CRYOGENIC CURRENT COMPARATOR

for

Beam Diagnostics

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OUTLINE

- **C**ryogenic **C**urrent **C**omparator (CCC) principle
- The CCC for DESY Hamburg
- Experimental results for an improved sensitivity
- Conclusions and Outlook

MOTIVATION

In any accelerator facility there is a need for beam control to assure the operation of the accelerator :

- Therefor a monitoring of beam parameters is necessary
  - Beam shape
  - Beam position
  - Beam intensity (number of charged particles)

MOTIVATION

Especially, in a transfer line of an accelerator facility there is a need for:

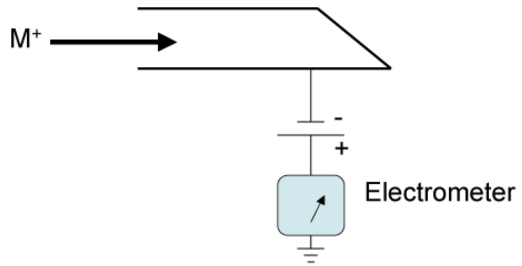
•On-line, non-destructive measurements of the intensity of charged particles beams

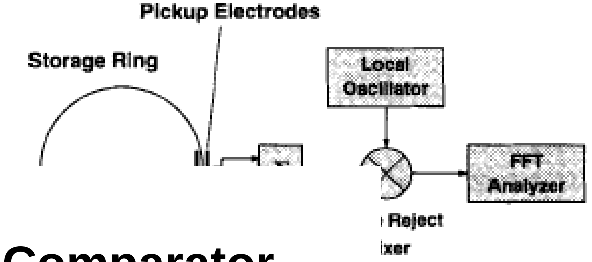
•in a wide frequency range from DC to several kHz

•with a high accuracy below 1 μA

ALTERNATIVE MEASUREMENTS

- Faraday Cup
  - Destructive
  - Low bandwidth



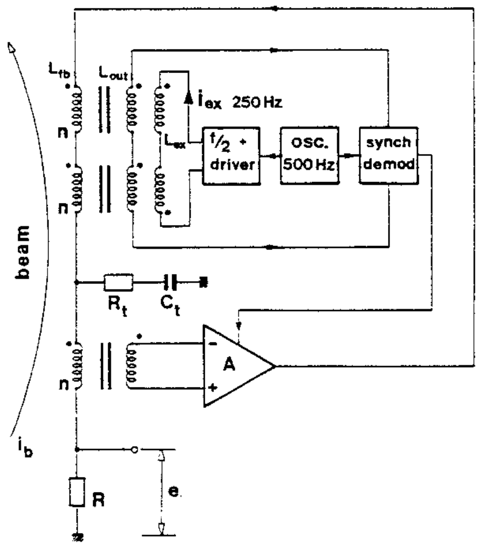


- Shottky r
  - Single
  - Averaging
  - Useful in storage rings

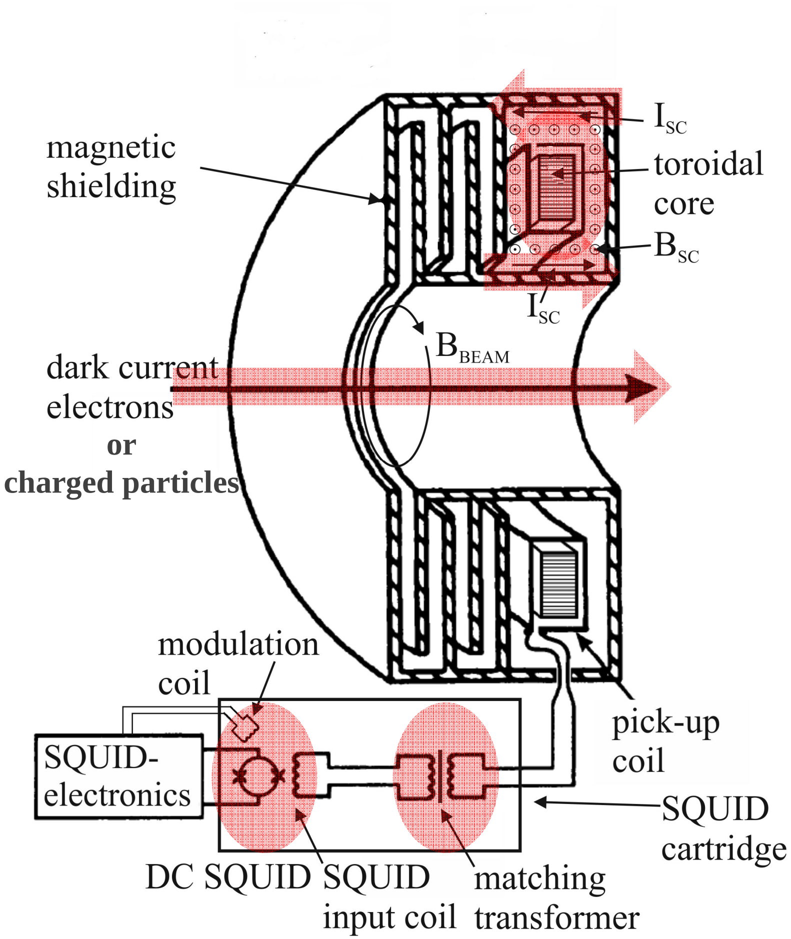
Solution:

SQUID-based Cryogenic Current Comparator

- DC Current Transformer
  - Low sensitivity
  - Low bandwidth



CRYOGENIC CURRENT COMPARATOR
CCC



Working principle

- B_{BEAM} by moving charged particles generates screening currents I_{SC} in the meander-shaped niobium superconductive shielding

- I_{SC} in turn generates B_{SC} which is transformed into a current by the superconductive niobium single-turn toroidal pickup coil with a ferromagnetic core.

- This current is measured by the high performance DC-SQUID, after being transformed by the matching transformer.

ADVANTAGES of the CCC

- Non destructive method
- High resolution (< 200 pA/√Hz, under laboratory conditions 13 pA/√Hz)
- Measurement of the absolute value of the current
- Exact absolute calibration using an additional wire loop
- Detection of DC as well as AC signals
- Independency of charged particle trajectories
- Independency of charged particle energies

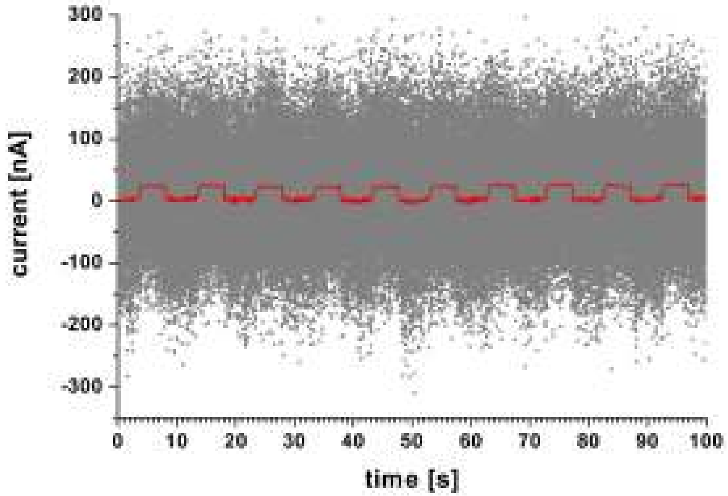
CCC at DESY Hamburg

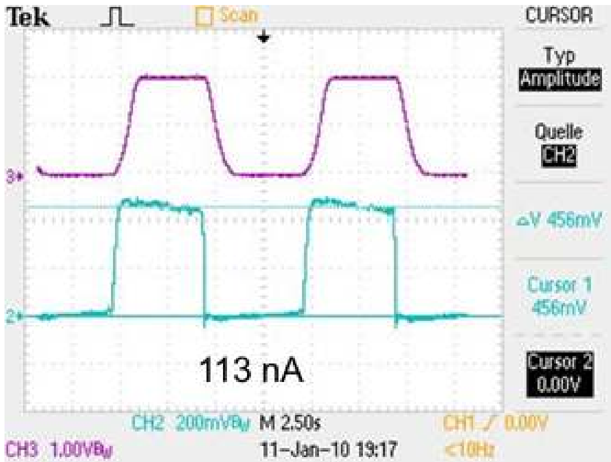
- Quality control of superconducting cavities for accelerators
- The most important criterion is the so-called ***dark current***
- Dark currents are caused by field emission of electrons in high gradient electrical fields
- Dark currents limit the accelerator performance by:
  1. Additional thermal load (T = 1.8 K)
  2. Propagating an unwanted particle current

