Workshop on „Low Current, Low Energy Beam Diagnostics“

Hirschberg-Großsachsen, November 24-25, 2009

The SQUID based Cryogenic Current Comparator – an useful tool for beam diagnostics

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Outline

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- Motivation
- Brief introduction to SQUID measurement technique
- **C**ryogenic **C**urrent **C**omparator (CCC) principle
- The CCC at GSI Darmstadt
- The CCC for DESY
- Experimental results
- Conclusions and Outlook

Motivation

In high energy physics there is a need for:

- Measurements of high energy ion beams in the range of 1 µA…1 nA without back action (e.g. GSI Darmstadt)
- Measurements of so-called dark currents of superconducting acceleration cavities in the range below 50 nA (e.g. DESY Hamburg)
- Measurements of charged particles in the CSR (e.g. MPI Heidelberg)

Solution: SQUID-based Cryogenic Current Comparator

Brief introduction to SQUID measurement technique

Superconducting **QU**antum **I**nterference **D**evice

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SQUID is an acronym for **S**uperconducting **QU**antum **I**nterference **D**evice and is the most sensitive magnetic flux detector known today.

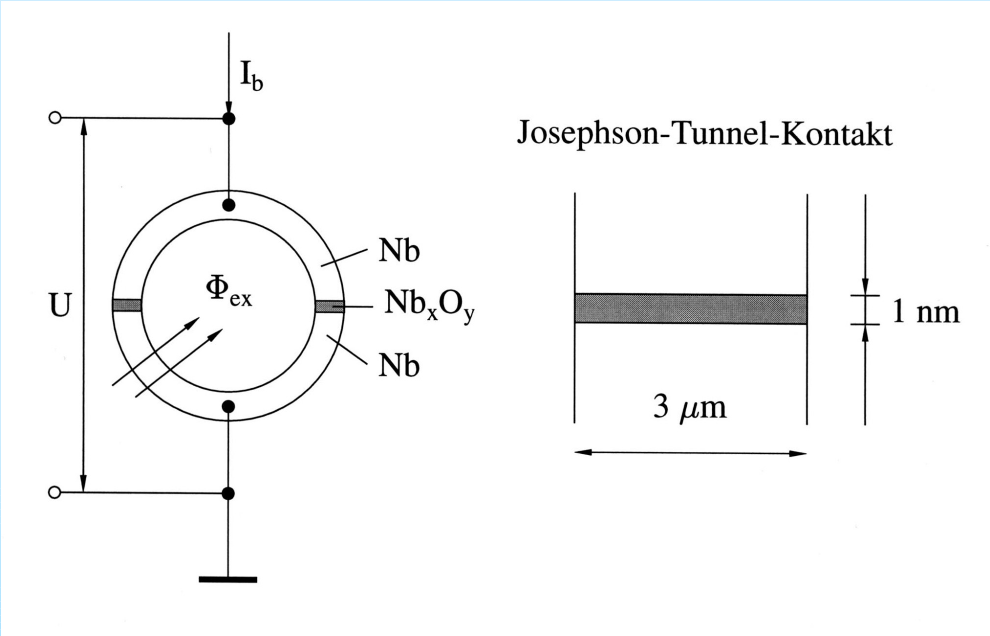
The working principle makes use of:

- superconductivity,
- the flux quantization in superconducting rings, and
- the Josephson effect.

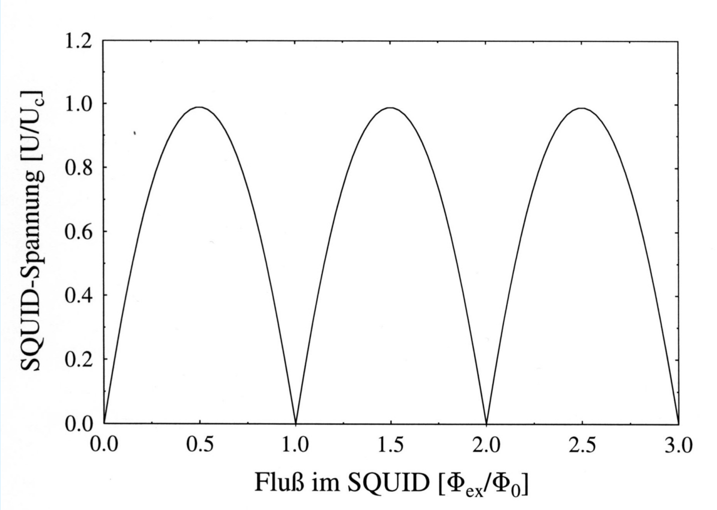
In principle, the SQUID consists of a superconducting ring with one or two weak links (Josephson tunnel junctions). We differ between:

- dc SQUID with two Josephson junctions and
- rf SQUID with one Josephson junction only.

DC-SQUIDs



Simplified scheme of a dc-SQUID and a tunnel junction



Output voltage of the SQUID vs. external magnetic flux

SQUID-Characteristics

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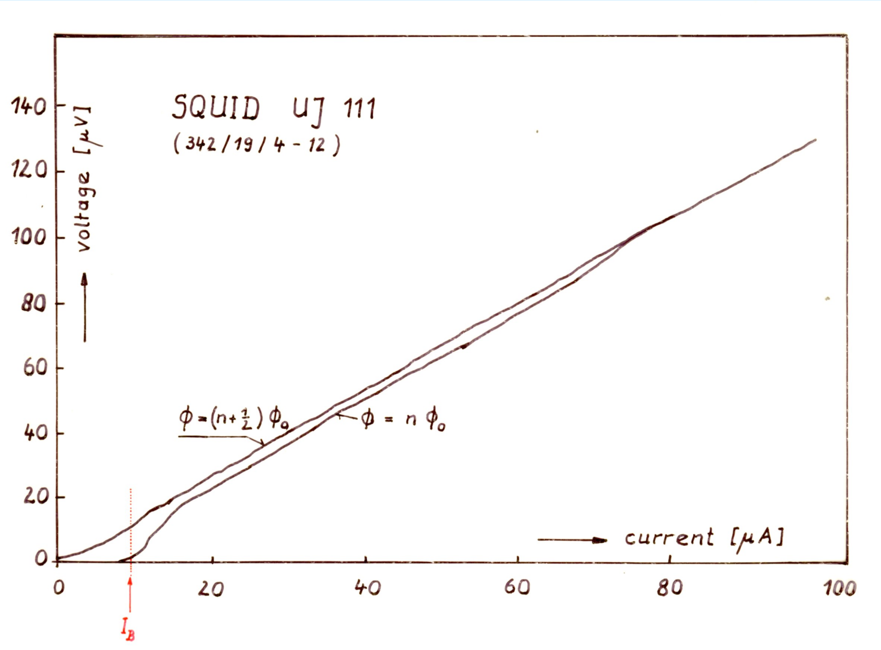
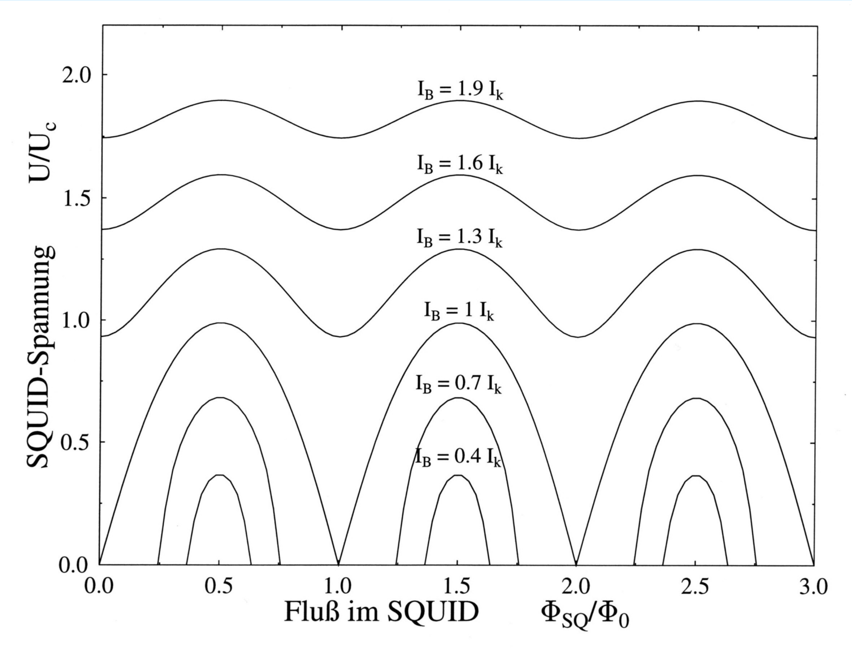
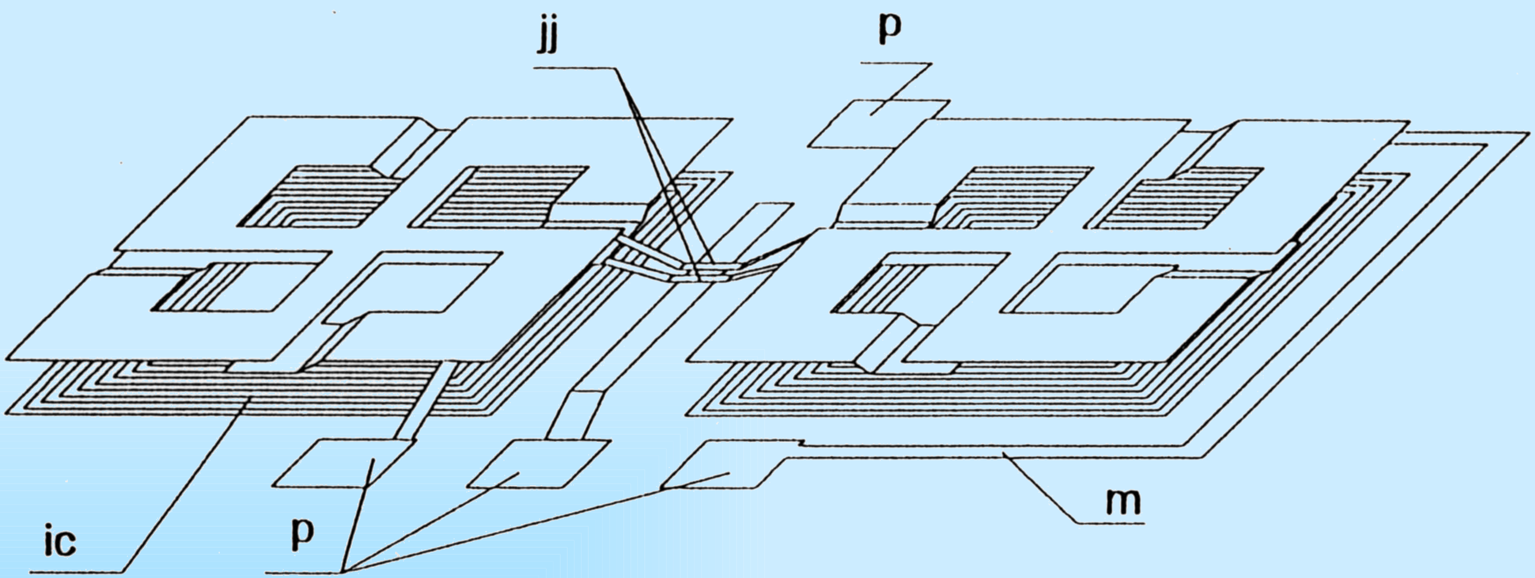


Voltage-Current-Characteristic of the SQUID *UJ 111*



Output voltage of the SQUID vs. external flux for different bias currents

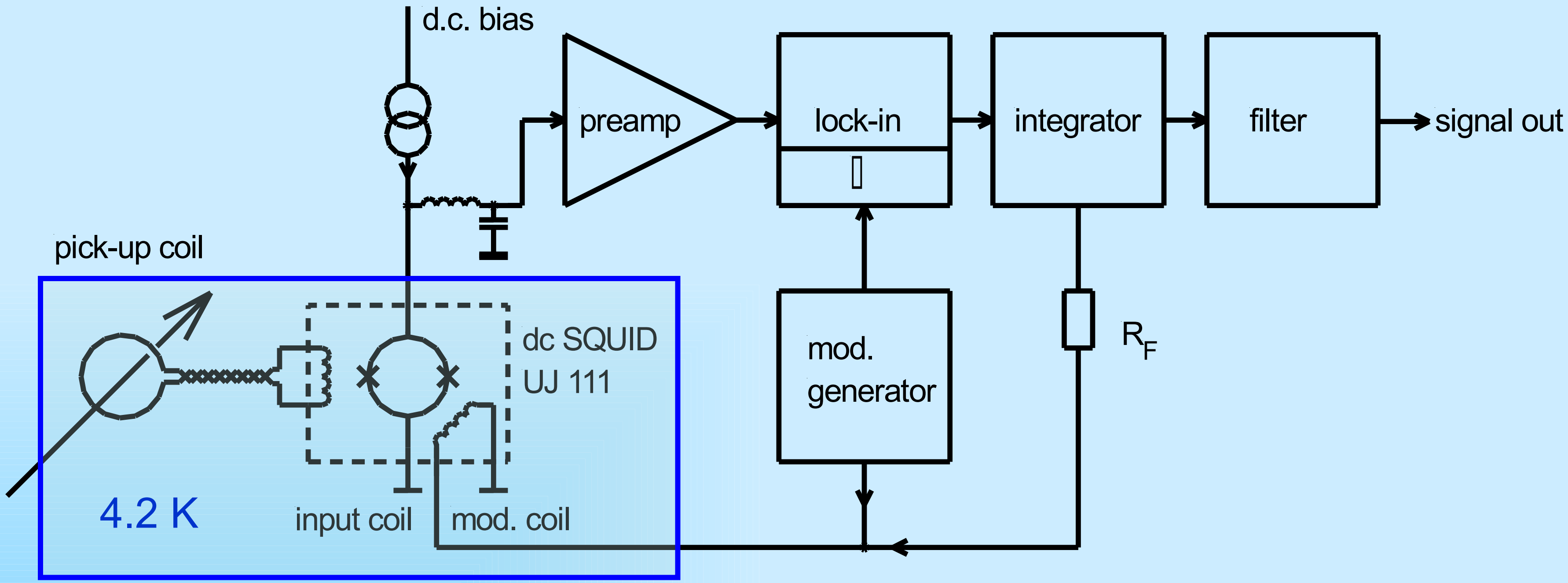
DC-SQUID lay-out



Simplified structure of the DC-SQUID *UJ 111* (FSU Jena).

jj: Josephson junctions, p: Nb contact pads, m: modulation coil, ic: input coil

Block diagram of the *dc SQUID system 5*



Simplified electrical scheme of the *dc SQUID electronics* of Jena University with the thin film dc SQUID *UJ 111*

