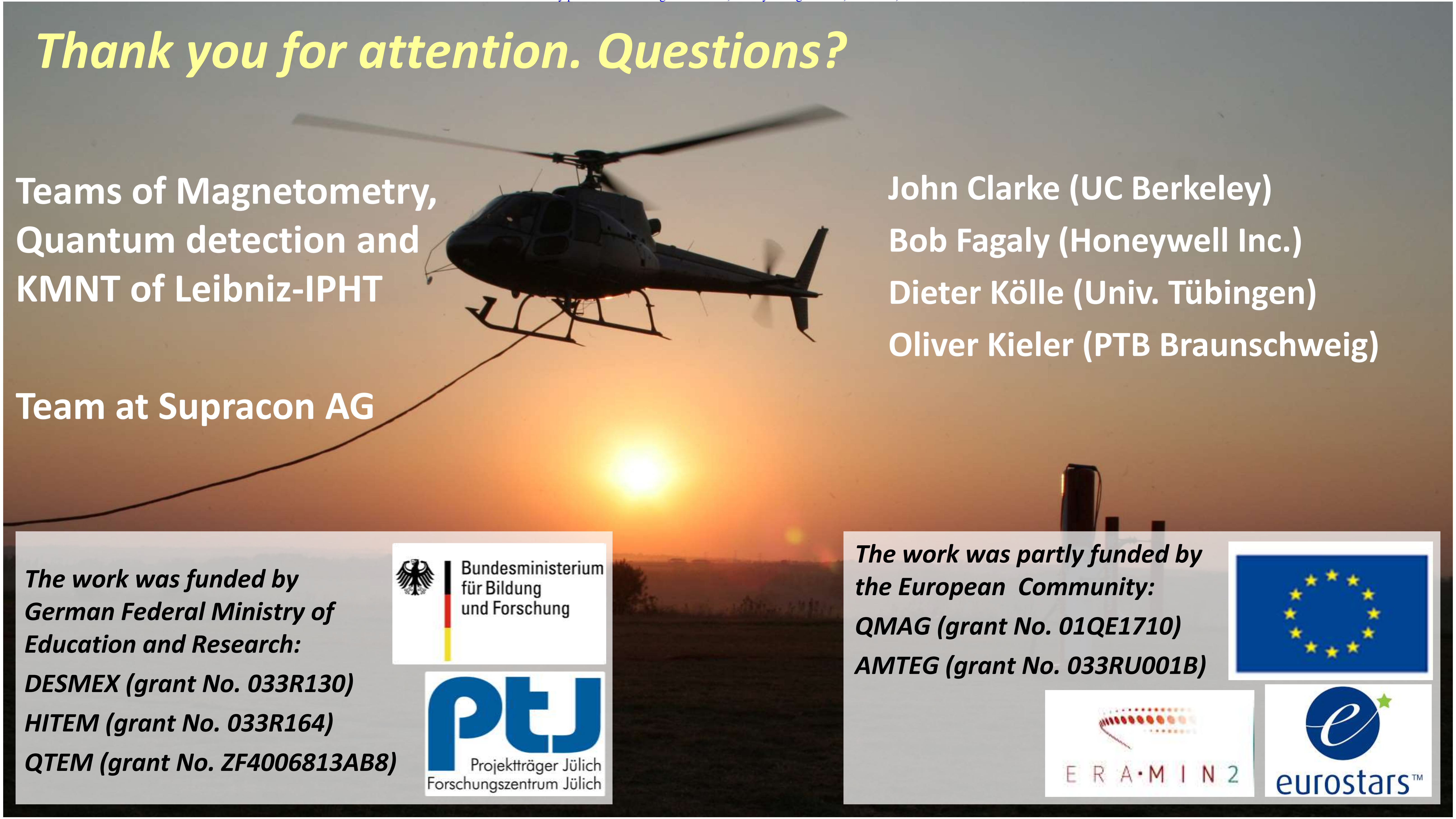
- no noise aliasing,
- reasonable complexity.

D. Bennett NIST 2018

Epilogue

- SQUID based Quantum magnetometers are a mature technology,
- SQUIDs are relative and broadband (10^{-4} - $10^{+9} Hz$) receivers with high sensitivity and resolution; at low temperatures, resolution of SQUID amplifiers is essentially limited by Heisenberg's Uncertainty Principle,
- wide range of applications enabled by the extreme resolution of the SQUIDs in physics, chemistry, biology, medicine, materials science, accelerator science, geoscience, cosmology, quantum technology and many more,
- SQUIDs in mineral exploration already a success story in discovering new targets; new instruments should be light-weight, streamlined, reliable ▶ unmanned platforms,
- main hurdles: cryogenics – small-size, low-power and cost coolers,
  overall system costs, safety and reliability,
- competition in some applications will getting harder since new types of Quantum magnetometers under development (OPM, NVCD, FRM); but in some applications SQUIDs are the enabling factor (especially if cooling is already used).

Thank you for attention. Questions?



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