RESULTS

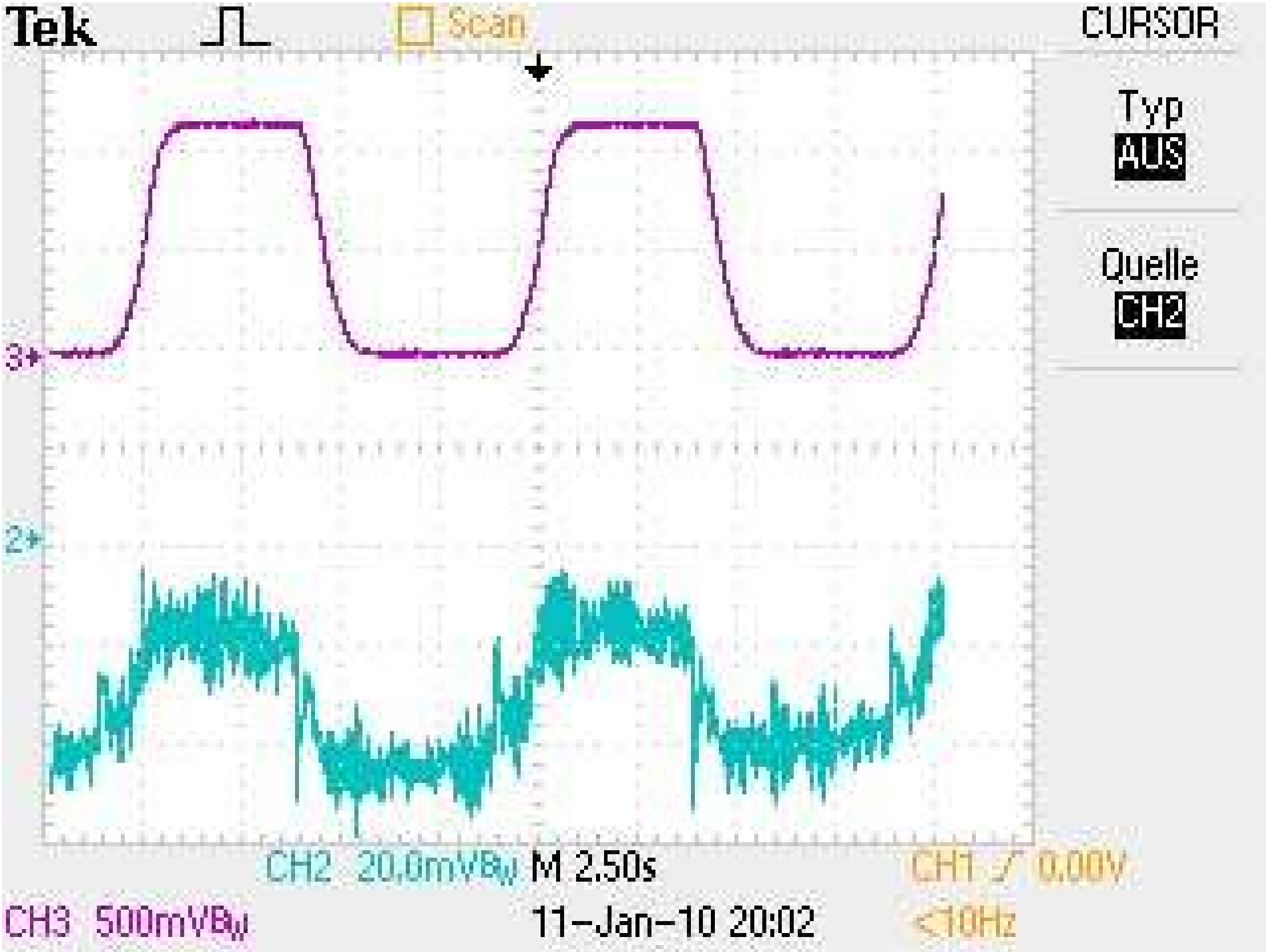
- Highly disturbed raw signals due to the acceleration environment (grey) Filtered by a low pass (5 Hz, red)
- overall current sensitivity of the CCC: 243 nA/V
- Purple: reference signal acceleration field Blue: CCC-Signal (10 Hz low pass, SR650) ΔU = 465 mV correspond to ΔI = 113 nA

View into the opened test facility “*HoBiCaT”* at BESSY





RESULTS



SQUID signal (blue), filtered by a low pass (10 Hz), ΔU = 21 mV correspond to ΔI = 5 nA
Reference signal (purple) of acceleration field

The Future: CCCs for FAIR

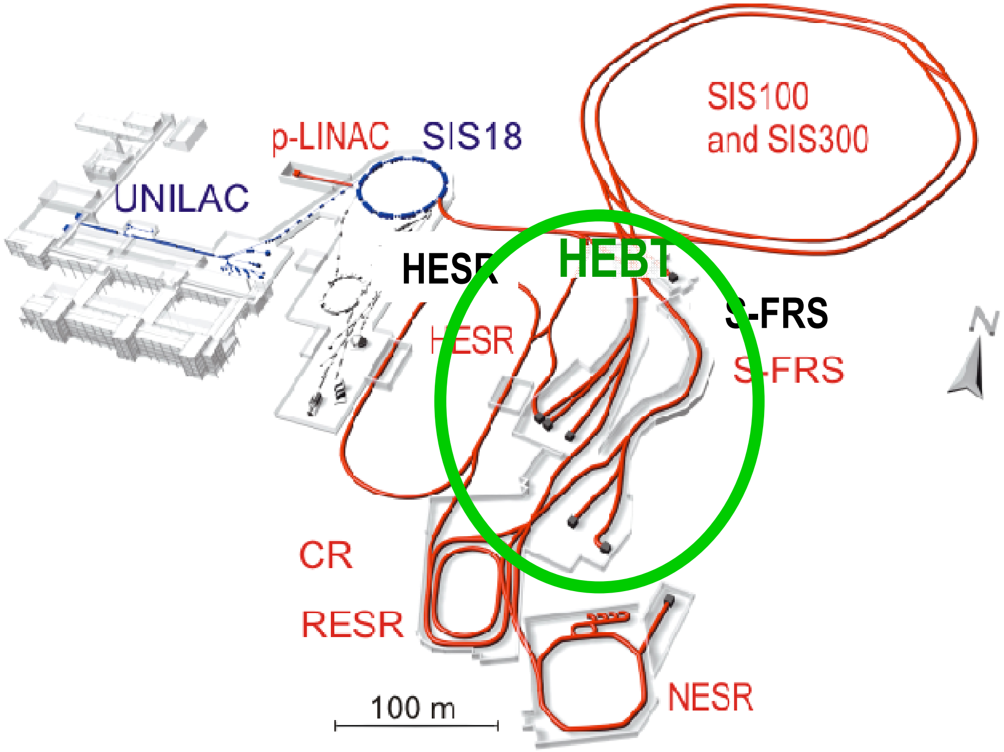
Goal of FAIR facility:
production of **'unprecedented' high intensity, high brightness ion beams**, beams of rare isotopes and antiprotons

High-Energy Beam Transport (HEBT) section requires detectors for online monitoring of very low currents of slow extracted ion beams

4 CCC installations foreseen in FAIR HEBT

Beamline	Location	Extraction type	Particle species
T1S1	SIS18-SIS100	slow, fast	ions, protons
T1X1	SIS100 extraction	slow, fast	ions,protons
T1D1	SIS100 ->dump	slow	ions, protons
TFF1	SFRS-Target	slow	ions

FAIR: Facility for Antiproton and Ion Research



For all 4 beam lines :

minimal Intensity: 10^4 pps

maximal intensity: 10^{12} pps

Ion	maximum beam current
p	160 nA
U^{28+}	4.5 µA

Improvement of overall current sensitivity and noise reduction

Properties of ferromagnetic materials at low temperatures

IMPROVEMENT of OVERALL CURRENT SENSITIVITY and NOISE REDUCTION

Extensive investigations on the ferromagnetic core material of the superconducting pickup coil necessary

- Fluctuation-Dissipation-Theorem (FDT)

–Current noise of a superconducting pickup coil L_S with losses R_S due to the core material in series to the superconducting input coil of a SQUID L_{SQUID} could be calculated with the Fluctuation-Dissipation-Theorem (FDT)

$$\left\langle I^2 \right\rangle = 4k_B T \int \frac{R_S(\upsilon)}{\left(2\pi\upsilon\left(L_{SQUID} + L_S(\upsilon)\right)\right)^2 + \left(R_S(\upsilon)\right)^2} d\upsilon$$

IMPROVEMENT of OVERALL CURRENT SENSITIVITY AND NOISE REDUCTION

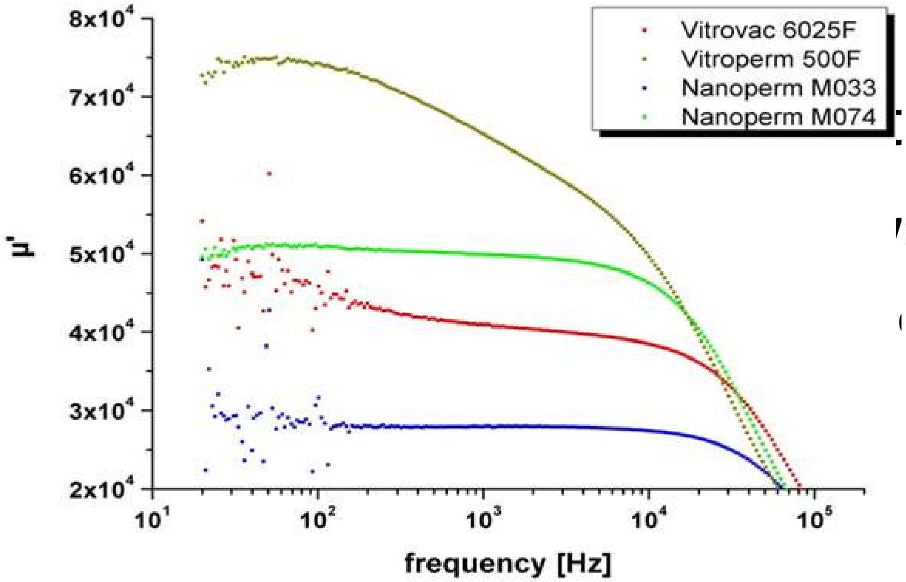
Extensive investigations on the ferromagnetic core material of the superconducting pickup coil necessary

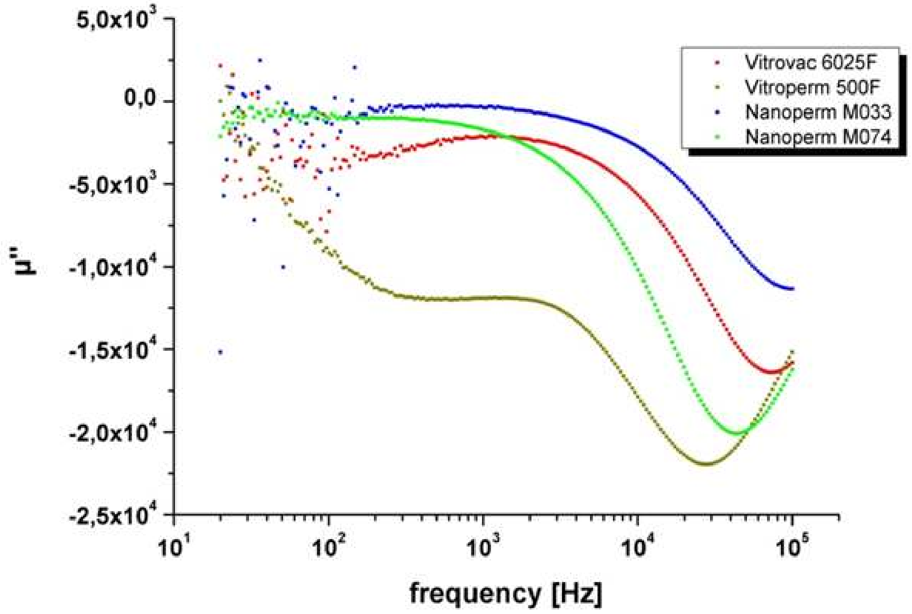
- For a CCC with a pickup coil, the current noise is dependent on the temperature T, the geometric inductance L and the complex relative permeability μ_r of the ferromagnetic core material. The relative permeability μ_r is also temperature as well as frequency dependent.