The *dc SQUID system 5* of Jena University

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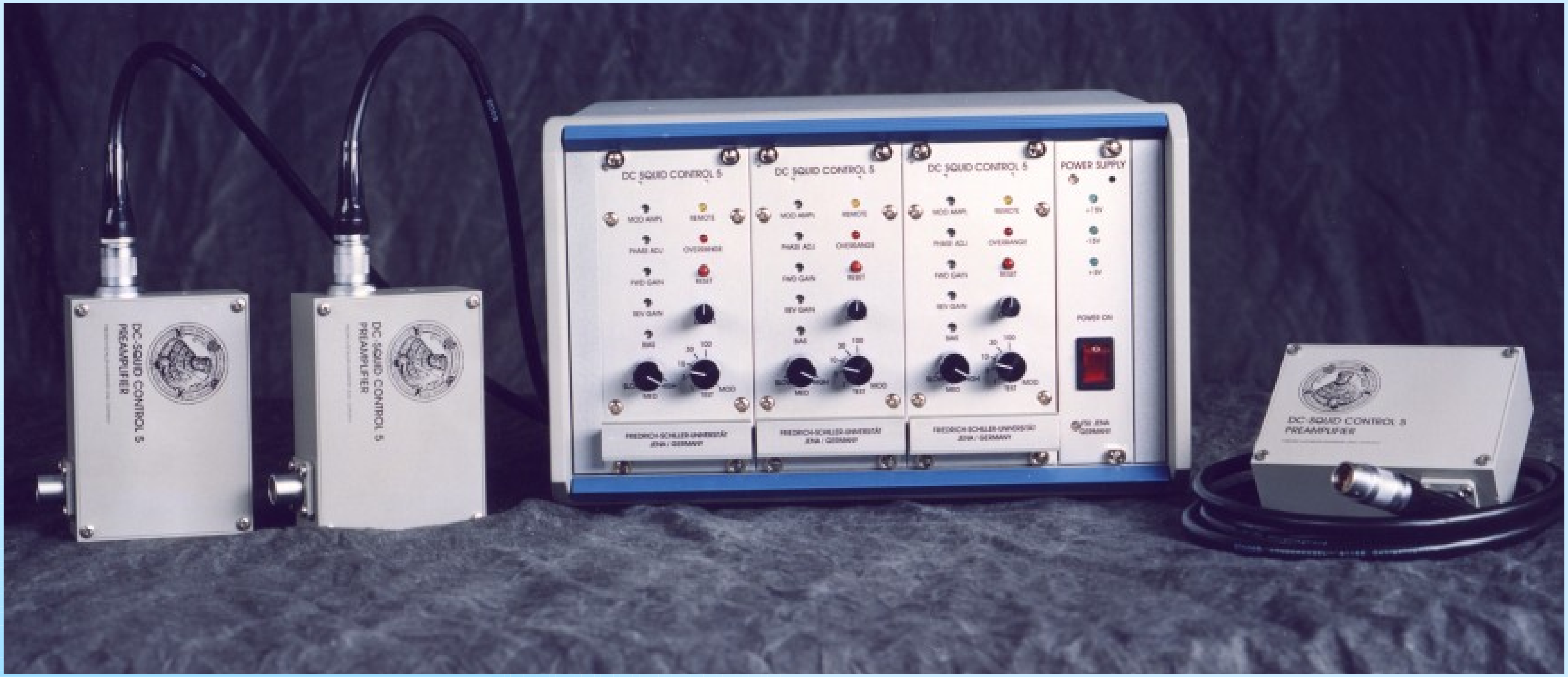

Photograph of the complete 3 channel *dc SQUID system 5* electronics with the connected low noise preamplifiers.

The *dc SQUID system 5* of Jena University

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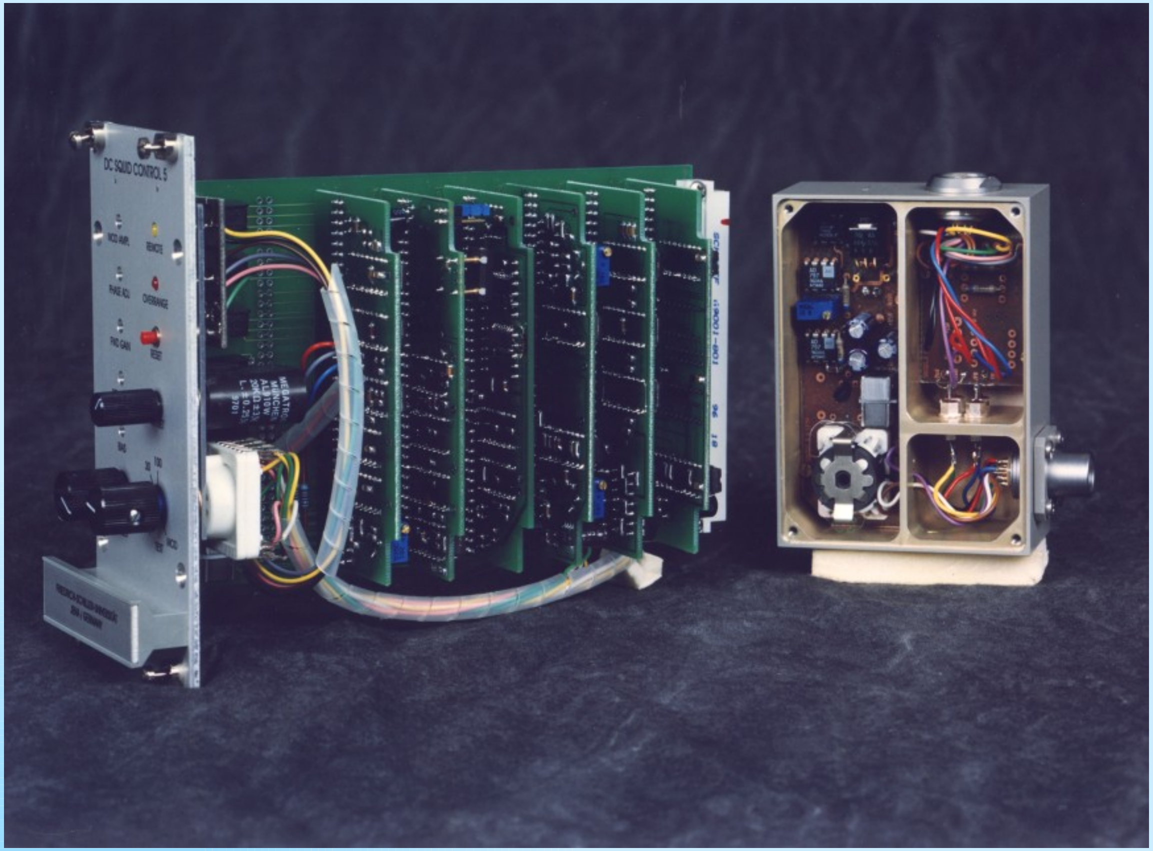

1 channel of the *dc SQUID system 5* (left) and the unclosed low noise preamplifier (right).

Main principle of the Cryogenic Current Comparator

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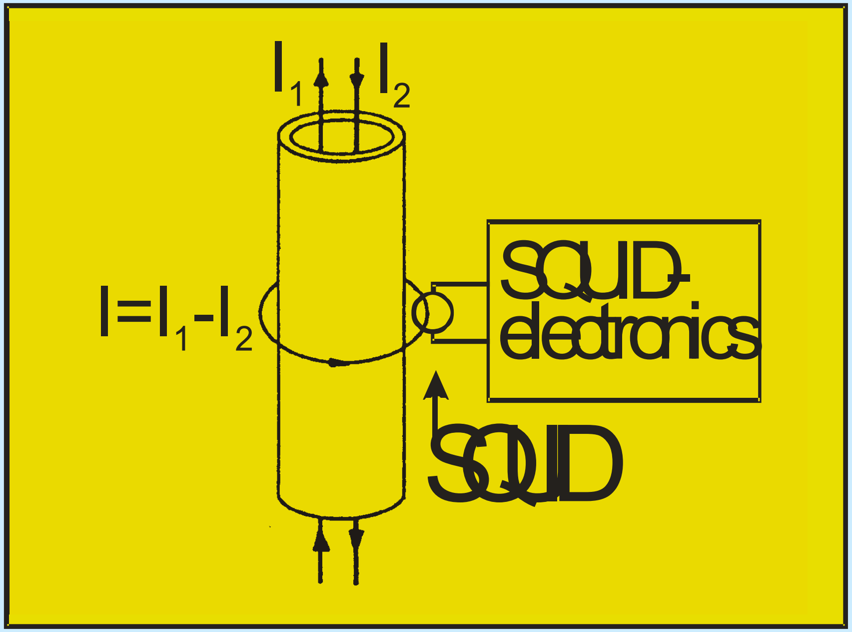
The CCC, first developed in 1972 by Harvey[†], consists of:

- a superconducting pickup coil
- a high efficient superconducting shield
- a high performance SQUID measurement system

For absolute current measurements:

$$I = I_1 - I_2 = i_{meas} - 0$$



[†] Harvey, *Rev. Sci. Instrum., Vol. 43, p. 1626, 1972*

Outstanding advantages of the CCC:

- Non destructive method
- High resolution (< 1 nA/√Hz)
- Measurement of the absolute value of the current
- Exact absolute calibration using an additional wire loop
- Independency of charged particle trajectories
- Independency of charged particle energies

Resolution limits

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The theoretical resolution of the CCC is limited, above all, by the thermal noise of the ferromagnetic core material:

- Thermal noise generates a noise current $\sqrt{\langle I^2 \rangle}$
- In connection with the inductance L this noise current gives rise of the magnetic flux noise $\Phi_{thermal}$
- For SNR > 1 the beam signal must meet the condition:

$$\Phi_{beam} = \int_A \vec{B} \cdot d\vec{f} \geq \Phi_{thermal} = L \cdot \sqrt{\langle I^2 \rangle}$$

Resolution limits

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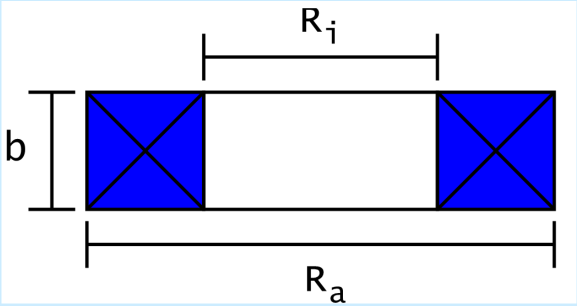
Minimum detectable current I_s:

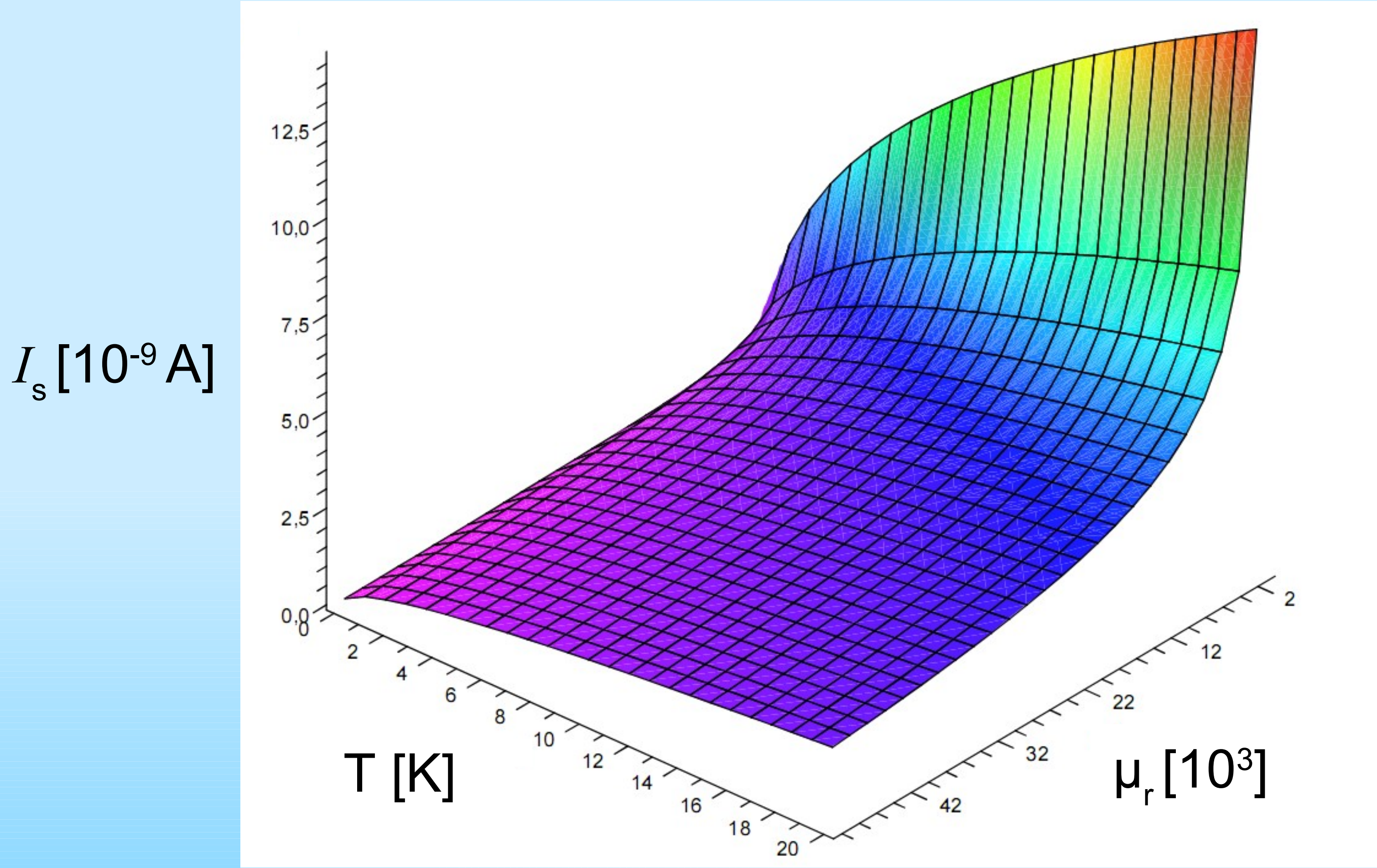
$$I_s = \frac{2\pi \sqrt{k_B T L}}{\mu_0 \mu_r f\left(R_a, R_i, b\right)} \Rightarrow I_s \propto \frac{1}{\sqrt{\mu_r}}$$

where T denotes the temperature, μ_r the relative permeability of core material, n the number of windings (n=1), and L the inductance of pick-up coil according to:

$$L = n^2 \cdot \frac{\mu_0 \mu_r b}{2\pi} \ln \frac{R_a}{R_i}$$



Resolution limits



Minimum detectable current I_s as a function of temperature and relative permeability μ_r calculated for the currently used single turn toroidal pick-up coil.

Magnetic material

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Vacuumschmelze Hanau

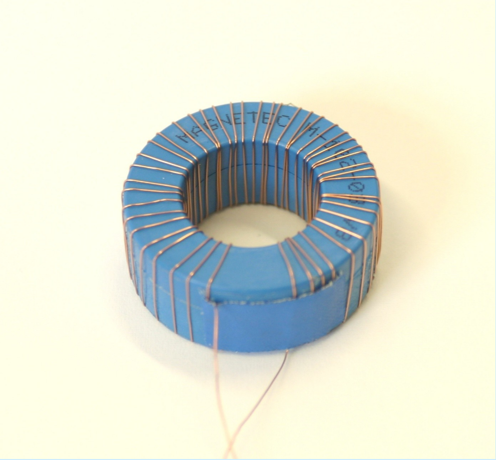
- **Vitrovac**
  - tape material
    VC 6025, μ_r ~ 5.000,
    VC 6155, μ_r ~ 2.000
  - toroidal tape wound cores
    VC 6025 F, VC 6030 F,
    VC 6150 F, VC 6200 F
    with different μ_r from 1.200 to 200.000 at 300 K
- **Vitroperm**
  - toroidal tape wound cores
    VP 250 F, VP 500 F
    with different μ_r from 6.000 to 130.000 at 300 K

Magnetec Langenselbold

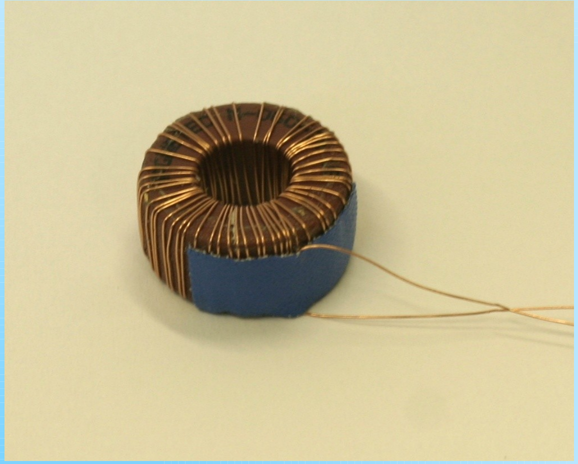
- **Nanoperm**
  toroidal tape wound cores in plastic cases in different dimensions
  with μ_r from 25.000 to 100.000 at 300 K

Nanoperm- magnetic cores

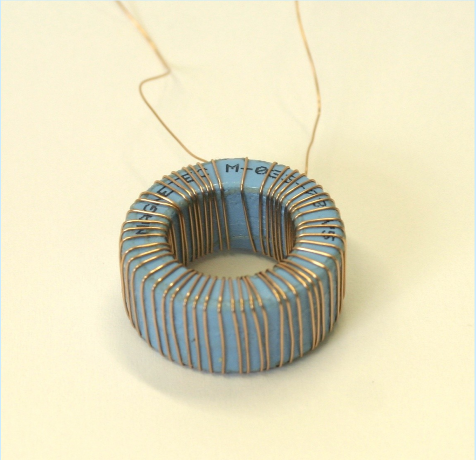
Nanoperm-toroidal tape wound cores



Nanoperm-toroidal tape wound cores M074 (50 windings)



Nanoperm-toroidal tape wound cores M060 (50 windings)



Nanoperm-toroidal tape wound cores M033 (50 windings)

A_L-values of magnetic materials at low temperatures

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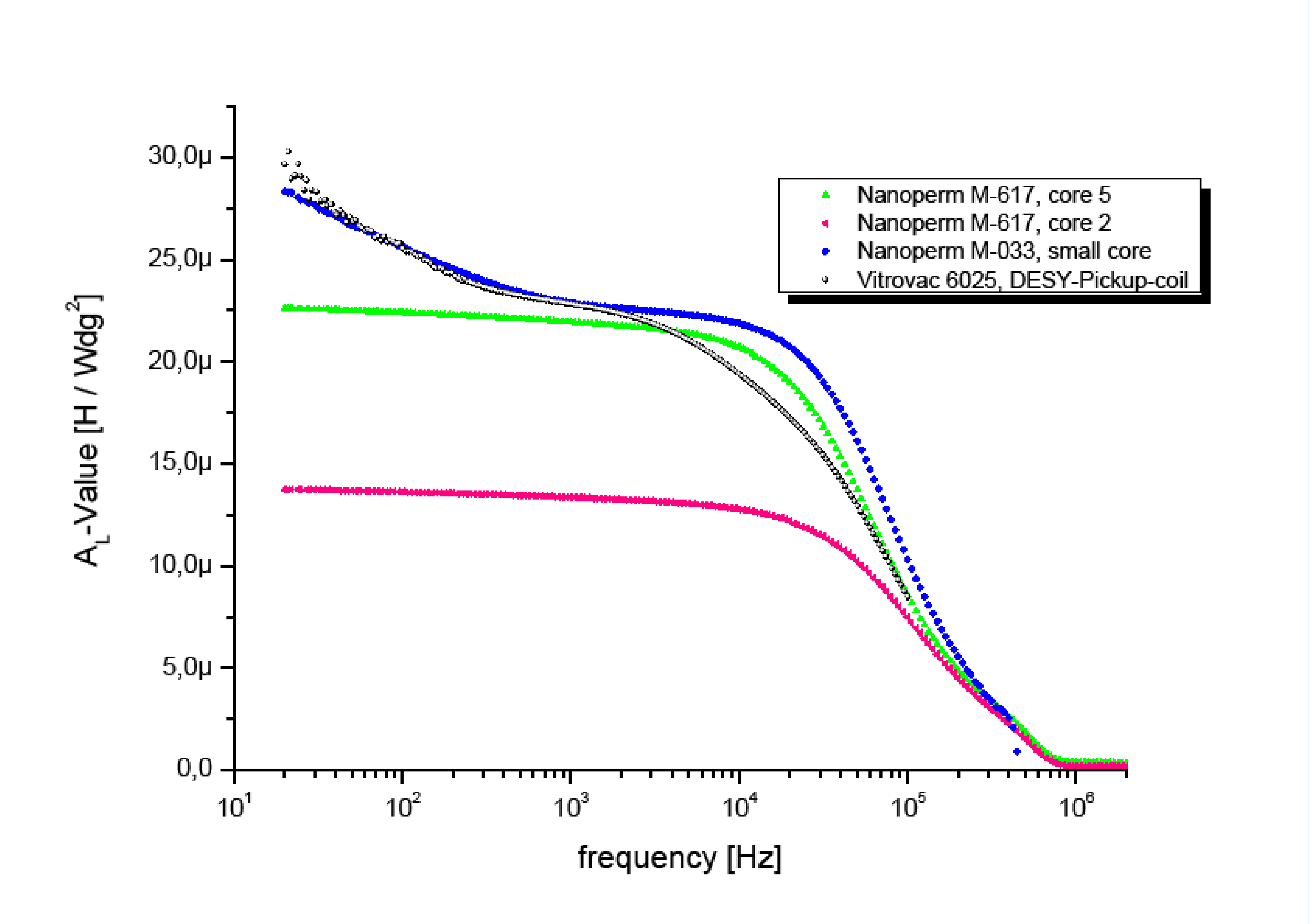
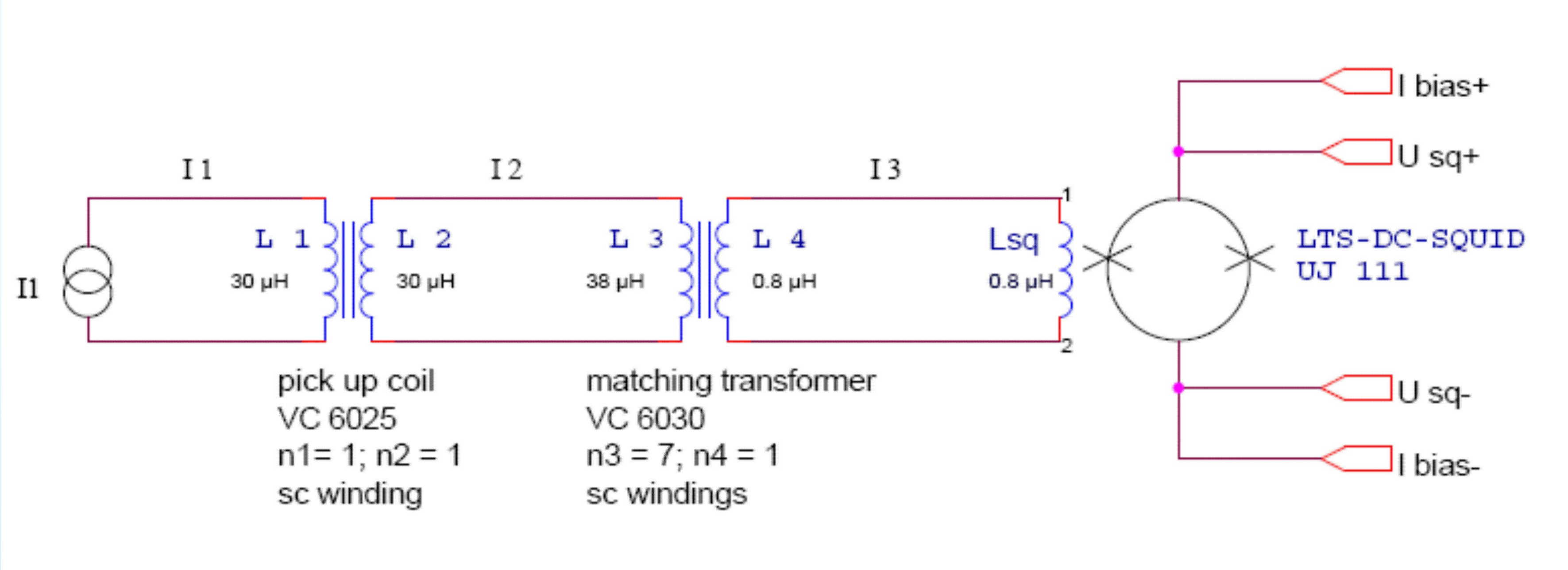


Electrical Scheme of the input circuit



Current gain

Short circuit current gain of a transformer:

$$\frac{I_2}{I_1} = \frac{n_1}{n_2}$$

Current gain of a stressed transformer with an inductive load:

$$\frac{I_2}{I_1} = \frac{n_1}{n_2} \cdot \frac{1}{1 + L_l / L_2}$$

Total current gain of the system (pick up coil – matching transformer – SQUID input coil:

$$\frac{I_3}{I_1} = \frac{n_3}{n_4} \cdot \frac{1}{1 + L_{SQ} / L_4} \cdot \frac{n_1}{n_2} \cdot \frac{1}{1 + \frac{L_3 \cdot L_{SQ}}{\left(L_4 + L_{SQ}\right) \cdot L_2}}$$

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Applications of the CCC

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- Measurement of high energy ion currents of accelerators

  Current resolution: **≤ 250 pA/√Hz**

  (GSI Darmstadt)
- Measurement of so-called dark currents of RF accelerator cavities

  Current resolution: **≤ 40 pA/√Hz**
  (DESY Hamburg)

Supercond. Sci. Technol. 20, pp. 393-397 (2007)

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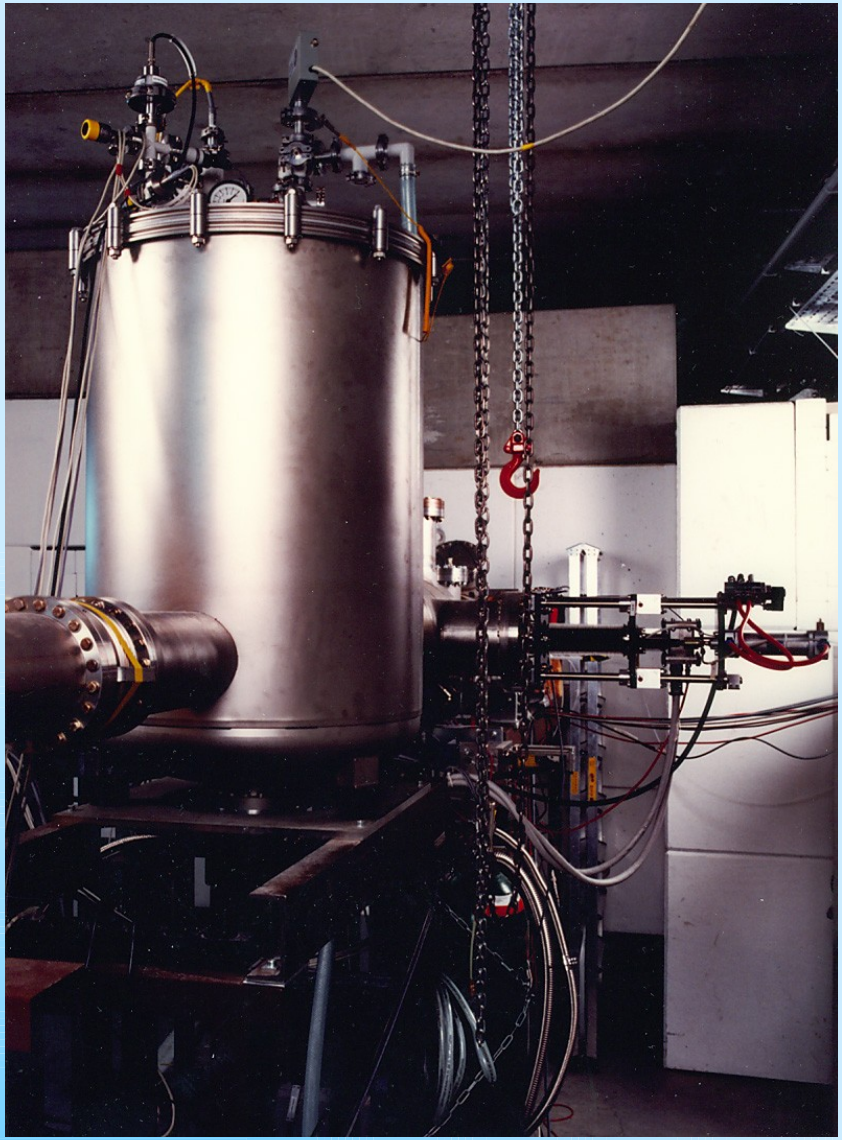
The CCC at GSI Darmstadt