$$\mu_r(T,\upsilon) = \mu_r'(T,\upsilon) + j\mu_r''(T,\upsilon)$$

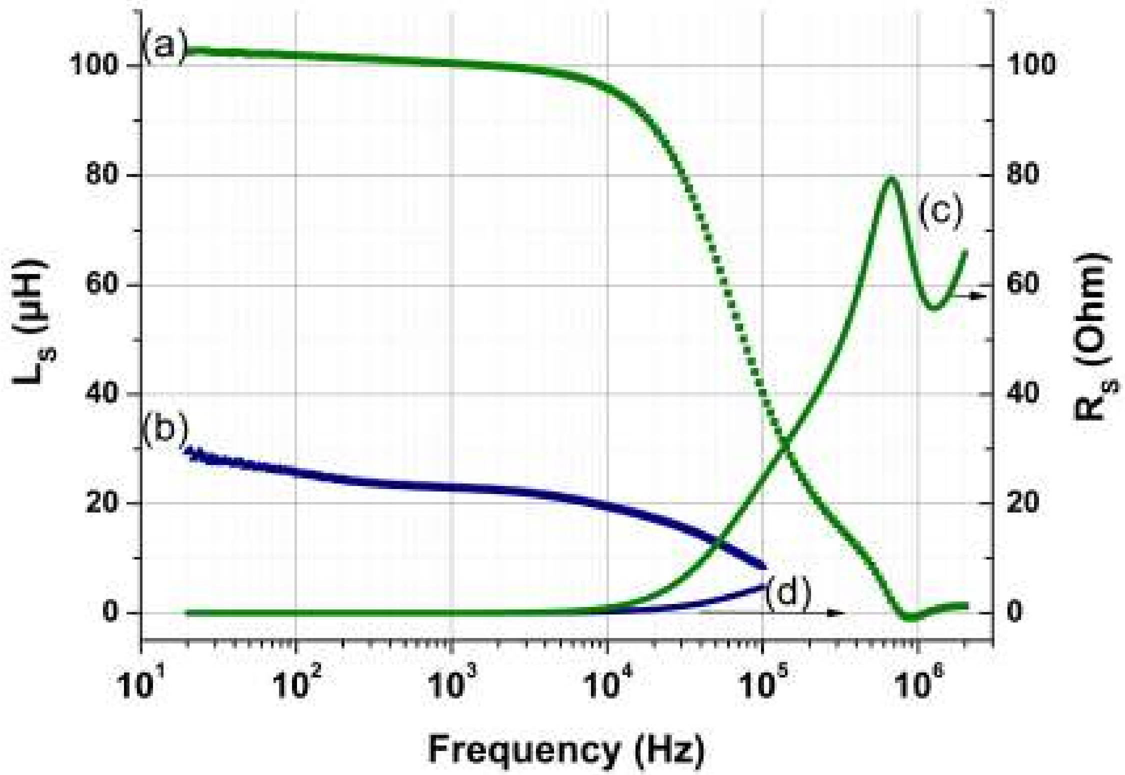
$$\mu_r' = \frac{L_s(T,\upsilon)}{L} \qquad \mu_r'' = -\frac{R_s(T,\upsilon)}{\omega L}$$

REQUIREMENTS to the CORE MATERIALS at 4.2 K





COMPARISON with DESY-CCC PICKUP COIL



Inductance L_S and resistance R_S at 4.2 K of Nanoperm M-764-01 core 2 [(a), (c)]
and DESY-CCC pickup coil (Vitrovac 6025) [(b), (d)].

Equipment

Need for commercial SQUIDs and SQUID-Electronics which are available on the market with reproducible properties.

UJ111 and SQUID-CONTROL 5

- The complete CCC should be prepared for a small series with several copies of this prototyp. But:
  - SQUID UJ111 only from inventory
    - Niobium technology is not available anymore
  - A new SQUID-Control 6 has to be developed to meet the requirements of FAIR (e.g. fully computer-controlled)
    - No manpower
- Need for commercial SQUIDs and SQUID-Electronics which are available on the market with reproducible properties.

COMMERCIAL SQUID-SYSTEMS
Magnicon GmbH, Hamburg

Low-noise SQUID sensor for almost all applications

- Additional positive feedback (APF) for direct readout
- Sensors without APF also available
- R-C shunt across input coil
- Optional current limiter (Q-spoiler) in series to input coil
- Optional feedback transformer in series to input coil
- Six input inductances available 24 nH to 1.8 µH
- Input sensitivity 2.2 $\mu A/\Phi_0$ to 0.2 $\mu A/\Phi_0$
- Typical flux noise @ 4 K 1.2 $\mu\Phi_0/H^{1/2}$
- Typical energy resolution @ 4 K 100 h
- 1/f corner frequency ~ 3 Hz

SEL-1 SQUID Electronics

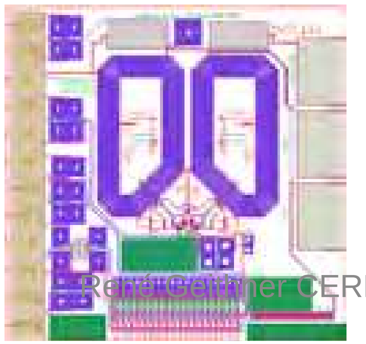
- Fully computer-controlled
- Dynamic field compensation allows magnetically unshielded SQUID operation

Preamp

- Low noise bipolar input stage
- White voltage noise 0.4 $nV/H^{1/2}$
- Voltage noise @ 0.1 Hz 0.6 $nV/H^{1/2}$
- White current noise 4 $pA/Hz^{1/2}$
- Current noise @ 0.1 Hz 50 $pA/H^{1/2}$

FLL Mode

- Maximum FLL bandwidth 6 MHz
- Fast external integrator reset <1 µs
- AC bias frequency < 250 kHz
- Aanalog output signal range ±13 V



Data Sheet
1-stage Current Sensor C5XL1W

Sensor ID: C509_C41

date measured		2012.01.25
nominal input inductance Lin (nH)		1000
input coupling 1/Min (µA/Phi0)		0,29
feedback sensitivity 1/Mf (µA/Phi0)		40,5
maximum voltage swing ΔVmax (µV)		40,1
voltage swing @ working point ΔVw (µV)		32,81
transfer coefficient Vphi (µV/Phi0)		489,2
heater current in liquid Helium via ±V (mA)		70
heating time in liquid Helium via ±V (s)		0,1
bias current Ib (µA)		10
bias voltage Vb (µV)		16
setup file name		C509_C41.stp
flux noise (µPho/√Hz)	@ 50kHz	1,03166
	@ 10kHz	1,04294
	@ 1kHz	1,06576
	@ 100Hz	1,21884
	@ 10Hz	1,37335
	@ 1Hz	2,04892
	@ 0.1Hz	3,67301

All values obtained with XXF-1 SQUID electronics @ 4,2K.

COMMERCIAL SQUID-SYSTEMS
Supracon Jena SQUID System (JESSY)

- Integrated input coil, a feedback coil for flux in the SQUID, a feedback coil for compensation of the input current, and a heater.
- Input and feedback coil are inductively coupled to the SQUID.
- Input inductances 0,42 μH
- Input sensitivity 0.26 $\mu A/\Phi_0$
- Typical flux noise @ 4 K <4 $\mu\Phi_0/Hz^{1/2}$

JESSY

- Fully computer-controlled
- Direct coupled

Preamp

- White voltage noise <0,33 $nV/Hz^{1/2}$
- White current noise <1,5 $pA/H^{1/2}$
- 1/f noise corner frequency <0,1 Hz
- Gain-bandwith product ~ 6 GHz

FLL Mode

- Small signal bandwith >10 MHz
- Slew rate [15...50 kHz] >15 $M\Phi_0/s$

Certificate

Sensor serial number: 0843
Sensor type: Current sensor SQUID
Model: CP2 blue

Test report number: 4SO/1970 - 18/24
Date: 18.10.2011
Signature:

	Parameter	Value	Unit
4.2K (open input coil)	critical current I_c	18,8	µA
	SQUID resistance R_n	2,86	Ω
	voltage swing ΔV	35	µV
	flux feedback coupling ΔI_{MOD}	10,3	µA
	current feedback coupling ΔI_{FB}	4,4	µA
	input coupling ΔI_{EK}	0,19	µA
	equivalent flux noise	5,26	$\mu\phi_0/Hz^{1/2}$
300K (room temperature)	input coil	58,9	kΩ
	flux feedback coil	2,0	kΩ
	current feedback coil	48,6	kΩ
	SQUID	120	Ω
	heater	110	Ω

This sensor has been fabricated and tested according to a quality managment system ISO 9001:2008

SQUID Current Sensors Model CPx blue with Thermal Switch

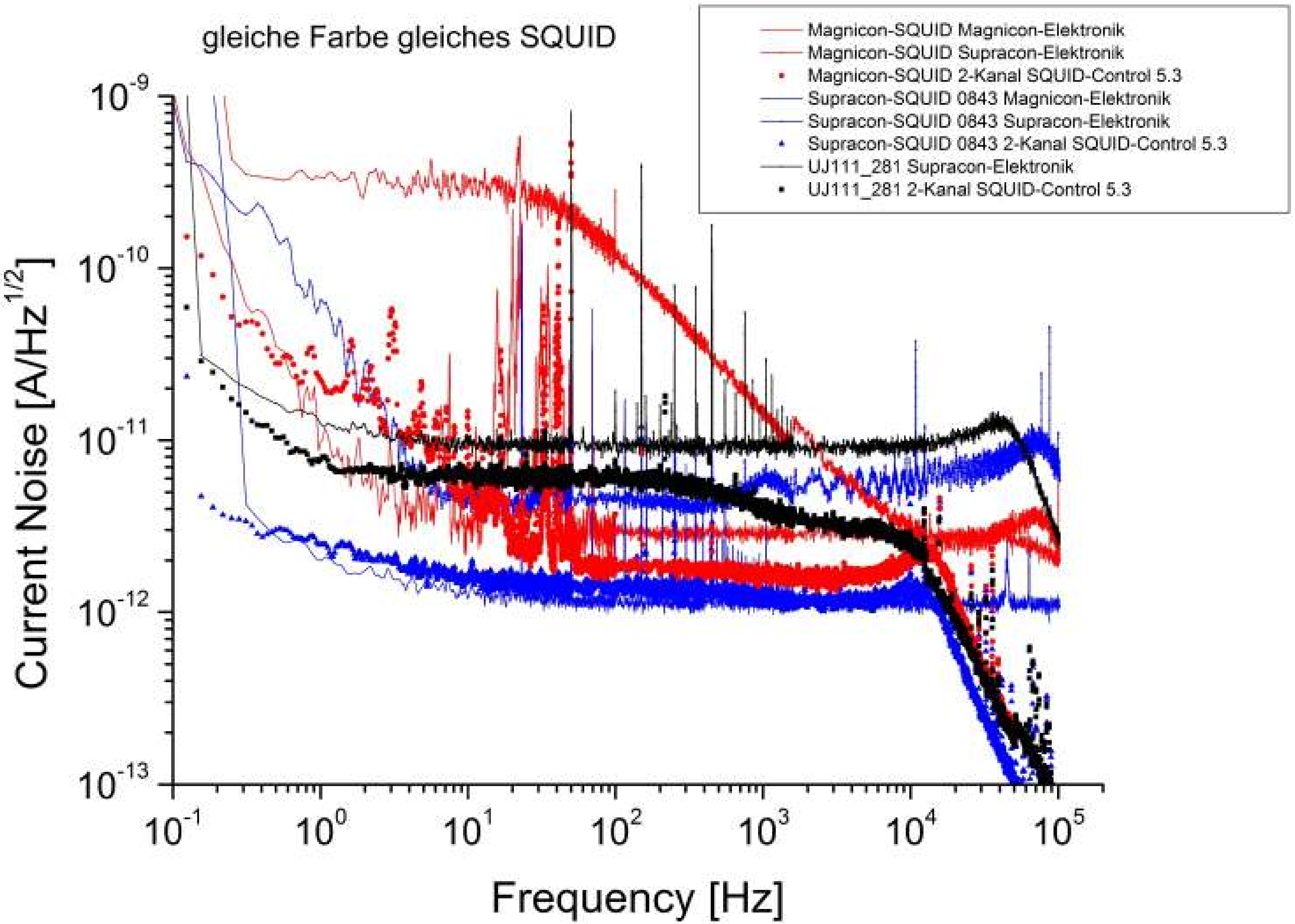
Main technical parameters

Model	SQUID inductance at open input coil (pH)	Input coil inductance (nH)	Input coil – SQUID mutual inductance (nH)	Current FB mutual inductance (nH)
CP1 blue	400	1850	27	21
CP2 blue	270	460	10.5	21
Cp3 blue	150	230	5.1	10
Cp4 blue	110	160	3.5	7.0
Cp5 blue	110	80	2.5	5.0
Cp6 blue	110	50	2.1	4.2

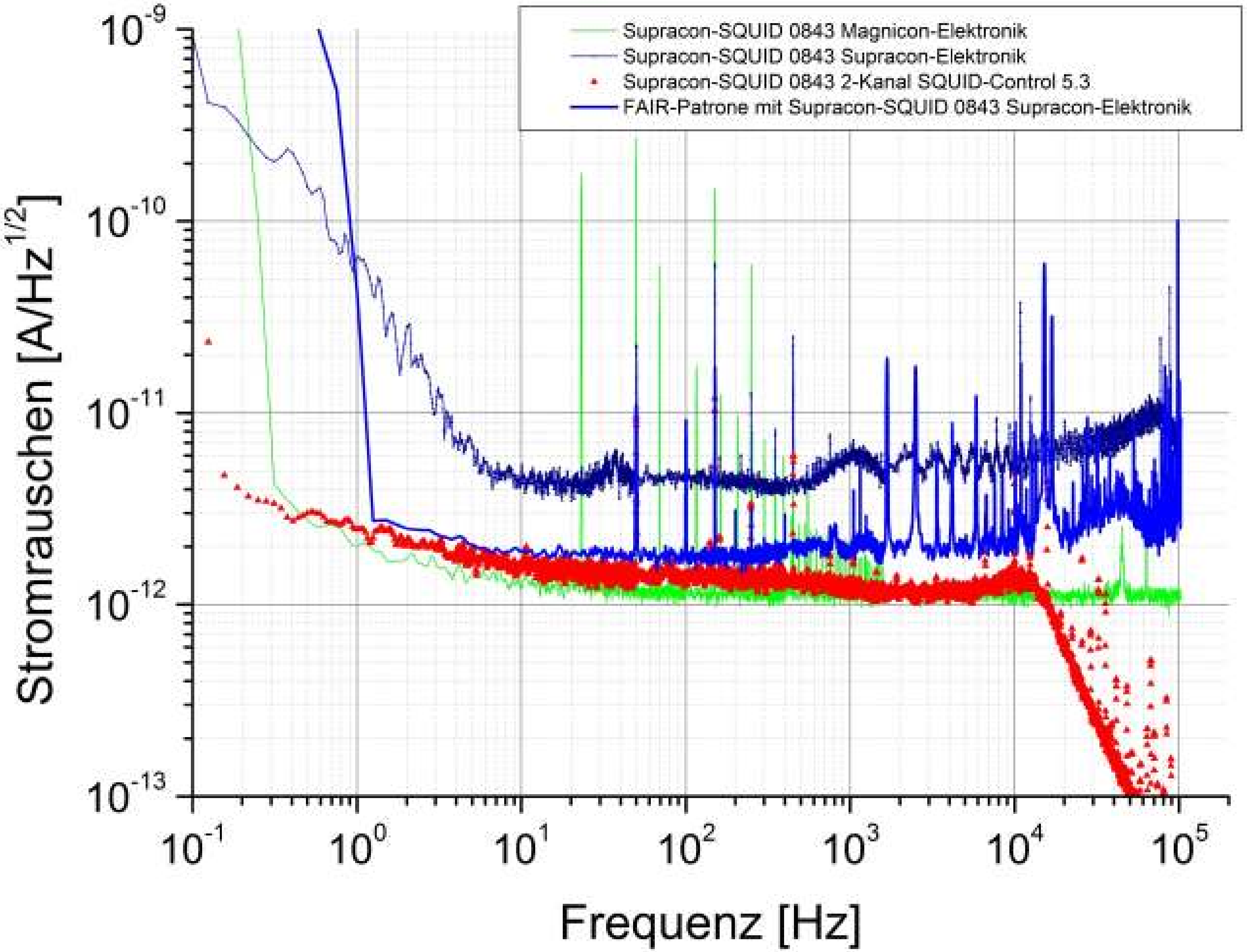
For all models	Value
Working temperature	≤ 5 K
Flux modulation coil – to – SQUID mutual inductance	200 pH
Flux modulation coupling *	10… 11 $\mu A/\Phi_0$
Resistance of the thermal switch when active *	15…25 Ohm
Heater current to activate thermal switch	8…10 mA
Heater current to expel a frozen flux	50…100 mA

* exact value will be given for every particular SQUID in certificate.