The CCC at GSI Darmstadt



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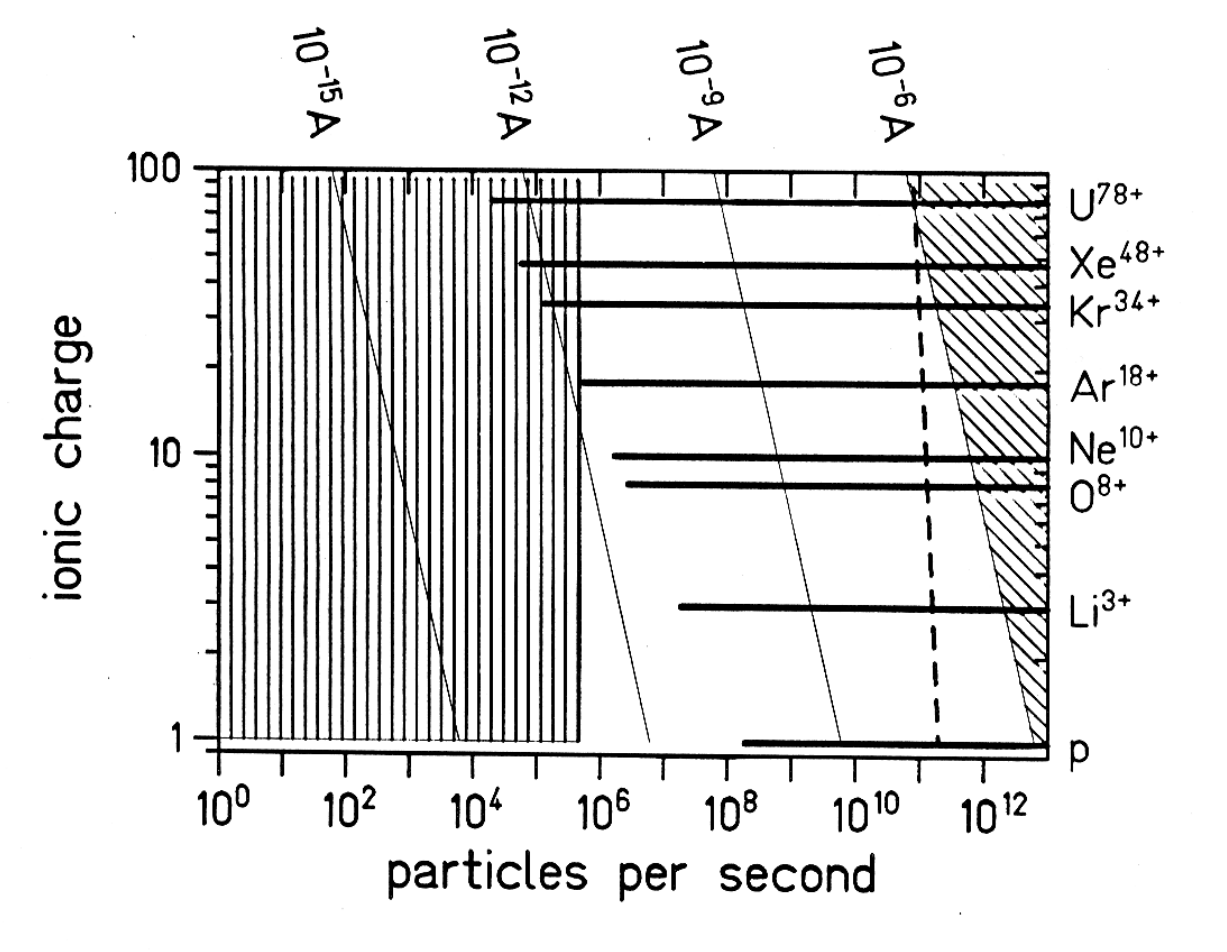
GSI (Darmstadt) and the Friedrich Schiller University Jena made an impressive demonstration of the capabilities of a CCC to measure extracted high energy ion-beams (Ar, Ne) with a resolution of:

0.25 nA/√Hz.

Motivation for the CCC at GSI Darmstadt



The SIS at GSI Darmstadt

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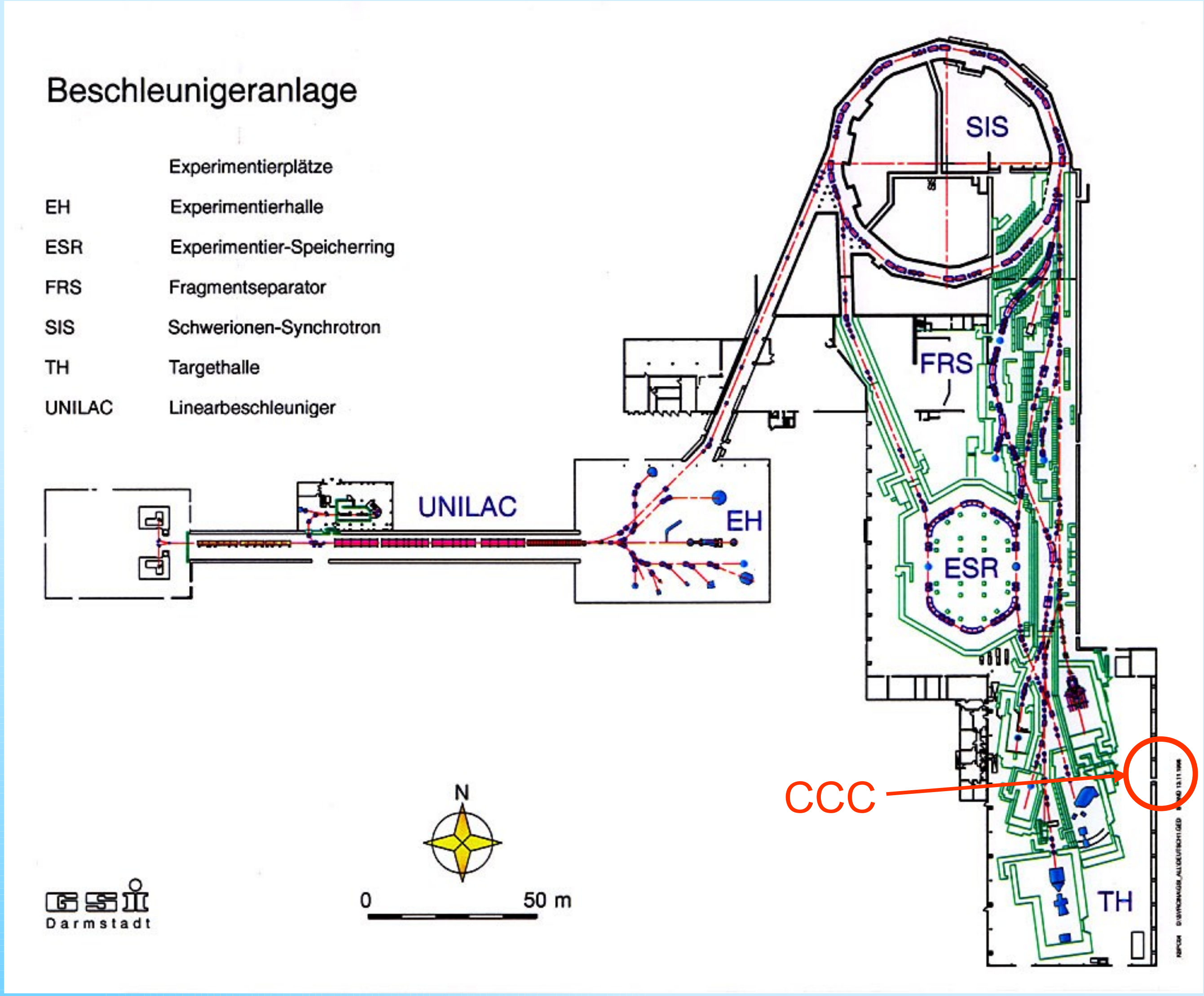
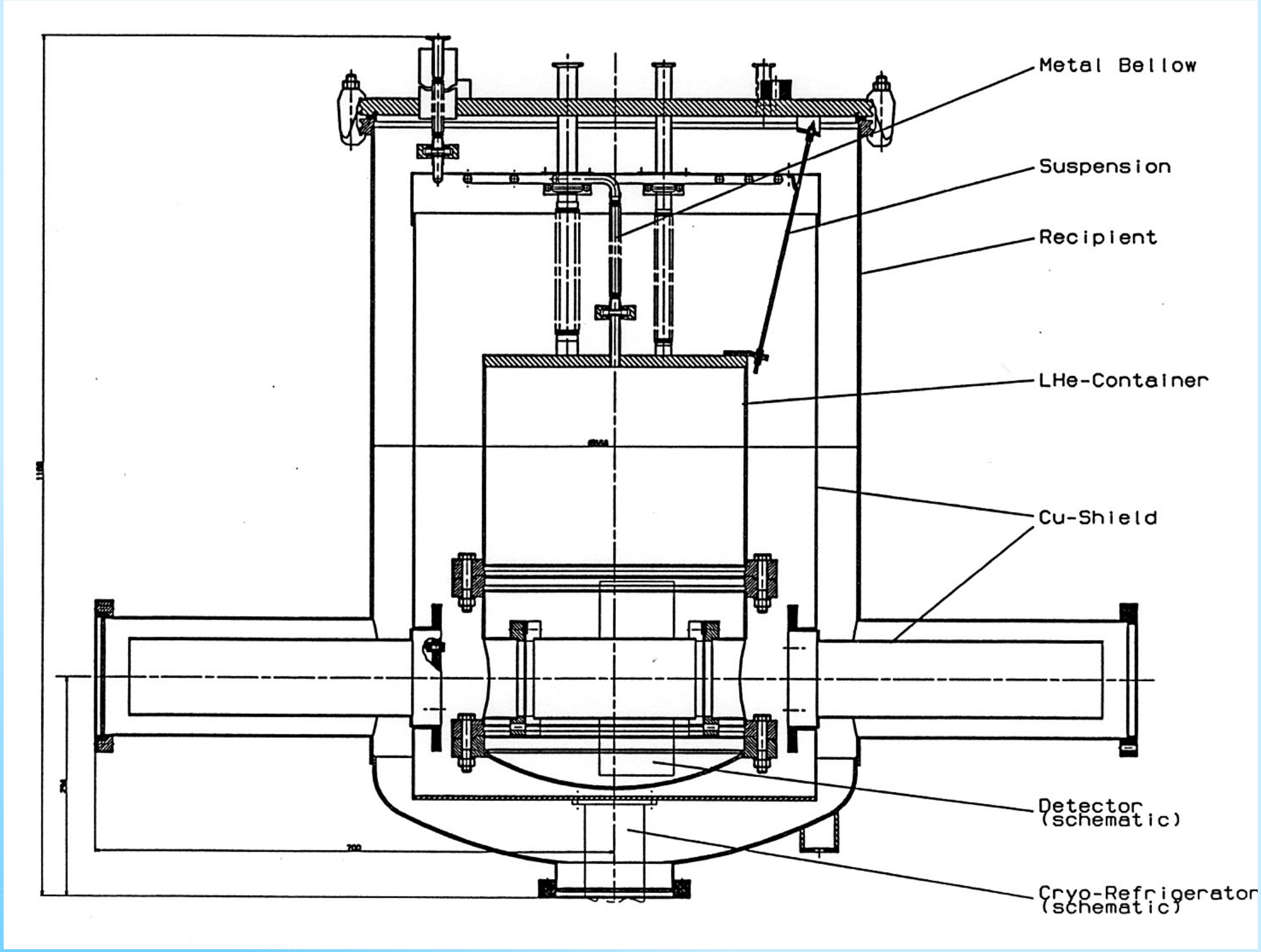
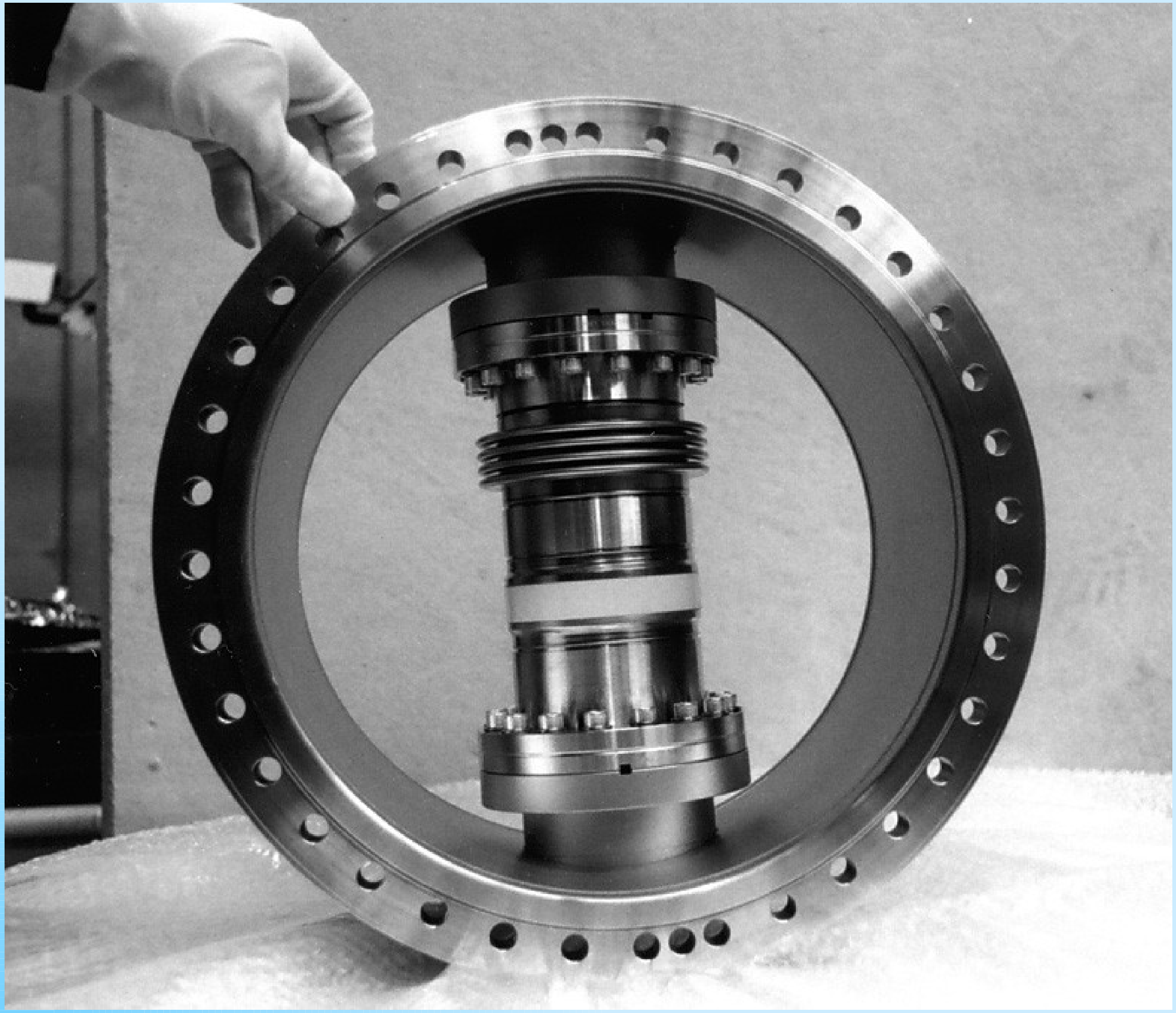