NOISE of SQUID-SENSORS



NOISE of SUPRACON SQUID-SENSOR with DIFFERENT ELECTRONICS

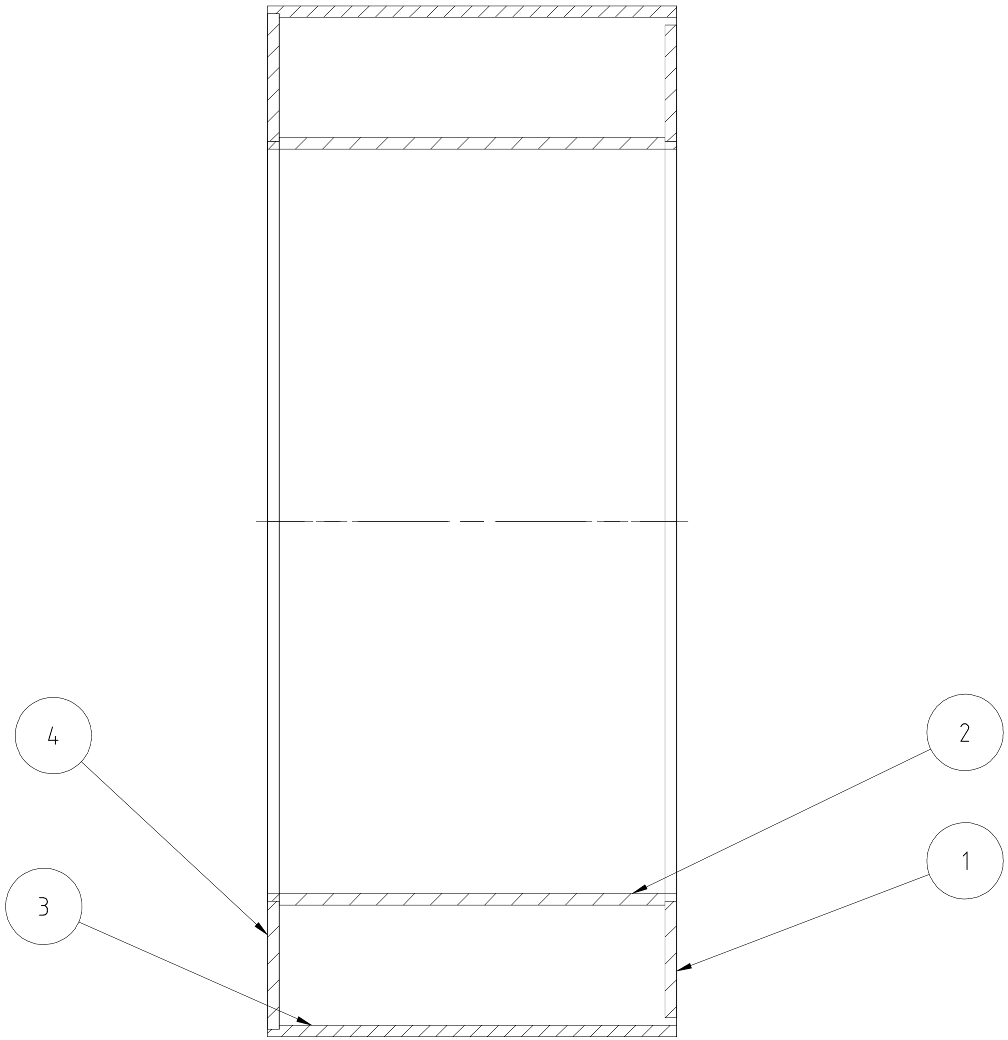


Construction

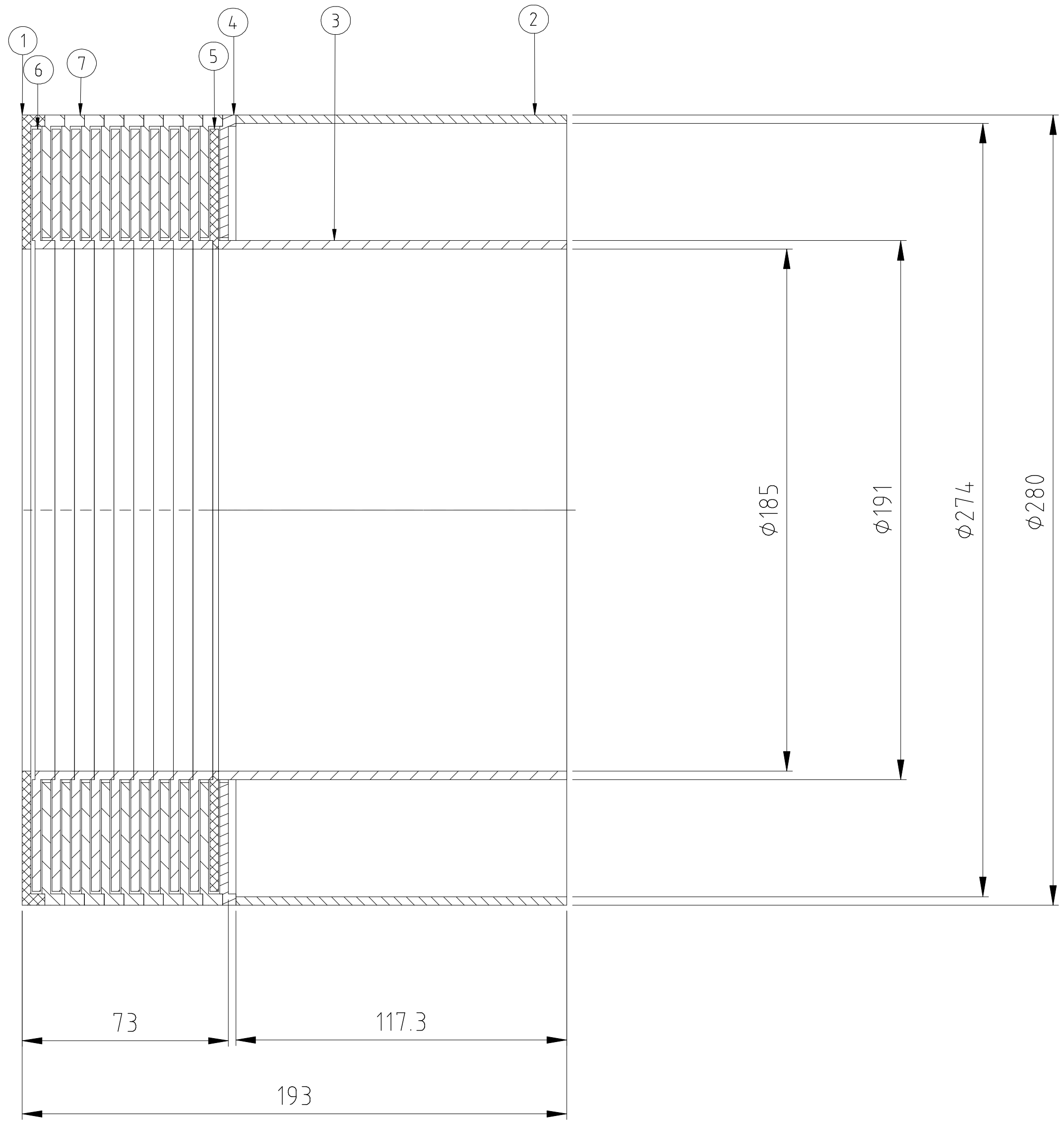
Modular design

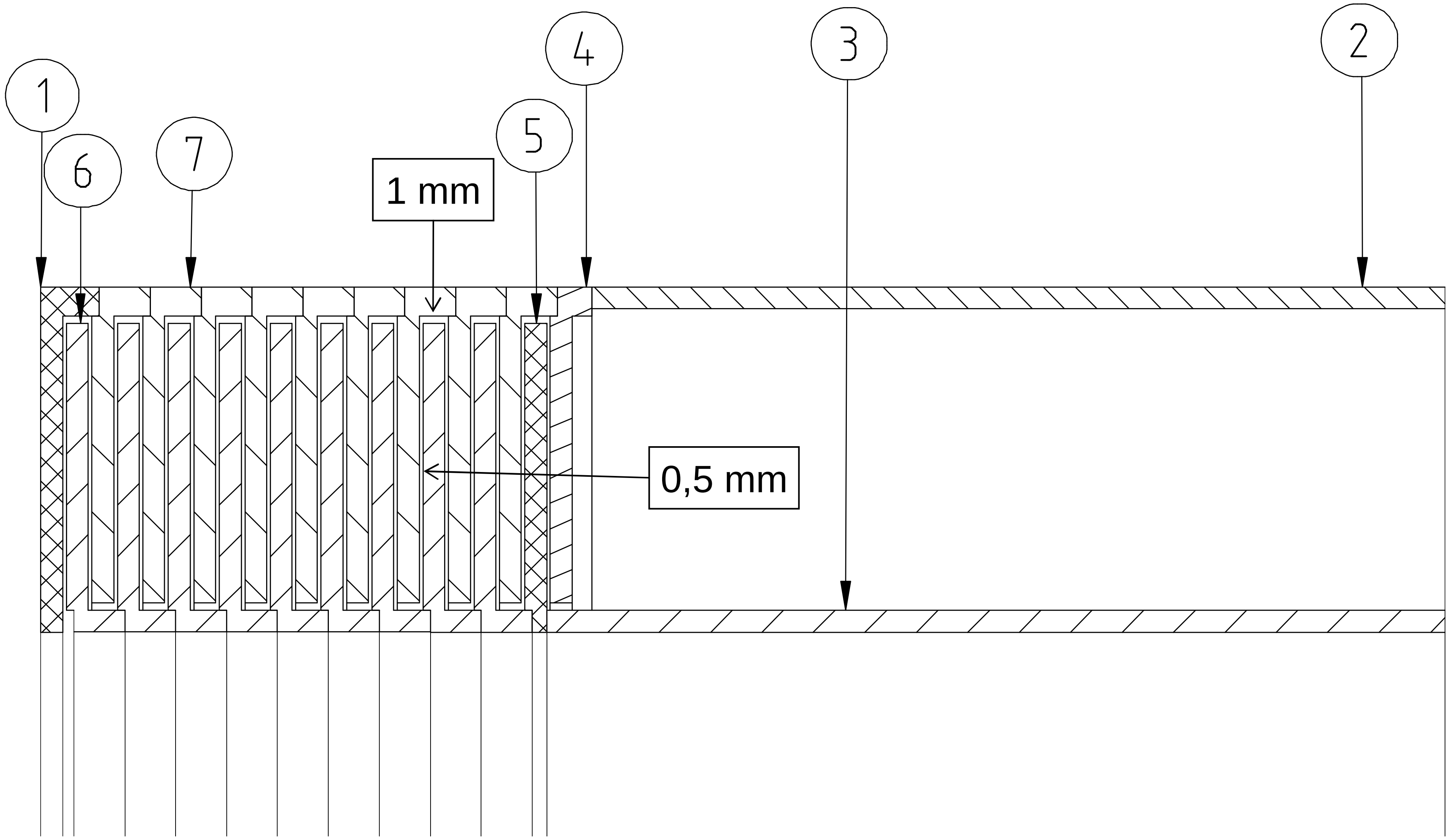
Electron beam welded

PICK-UP COIL

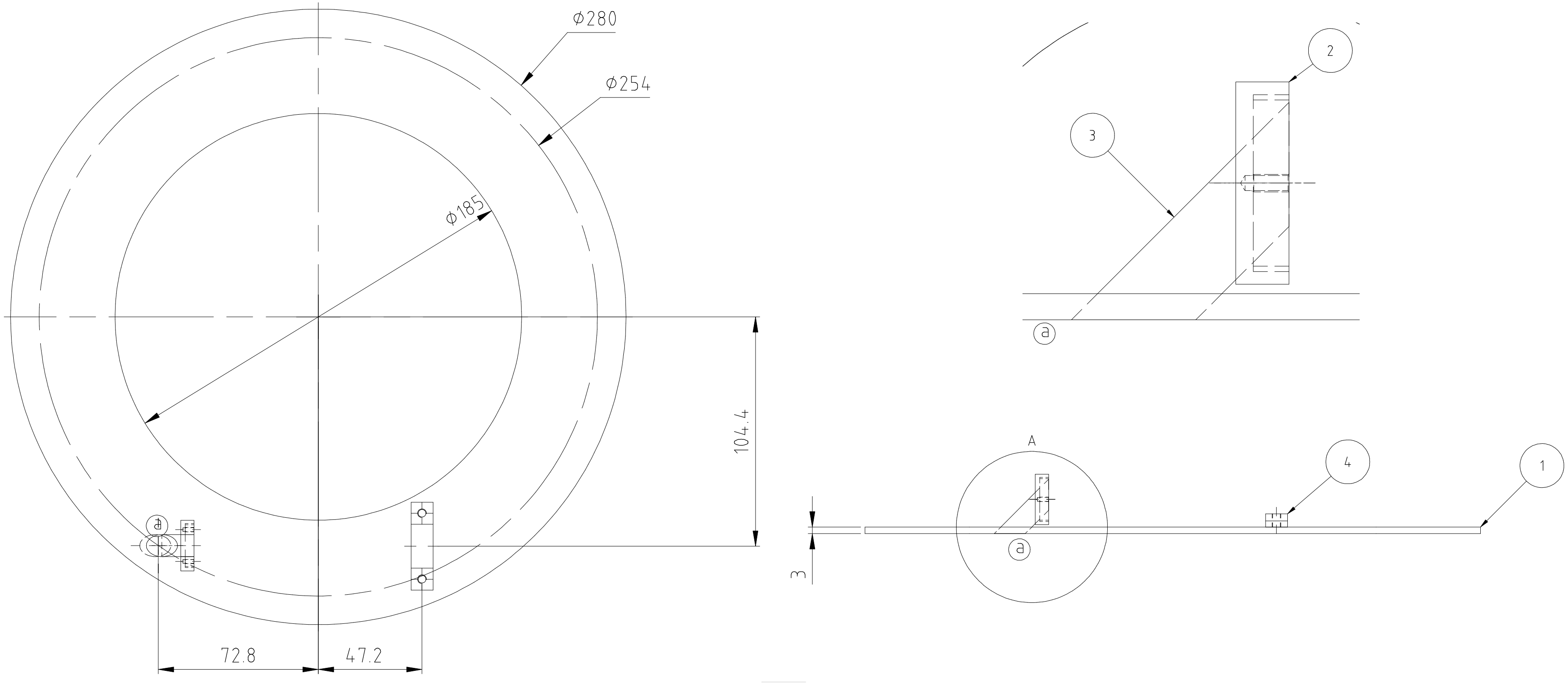


SHIELDING

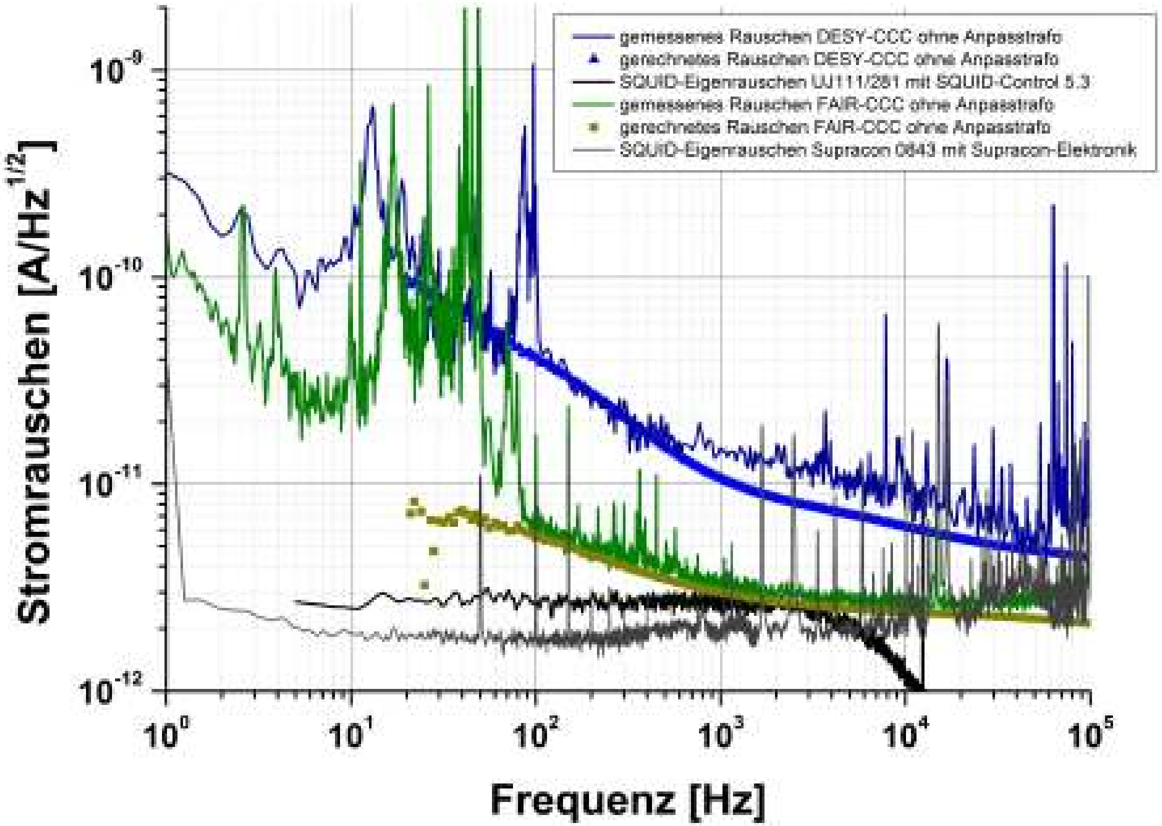



1
6
7
1 mm
5
4
3
2
0,5 mm

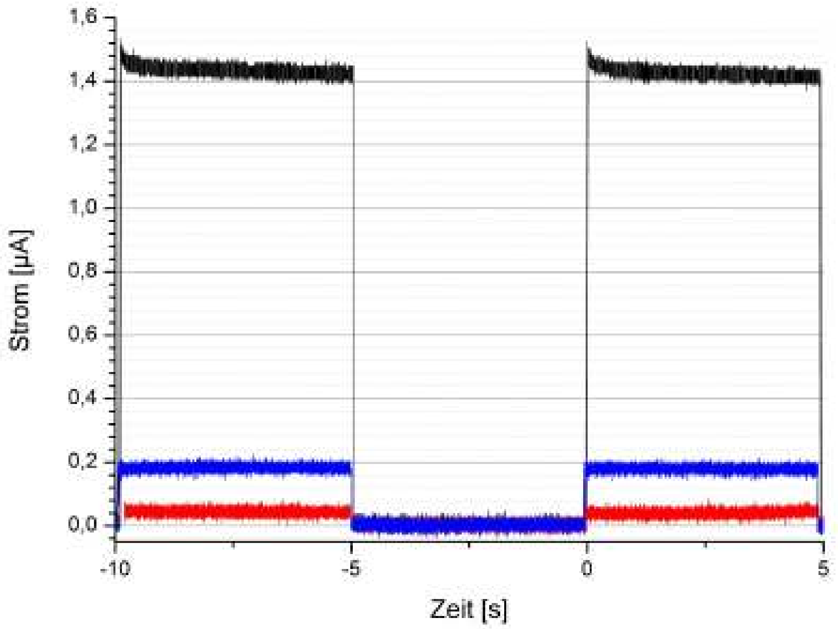
TOP COVER of SHIELDING with FEED-THROUGH and ADAPTER for SQUID-CARTRIDGE