Cross section of the CCC



Technical details of the CCC



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

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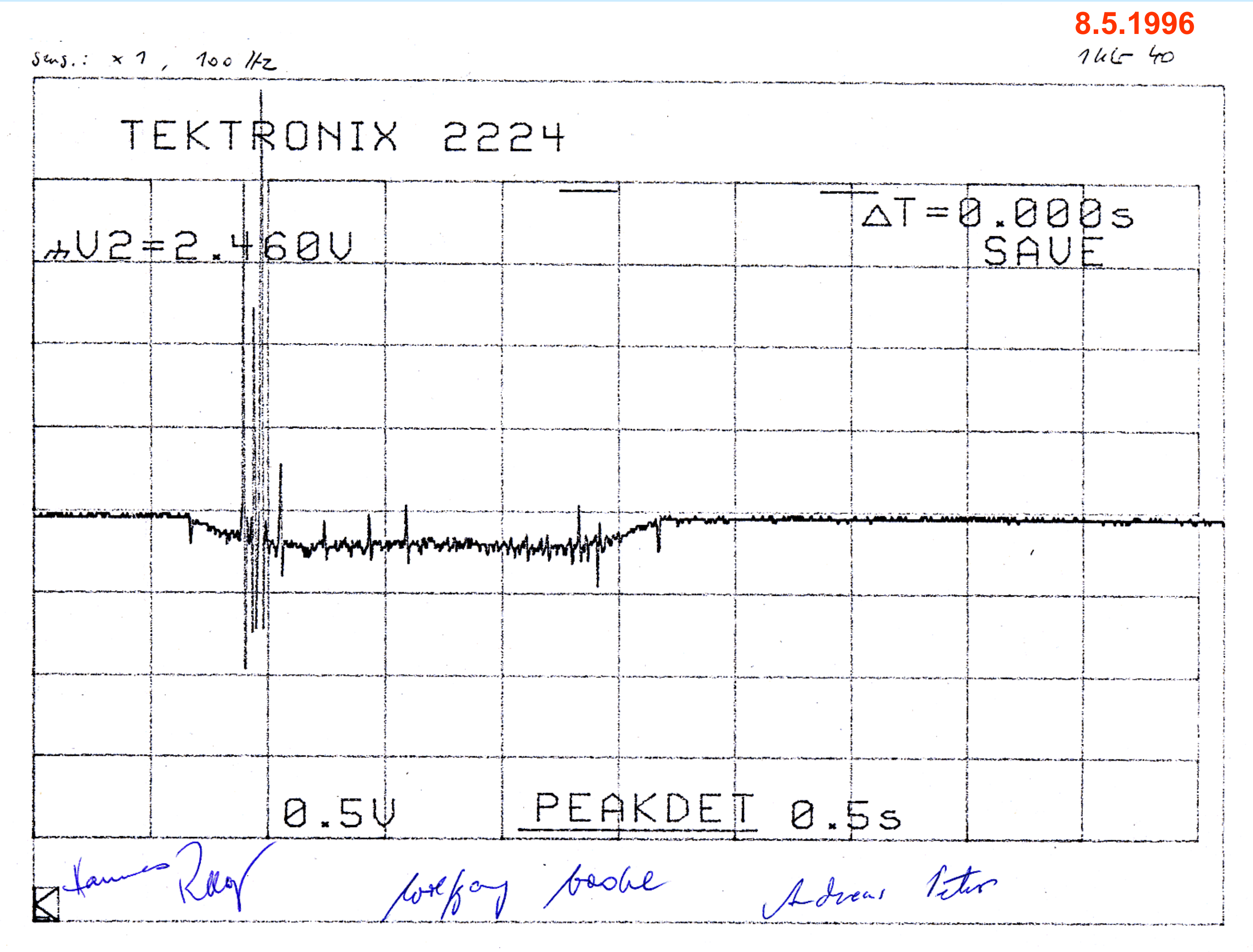
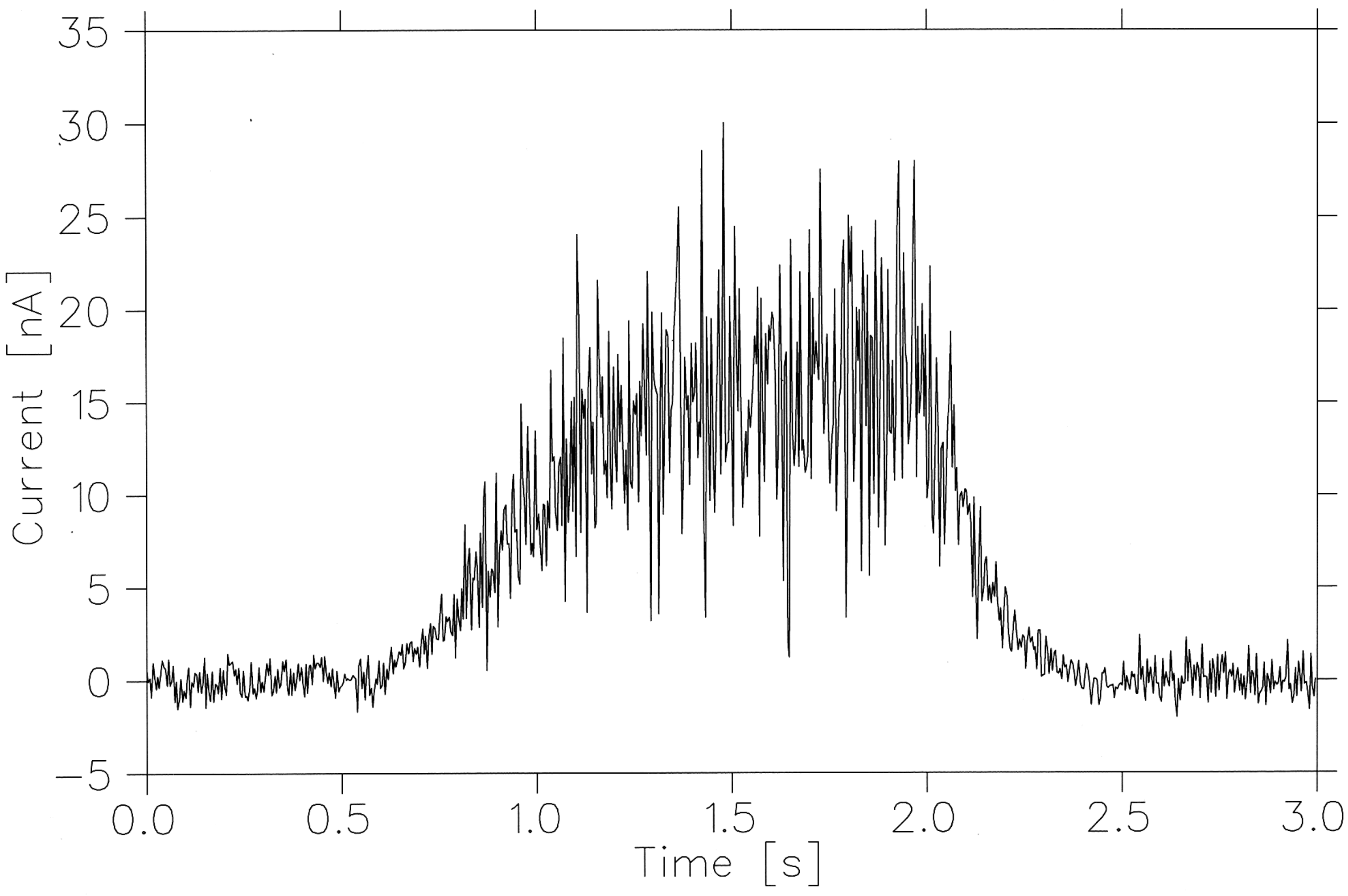


High resolution beam measurement



The CCC at DESY Hamburg

Motivation

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The performance of superconducting cavities of accelerators is characterized by the Q-value vs. gradient dependency, measured in a cavity test stand (e. g. “*CHECHIA*” at DESY or “*HoBiCaT” at BESSY*).

But unfortunately there is:

“The existence of so-called ***dark currents*** (vs. gradient) which may have an influence on the accelerator operation”.

The CCC for X-FEL

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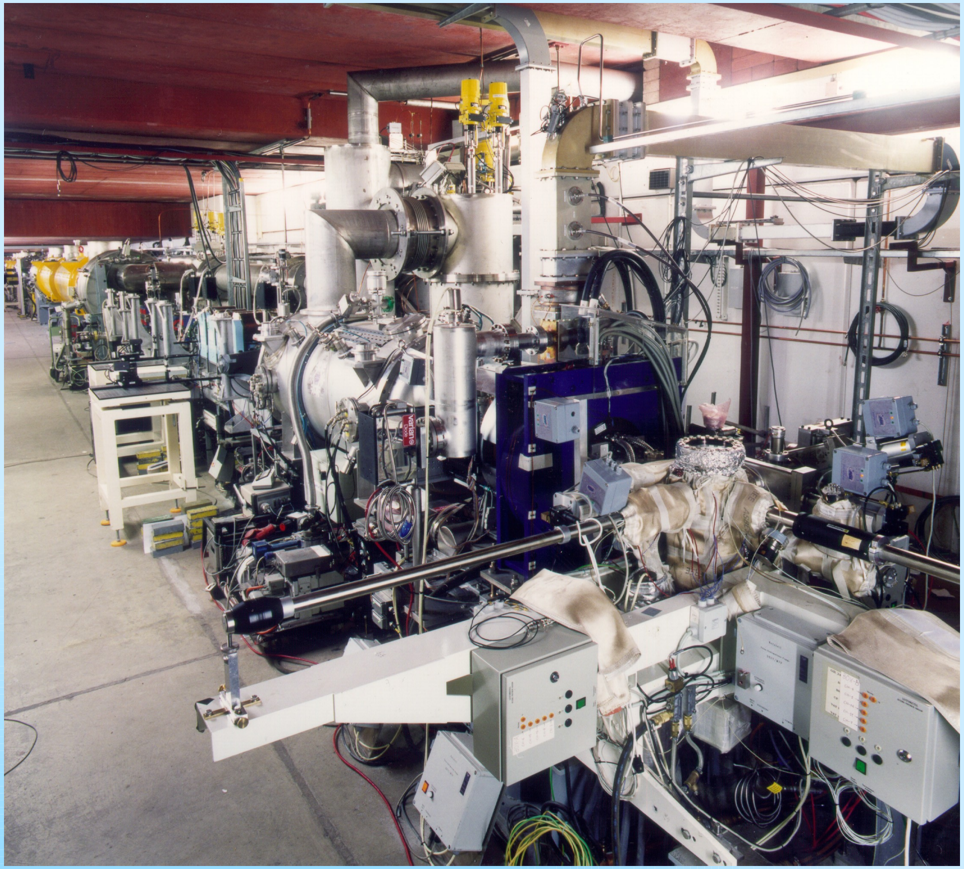

In collaboration with Jena University, GSI and DESY a CCC for the measurement of dark currents of the X-FEL accelerator cavities is under construction.

Dark currents:

– Unwanted particle source

– Limit the accelerator performance by
  - Additional thermal load (T = 1.8 K)
  - Propagating dark current

– An avalanche instability due to the propagating dark current arise if (statistically): number of emitted electrons/cavity period > 1

– This limits the dark current of a 9-cell cavity to **i_{dark} < 50 nA**

Dark currents:

- Are caused by field emission of electrons in high gradient fields
- The forces of the applied external field are higher than the bounding forces inside the crystal structure.

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Potential emitters are:

- Imperfections of the cavity shape, e. g. corners, spikes and other discontinuities where occur high field gradients
- Imperfections of the crystal matter, e. g. grain boundaries
- Inclusion of “foreign” contaminants (In, Fe, Cr, Si, Cu,... microparticles)

Dark current simulations

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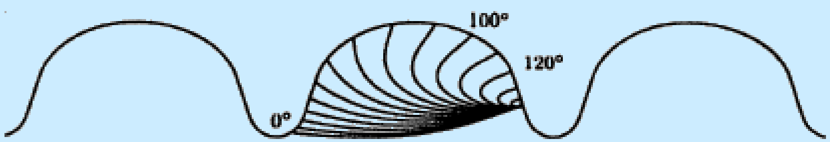
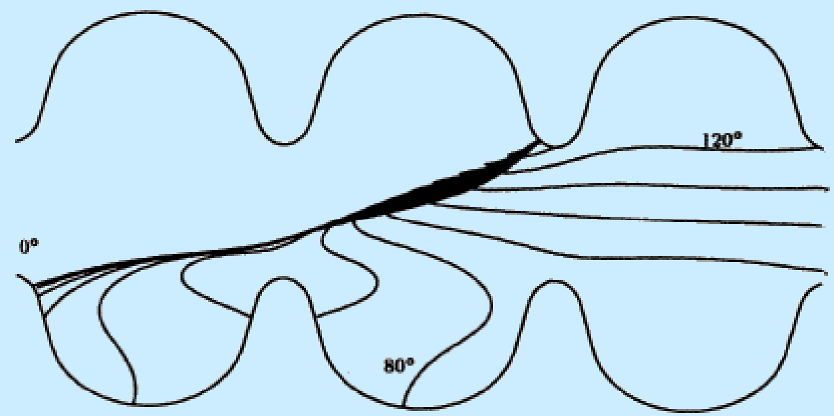