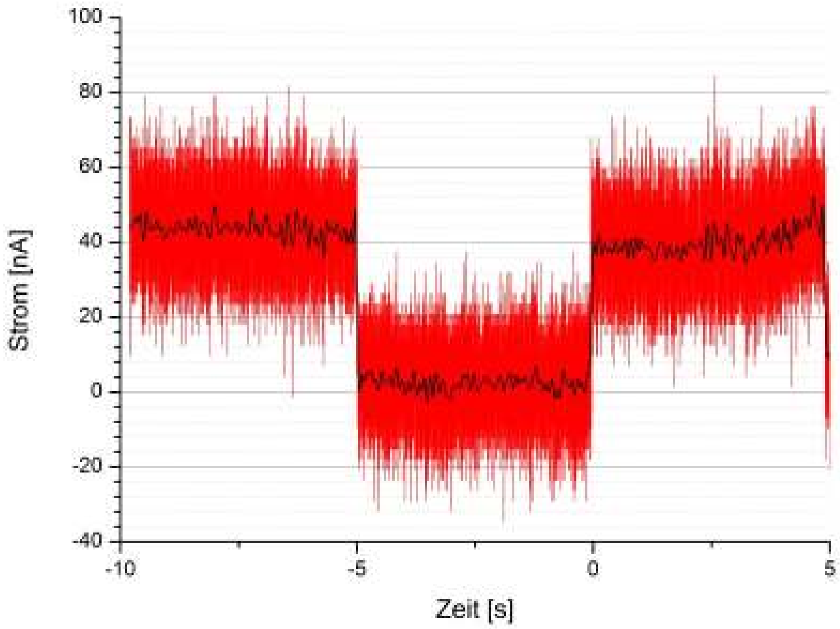


CURRENT NOISE CALCULATIONS and MEASUREMENTS

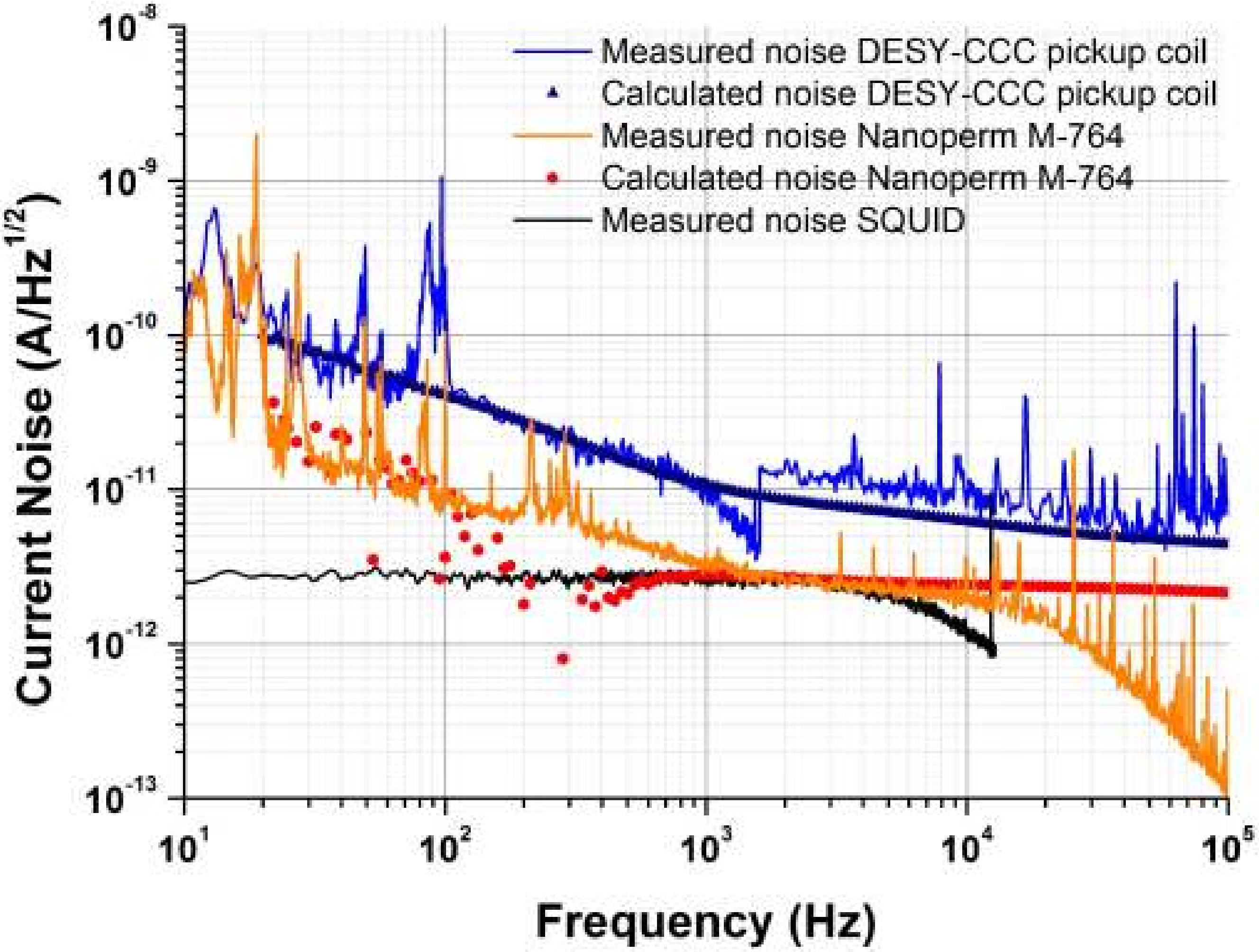


STEP FUNCTION RESPONSE



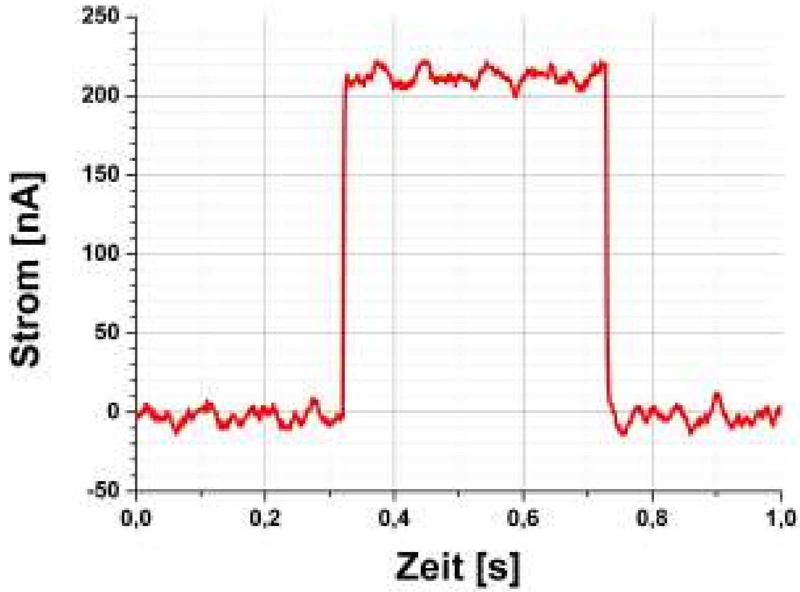


Current Noise calculations and measurements



step function response

- A current pulse of about 210 nA is fed through the Calibration Winding (approx. 0.5 Φ_0)
- No use of frequency filters or time averaging
- Signal-to-noise ratio is about 10



Outstanding advantages of a SQUID based CCC

- Non-destructive measurement method
- High resolution (< 1 nA/√Hz) – no alternatives
- No averaging
- Measurement of the absolute values of the current
- Exact absolute calibration using an additional wire loop
- Independency of charged particle trajectories and particle energies
- Negligible low drift

Summary and Outlook

- In 1996 first successful proof of the function of a SQUID-based CCC in the beam line at GSI
- Measurement of high energy ion currents of accelerators with a current resolution of **≤ 250 pA/√Hz at** GSI
- Construction and commissioning of a specialized CCC for measuring of dark currents of RF accelerator cavities with a current resolution of **≤ 500 pA/√Hz** at DESY
- Application of DESY's CCC in the HoBiCaT test stand at BESSY for measuring of dark currents with a resolution of **≤ 1 nA/√Hz**
- Noise limited current resolution under quiet conditions at Low Temp. Lab of FSU Jena: **≤ 13 pA/√Hz**

- **What are the next plans?**

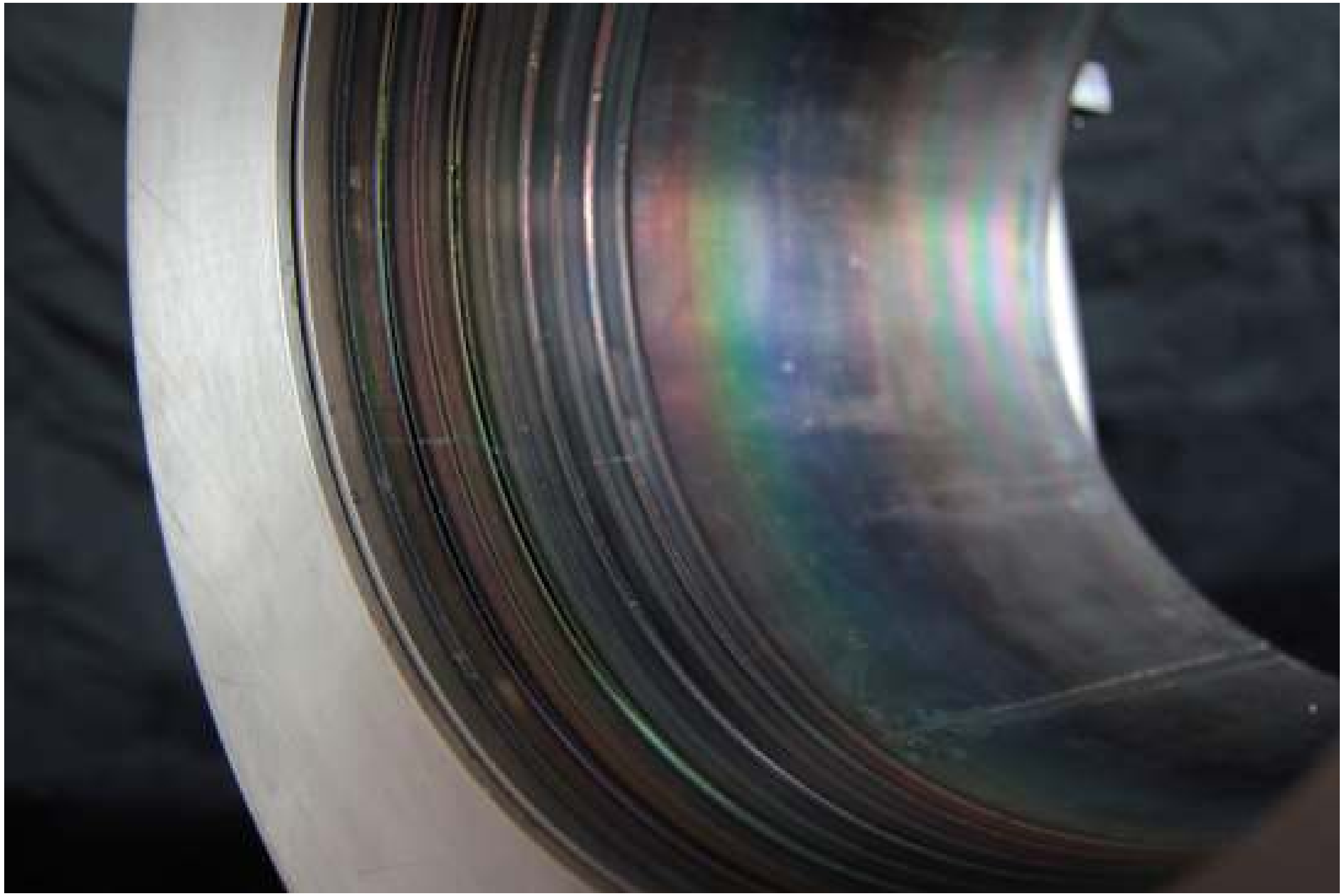
- An improved CCC is presently under construction for the Cryogenic Storage Ring at MPI für Kernphysik / Heidelberg
- 4 CCC installations are foreseen in FAIR-HEBT at GSI

CONCLUSIONS

- Measurements at GSI and HoBiCat demonstrated the suitability of the CCC as a non-destructive beam monitor for intensities down to 5 nA.
  - Measurement of high energy ion currents of accelerators and dark currents of RF accelerator cavities with a current resolution of **≤ 250 pA/√Hz**
  - Noise limited current resolution at Low Temp. Lab of FSU Jena: **≤ 13 pA/√Hz**
  - Work through some challenges like mechanical disturbances, and noise reduction
- Extensive investigations on ferromagnetic core materials at low temperatures were done.
- Nanoperm M-764-01 is the material of choice with relatively high frequency independent permeability.
- The current resolution in laboratory environment is reduced by a factor of more than three to 2.5 pA/ √ Hz in the white noise region.
- The total noise in the frequency range from 20 Hz up to 10 kHz would be reduced by a factor of more than three to 28 nA compared to 87 nA for the DESY-CCC pickup coil.

CONCLUSIONS

- Measurements at GSI and HoBiCat demonstrated the suitability of the CCC as a non-destructive beam monitor for intensities down to 5 nA.
- Extensive investigations on ferromagnetic core materials at low temperatures were done.
- The current resolution in laboratory environment is reduced by a factor of more than three to 2.5 pA/ √ Hz in the white noise region.



OUTLOOK

- Characterization of the completed CCC in the Low Temperature Lab
  - Sensitivity
  - Current resolution
  - Bandwidth
  - Field attenuation
- Test in Beamline at GSI

THANK YOU FOR YOUR ATTENTION!

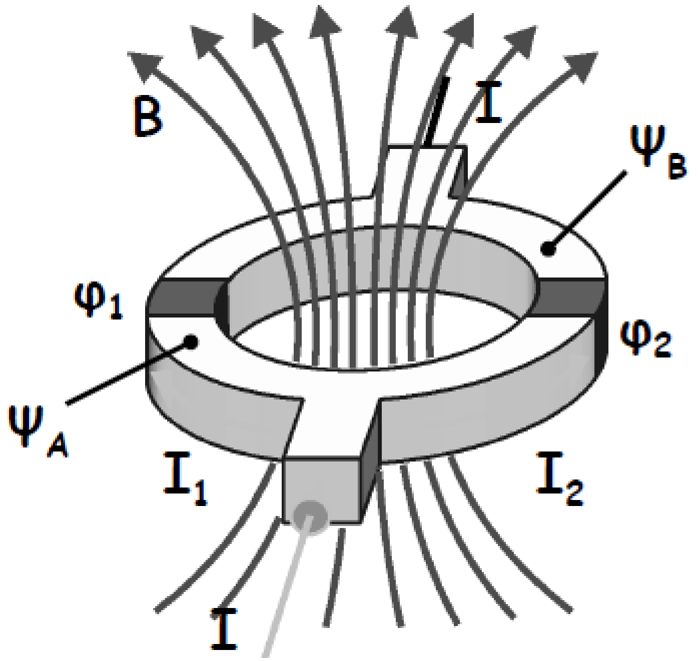
DC-SQUID

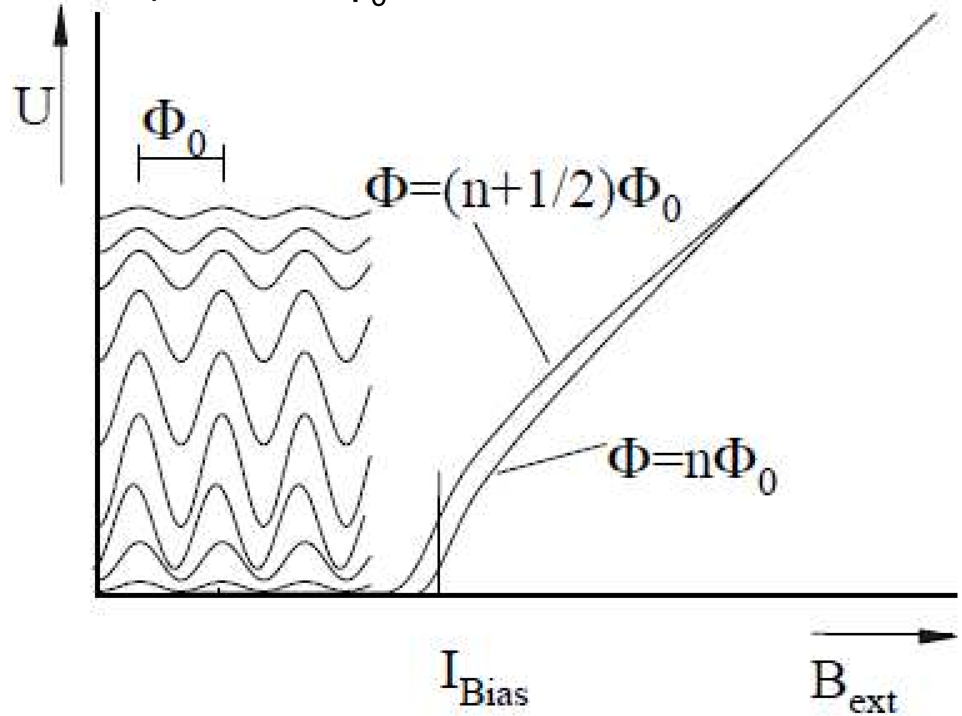
(**S**uperconducting **QU**antum **I**nterference **D**evice)