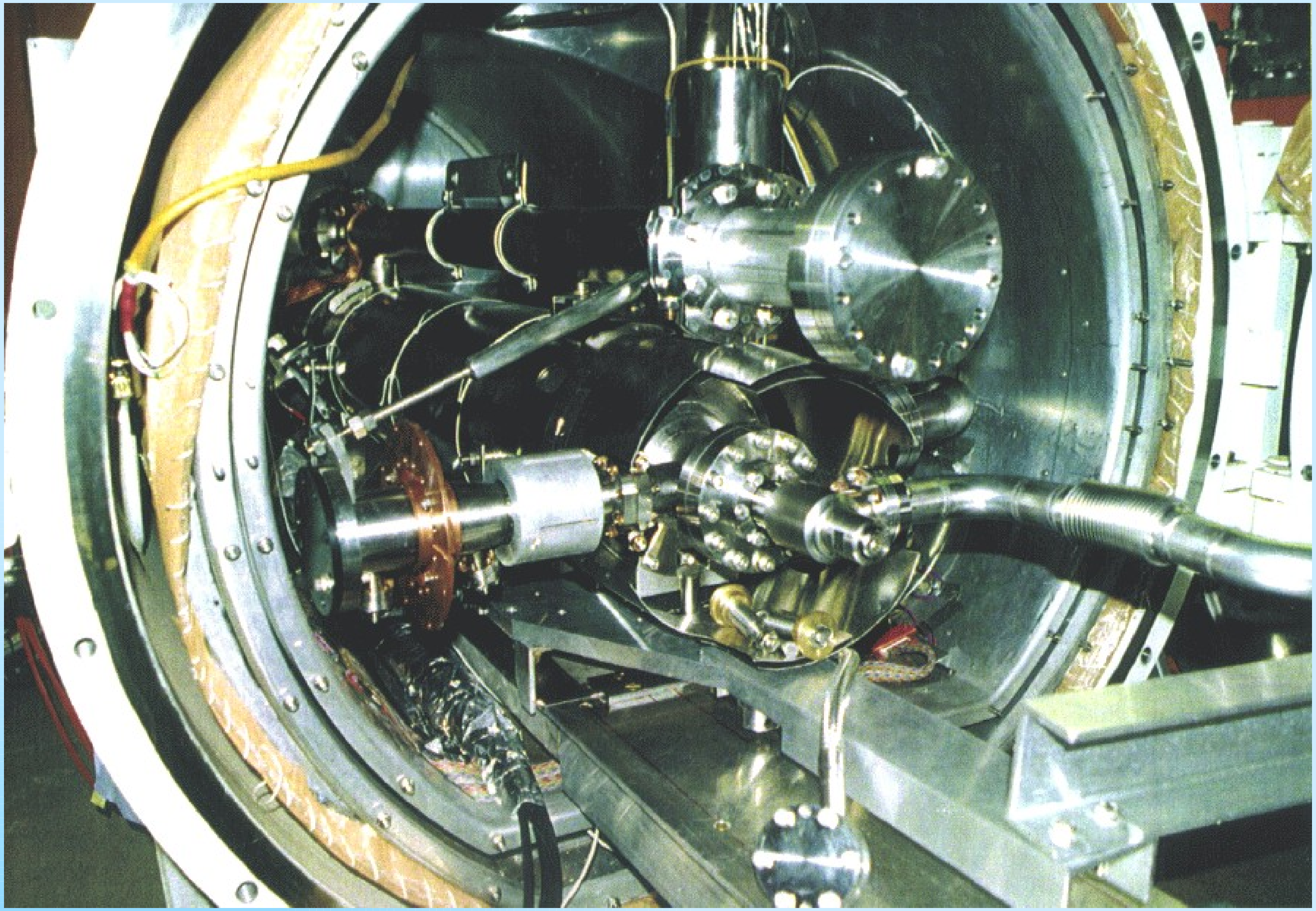
Dark current simulations



Reference

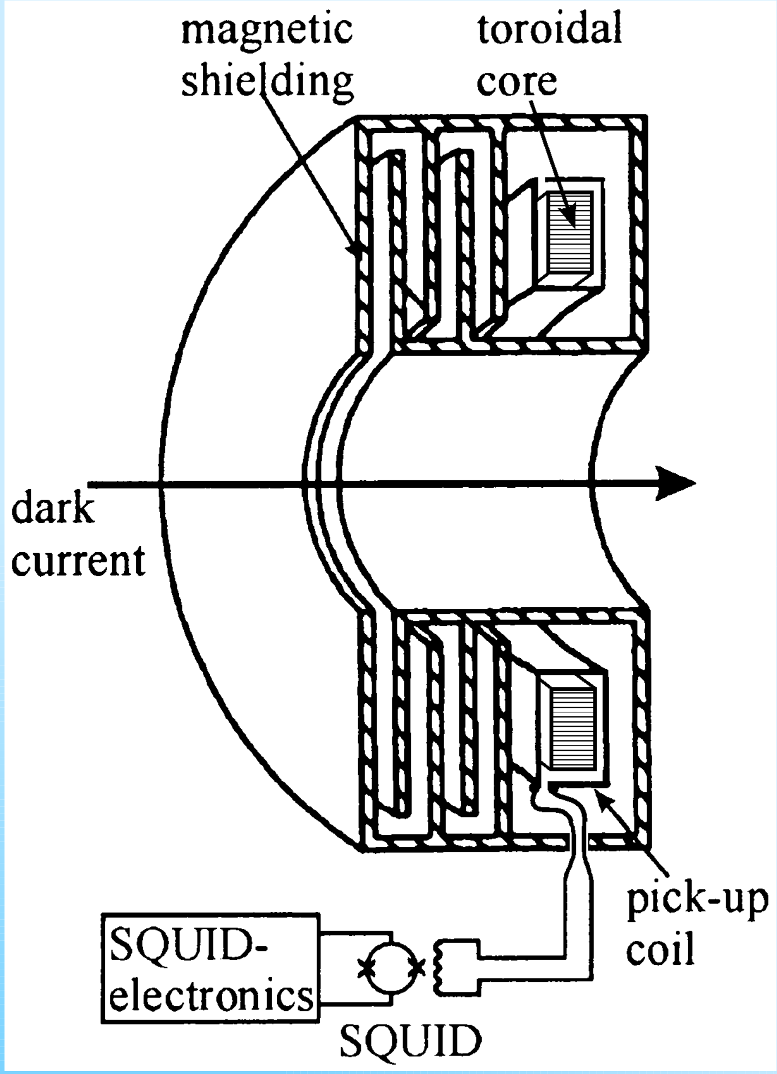
C. Stolzenburg, “Untersuchungen zur Entstehung von Dunkelströmen in supraleitenden Beschleunigungsstrukturen”, (in German); Ph. D. Thesis, University of Hamburg 1996.

CECHIA test facility



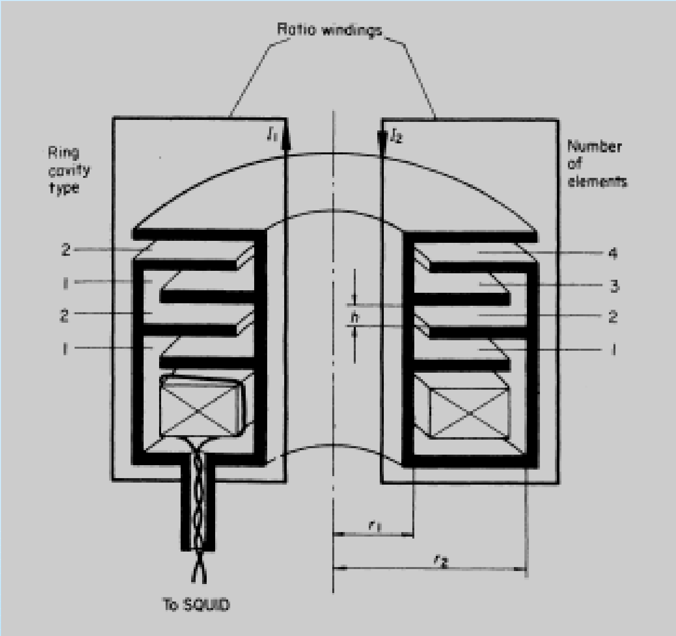
The proof measurements will be performed in the so-called „CHECHIA" test stand at DESY.

Pickup coil with meander-shaped shield



The single turn, superconducting pickup coil is arranged on a toroidal core (VITROVAC, Vakuumschmelze Hanau).

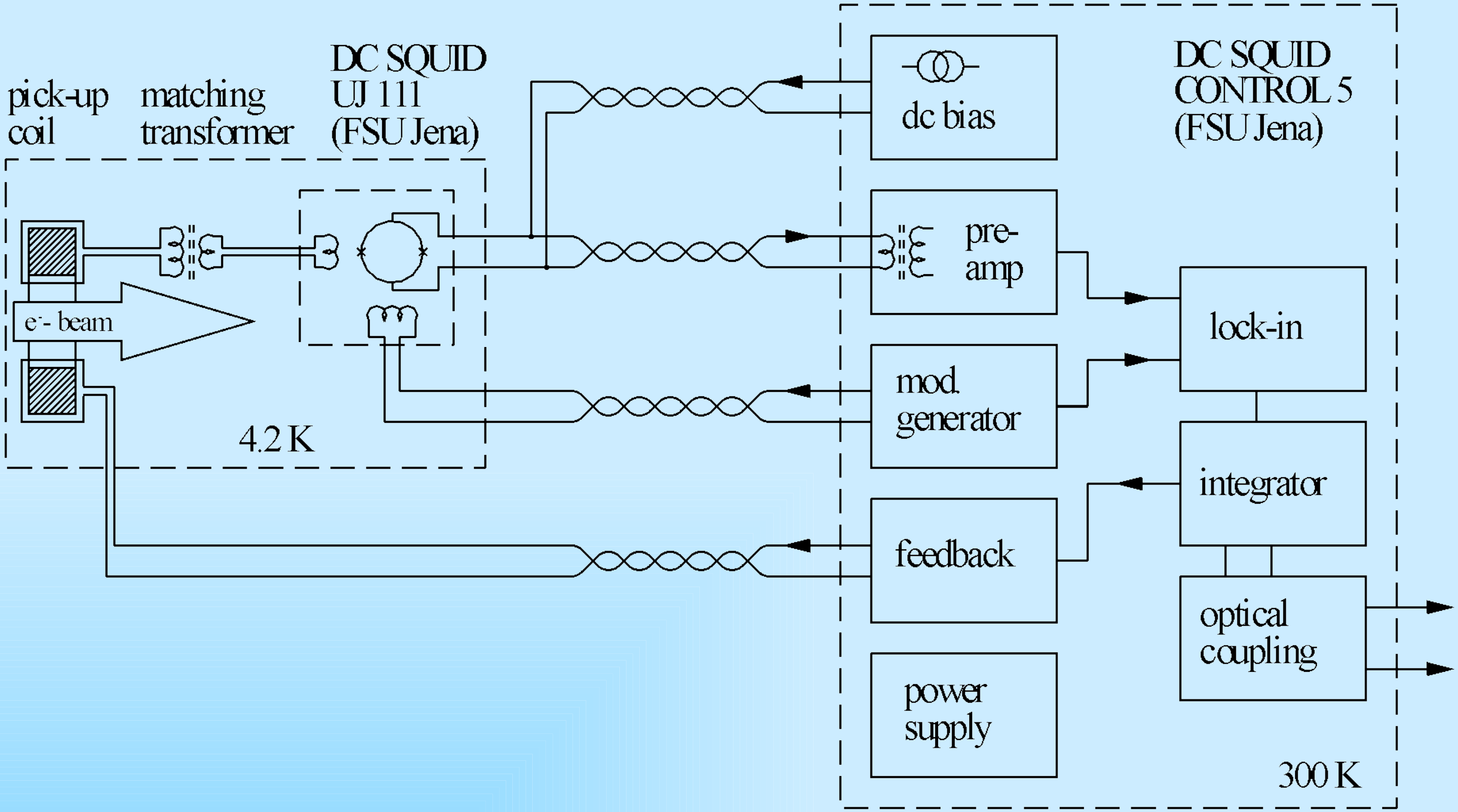
Superconducting shielding



The resolution of the CCC is reduced if the toroidal pickup coil operates in the presence of external magnetic back-ground fields. As this is in practice un-avoidable, an effective shielding has to be applied.

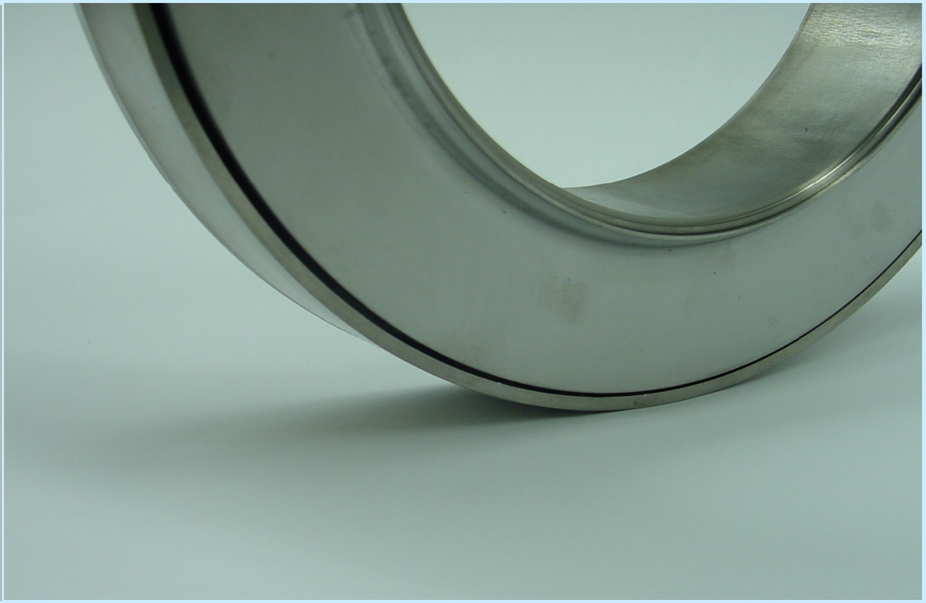
- A circular, meander-shaped shielding structure is able to pass the azimuthal magnetic field of the dark current, while strong attenuating non-azimuthal field components.
- A superconducting shielding material (niobium, lead) leads to an ideal diamagnetic conductor (Meissner-Ochsenfeld effect), providing an expulsion of external magnetic fields.

Electrical scheme of the CCC



A DC-coupled field compensation feedback loop is part of the SQUID electronics. The SQUID input coil and the pickup coil form a super-conducting loop, so that the CCC is also able to detect DC-currents.

Pick-up coil



Toroidal core (VITROVAC 6025-F) housed in a VESPEL insulator.

Completed niobium toroidal pick-up coil with included VITROVAC core.