- Superconductive ring with two weak links
- Critical current I_c depends periodically on magnetic flux Φ through SQUID area

$I_{max} = 2I_c \left|\cos(\pi \cdot \Phi / \Phi_0)\right|$ with $\Phi_0 = h/2e \approx 2{,}07 \cdot 10^{-15} Wb$

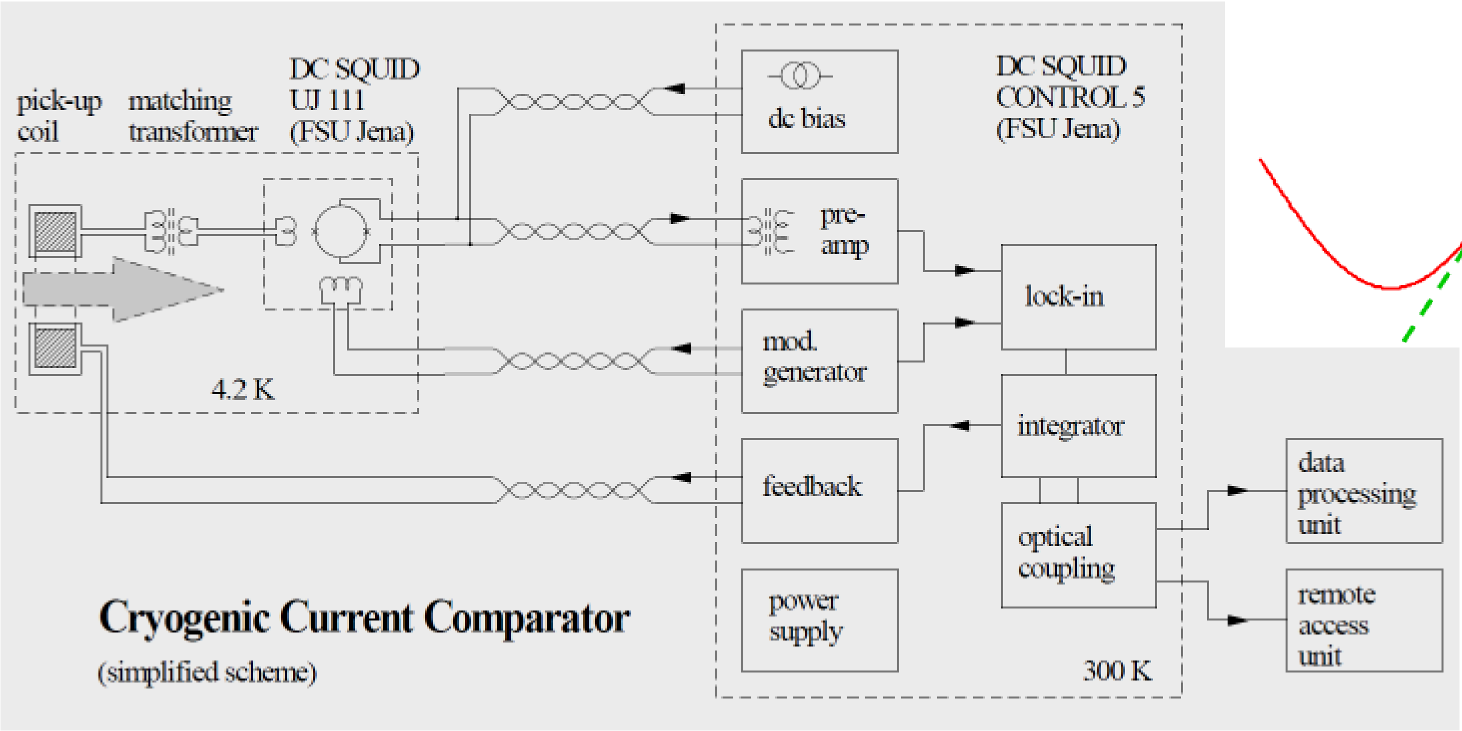
- Set I_{bias} to a fixed value above I_c, U also depends on φ_0

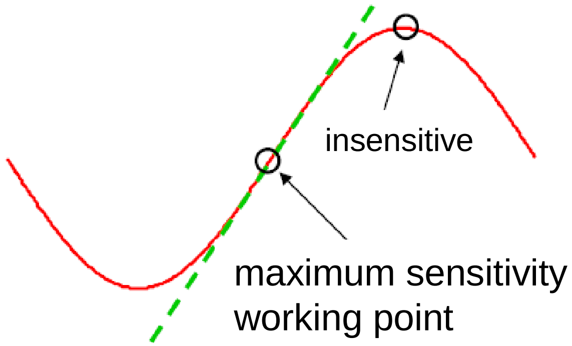




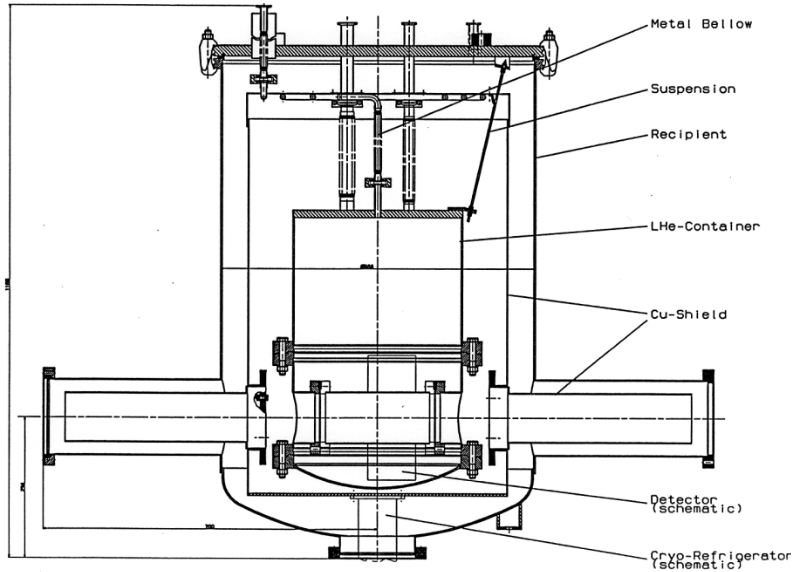
DC-SQUID OPERATION

Working principle of SQUID electronics in flux-locked loop (FLL) mode

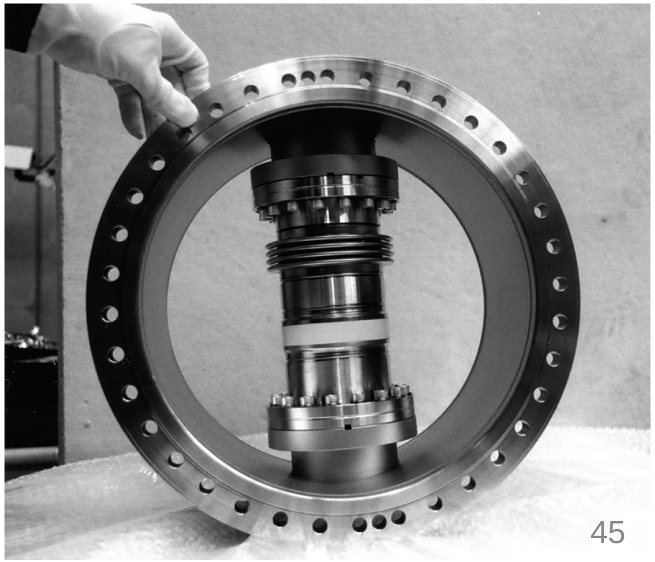




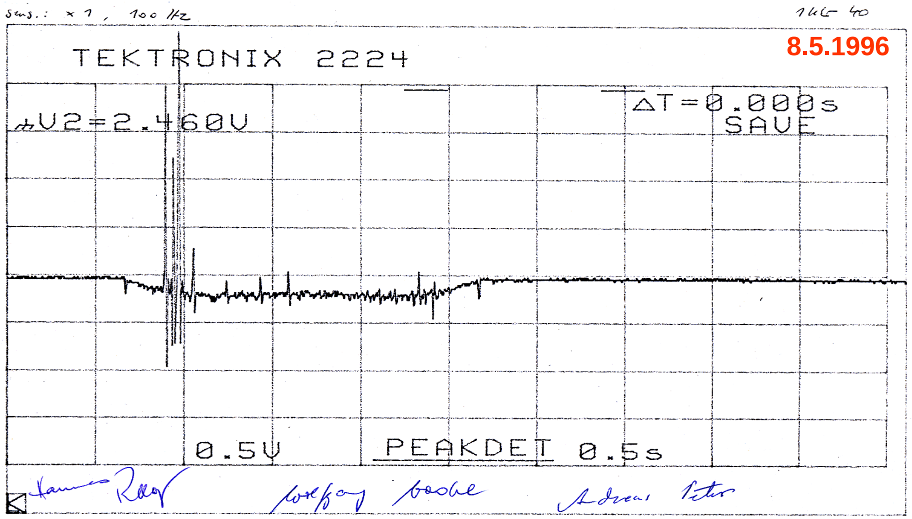
The CCC at GSI Darmstadt



Photography of the CCC assembled in the beam line and some technical details.



First beam measurement ($^{20}Ne^{10+}$)



Achieved current resolution:

≤ 250 pA/√Hz