Experimental equipment

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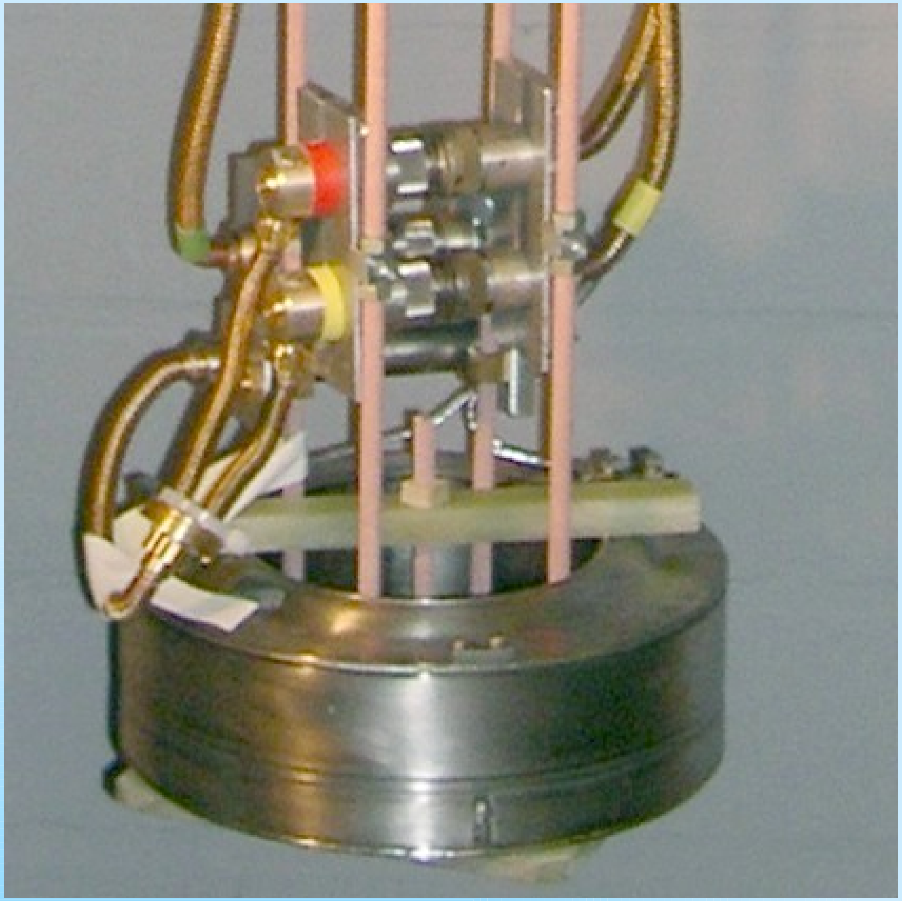
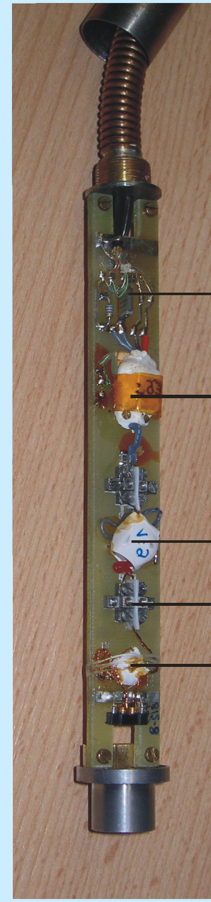
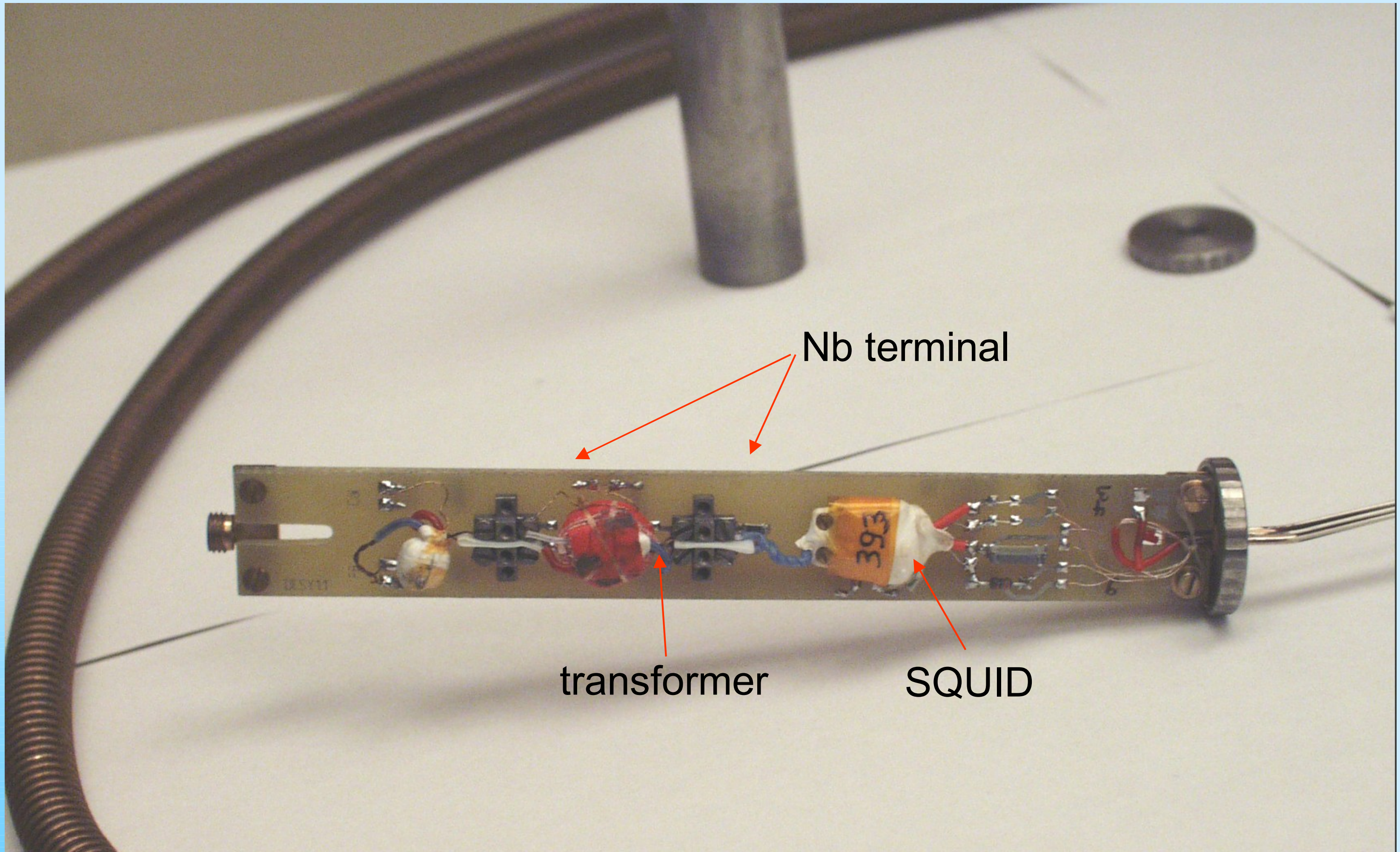


The completed niobium pick-up coil of the CCC with all special cabling for the SQUID prepared for low temperature tests in a wide-neck Helium cryostat.

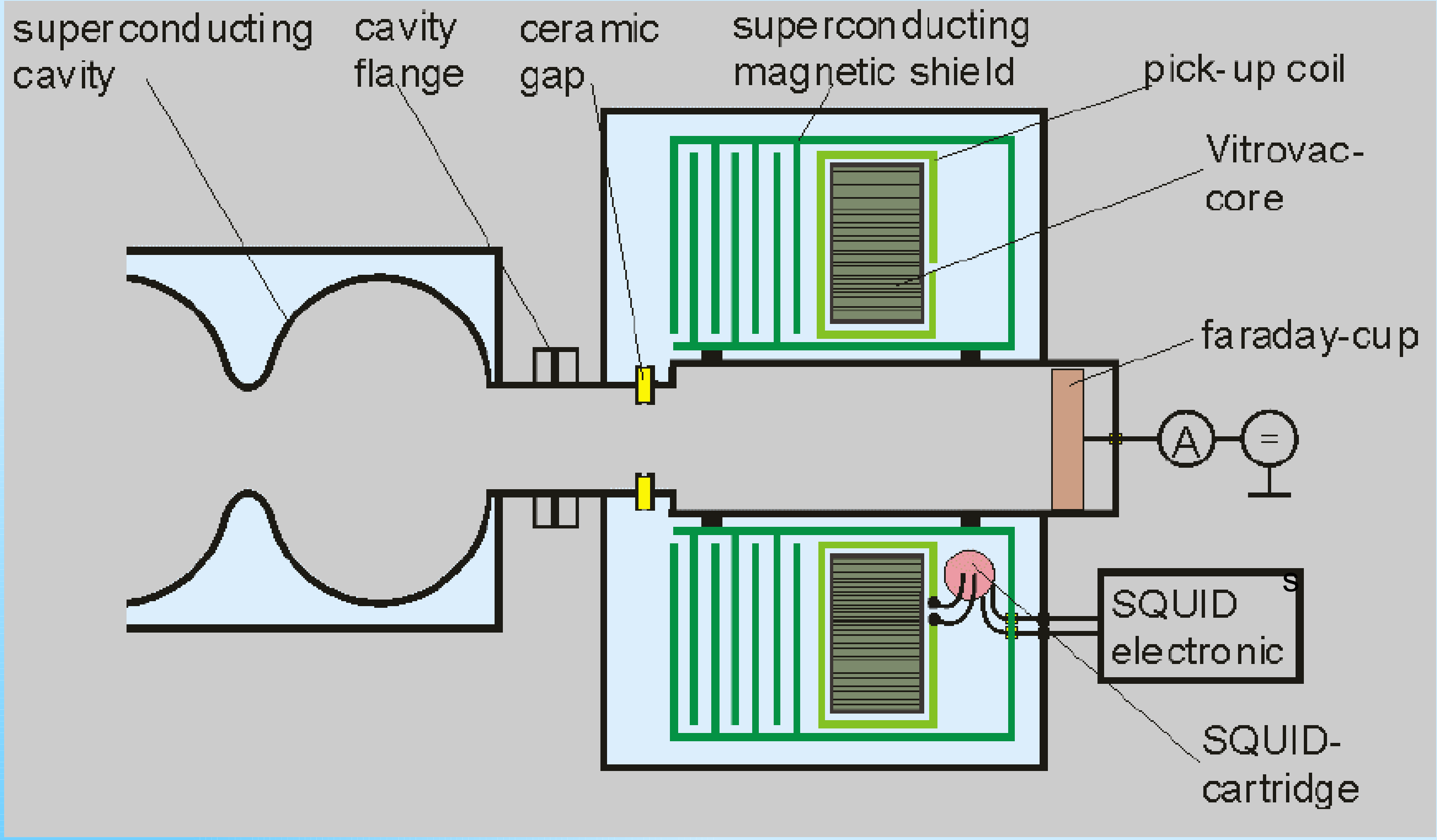


Low temperature probe with LTS SQUID, matching transformer and read-out circuit.

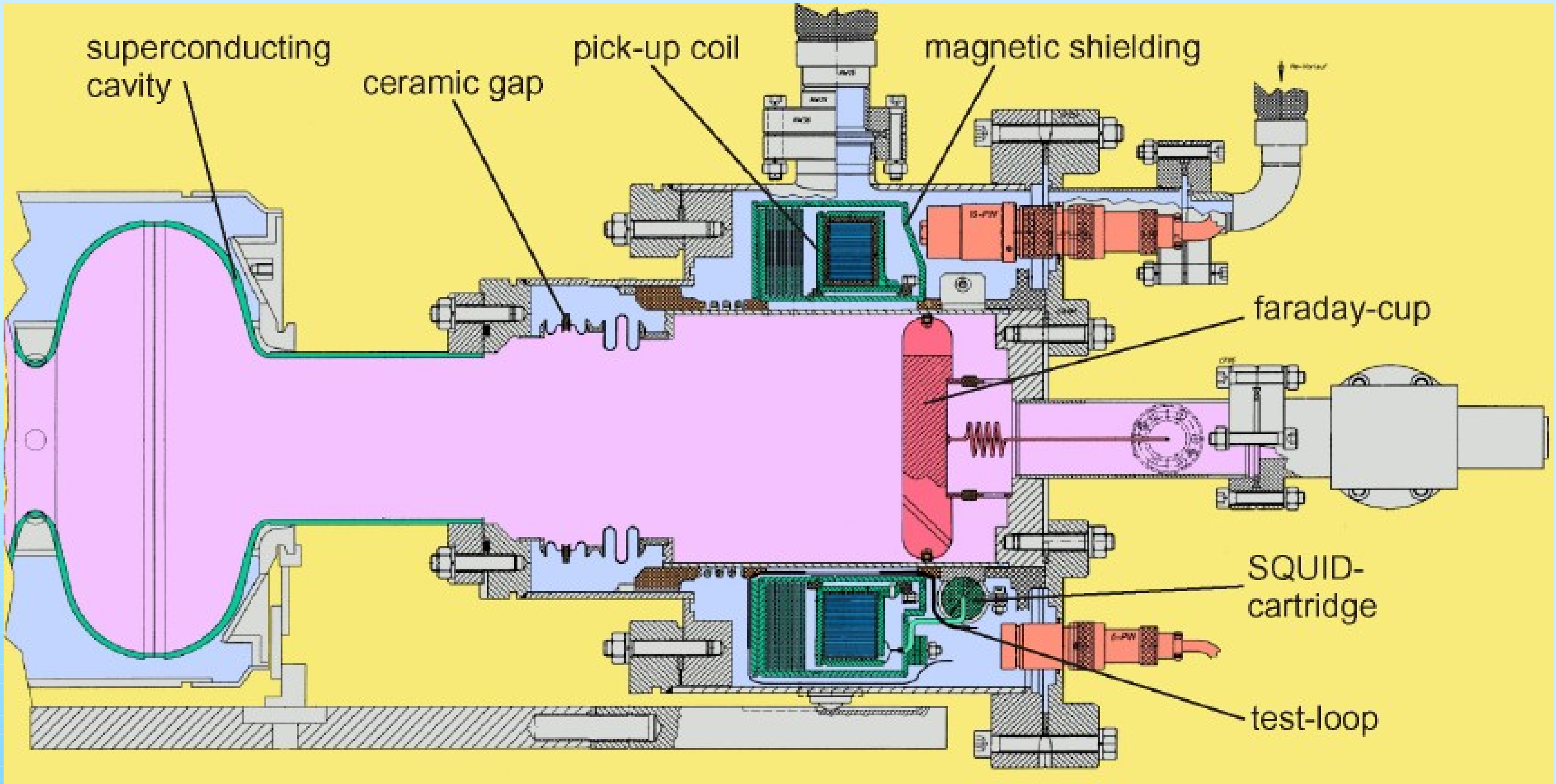
Measuring head with LTS DC-SQUID *UJ 111* (FSU Jena)



Schematic view of the CCC



Cross section of the dark current measurement equipment



blue: Liquid Helium
green: Superconductive materials

pink: Ultra high vacuum
yellow: Insulating high vacuum of CHECHIA

Experimental Results

Noise measurements and SQUID response
(with connected pick-up coil)

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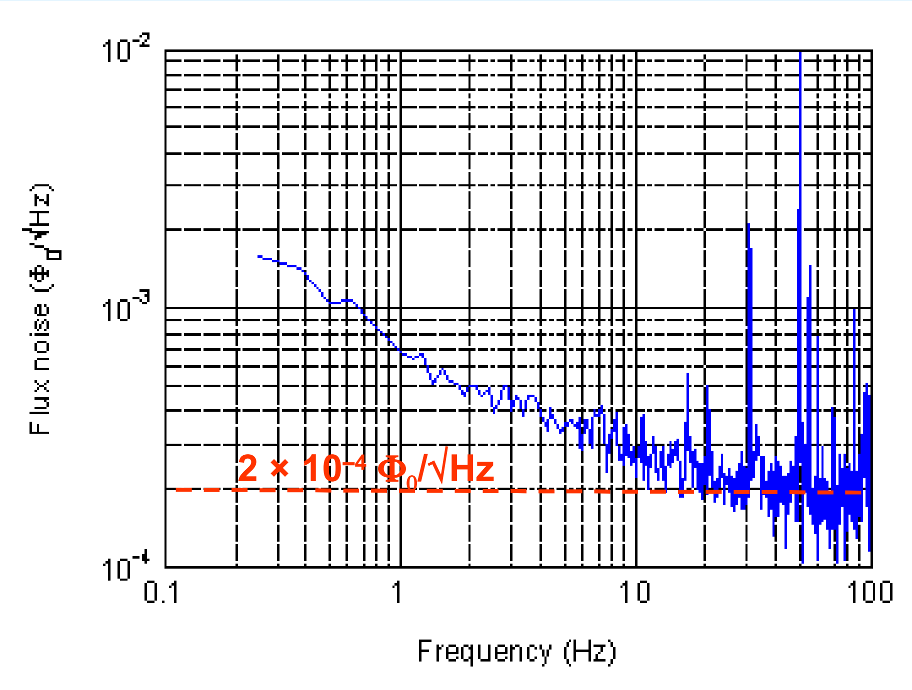

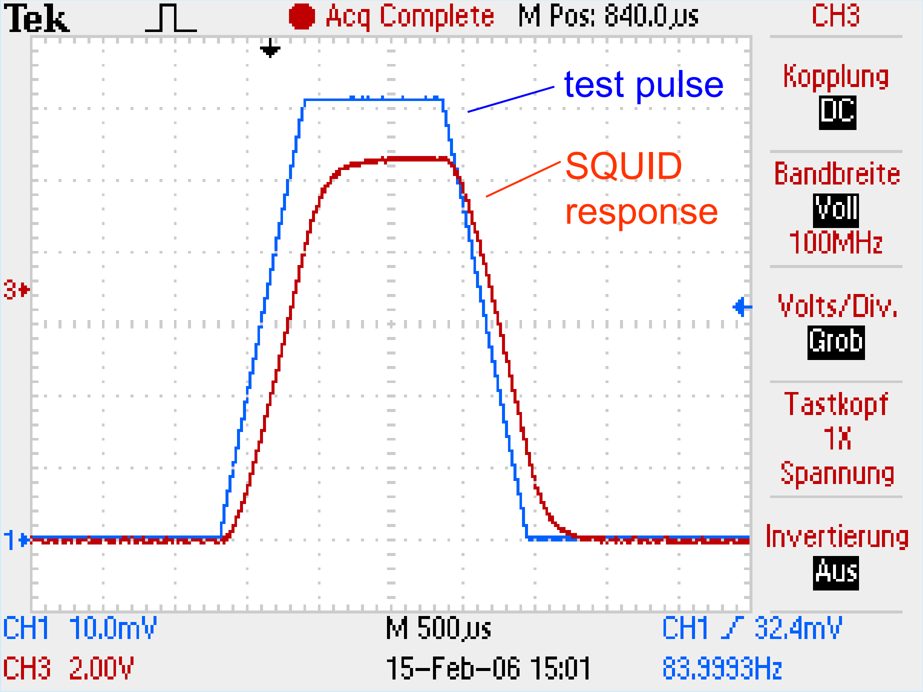

Spectral flux noise density of the SQUID system with connected pick-up coil.

blue: test signal (1 ms current pulse)
red: SQUID system response

CCC tests with simulated dark current
(in the noisy environment at DESY)

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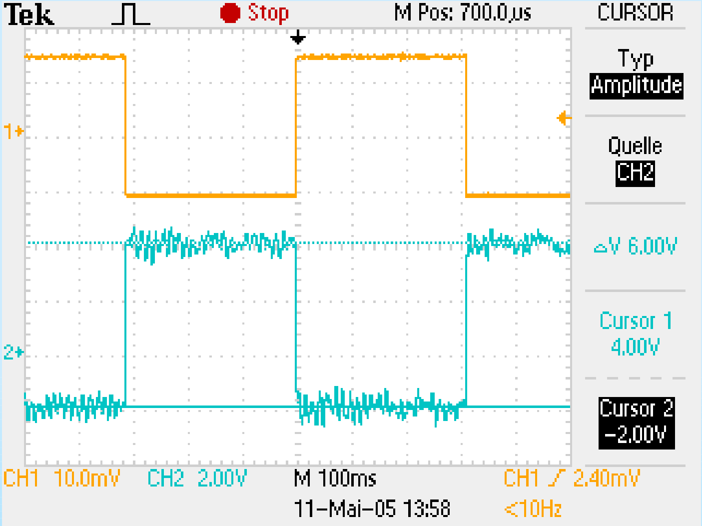
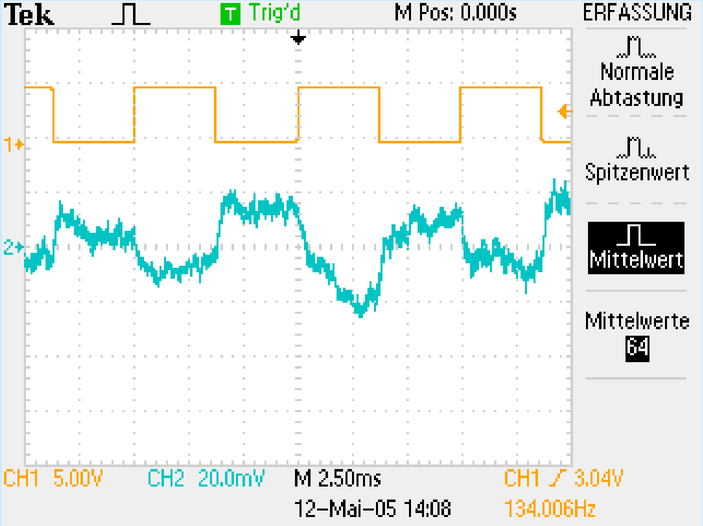


126.5 nA current pulse through the calibration coil (upper curve) and SQUID response (lower curve).



1.3 nA current pulse through the calibration coil (upper curve) and SQUID response (lower curve).

Inductance of pick-up coil

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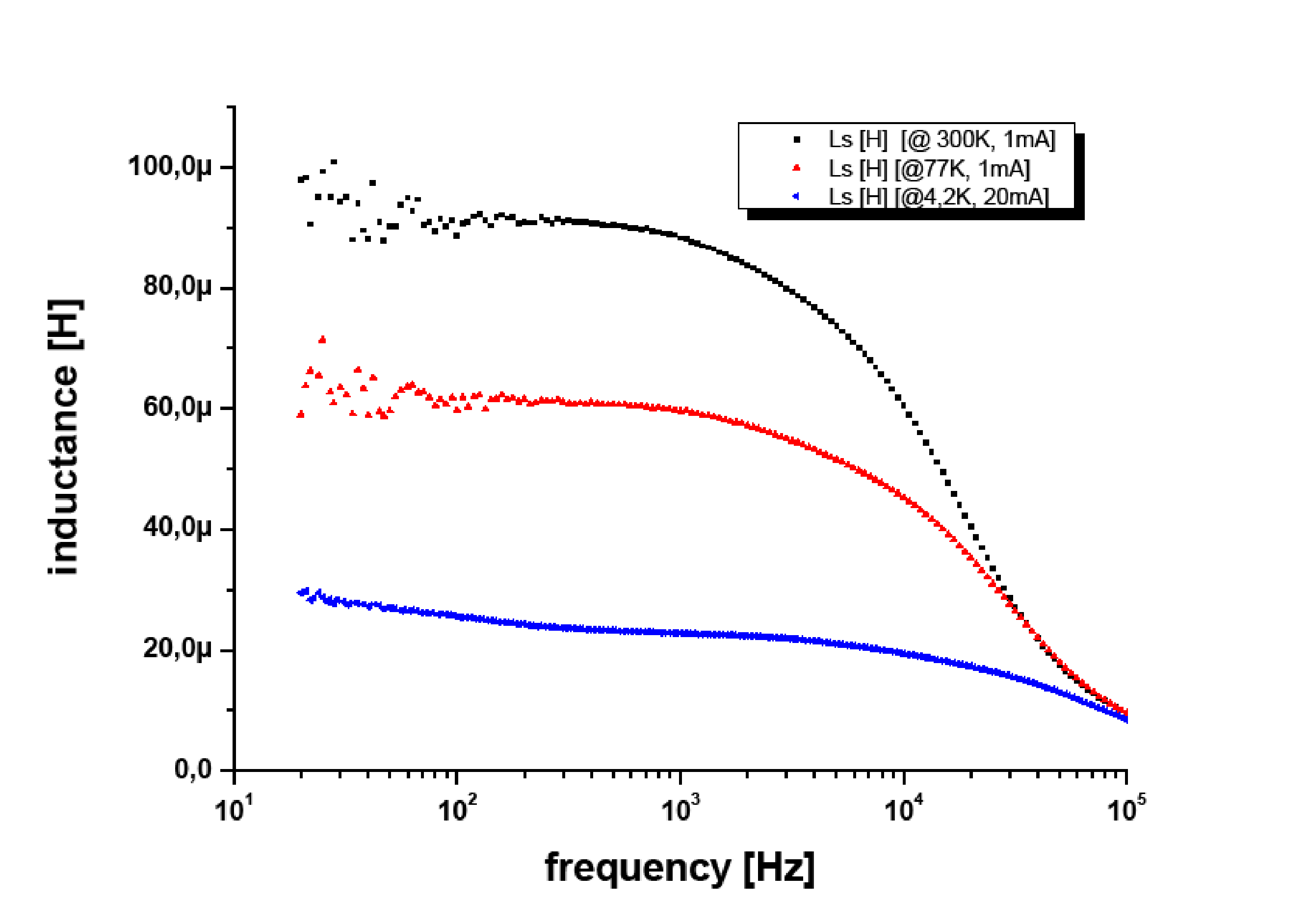

Inductance of the recent pick-up coil of the DESY-CCC in dependence of the frequency at different temperatures.

Spectral flux noise density of the CCC using different core materials

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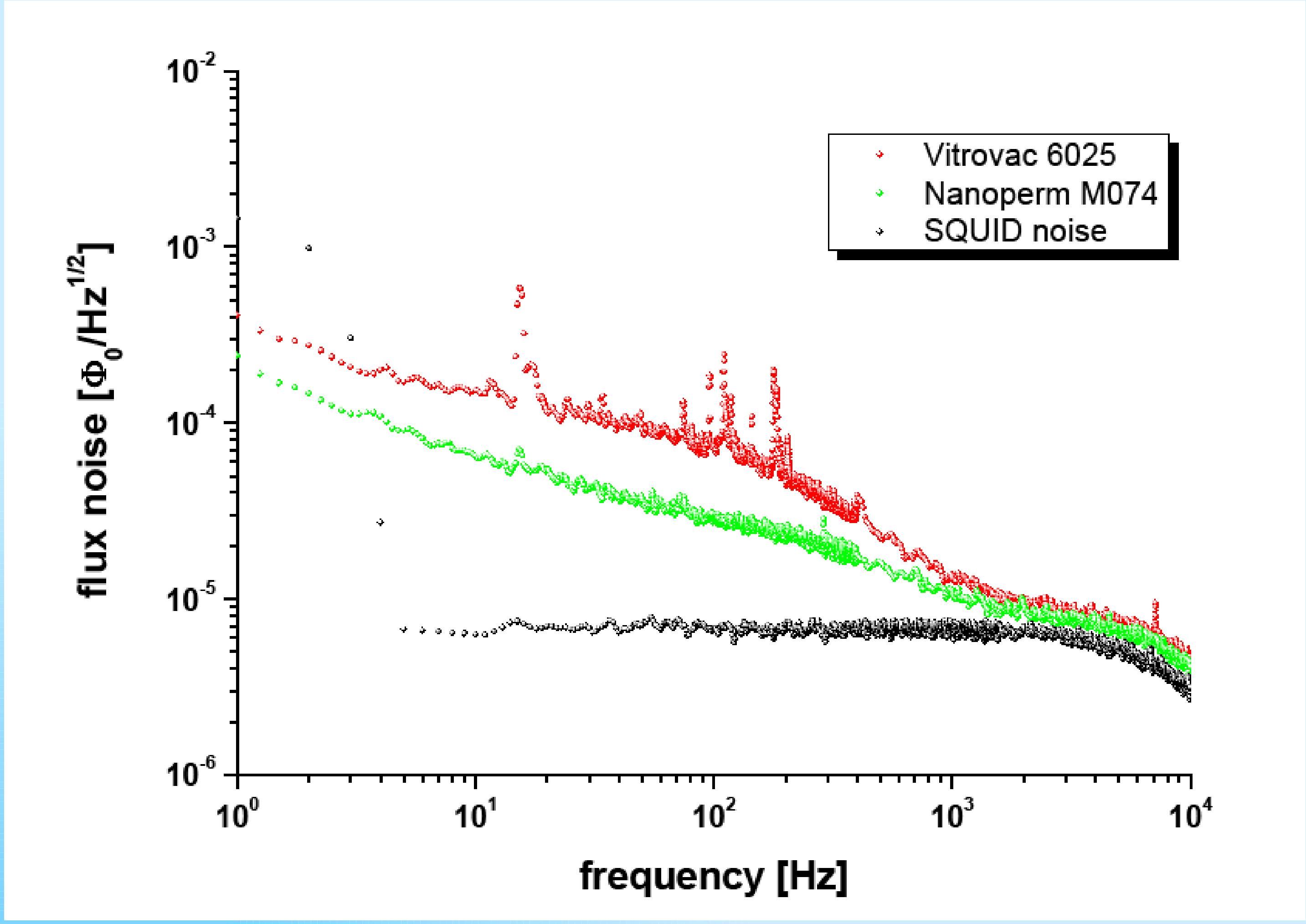

Measured performance of the DESY-CCC

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- System bandwidth: dc...70 kHz
- System sensitivity: 167 nA / Φ_0
- Flux noise (in the white noise region): $8\times10^{-5}\ \Phi_0/\sqrt{Hz}$
- Corresponding current noise: 13 pA $/\sqrt{Hz}$

But:
The current resolution of the final system will be decreased due to the additional noise contribution of
- disturbing magnetic background fields and
- mechanical vibrations of environment.

Conclusions and Outlook

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- Tests of the pick-up coil with connected SQUID system were successfully done in a wide-neck LHe cryostat.
- The superconducting meander-shaped flux transducer is used to attenuate the magnetic background noise.
- Measurement bandwidth: **dc...70 kHz**
  CCC current sensitivity: **< 200 nA/Φ_0**
- Noise limited current resolution (at LT Lab) : **40 pA/√Hz**
- Noise limited current resolution (at DESY) : **500 pA/√Hz**
- Magnetic flux drift of the CCC: **$< 2 \times 10^{-5}\ \Phi_0$/s**

- Currently the DESY-CCC is ready for installation in the HoBiCaT test stand at BESSY.

SQUID-based CCC:

- No back actions
- Highest sensitivity – no alternatives
- Easily calibrated (by electrical current)
- Measurement of absolute current values
- Negligible low drift

Acknowledgment

Co-workers

- R. Neubert
- R. Geithner
- A. Steppke
- S. Hechler

Collaboration

- A. Peters, GSI Darmstadt/HIT Heidelberg
- M. Schwickert, H. Reeg GSI Darmstadt
- K. Knaack, K. Wittenburg DESY Hamburg
- T. Siebert, R. von Hahn MPI Kernphysik, Heidelberg

References

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Simulated beam signal