Beam Diagnostic and Instrumentation for Particle Accelerators
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News about the Cryogenic Current Comparator for Beam Diagnostics

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Outline

- 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
- Future Installations at FAIR and CSR
- Conclusions and Outlook

Motivation

In any accelerator facility there is a need for:

- Non-destructive measurements of high energy ion beams in the range of 1 μA…1 nA (e.g. GSI Darmstadt)
- Measurements of so-called dark currents of superconducting acceleration cavities in the range below 1 μA (e.g. X-FEL at DESY Hamburg)
- Measurements of charged particles in the CSR of MPI Heidelberg
- Precise determination of beam intensity for FAIR (GSI Darmstadt) ranging from 10^4 antiprotons to 5×10^{11} uranium ions

Solution: **SQUID-based Cryogenic Current Comparator**

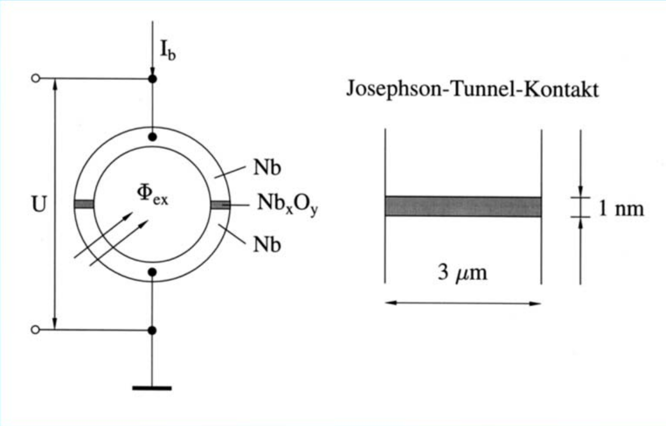
Superconducting **QU**antum **I**nterference **D**evice

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

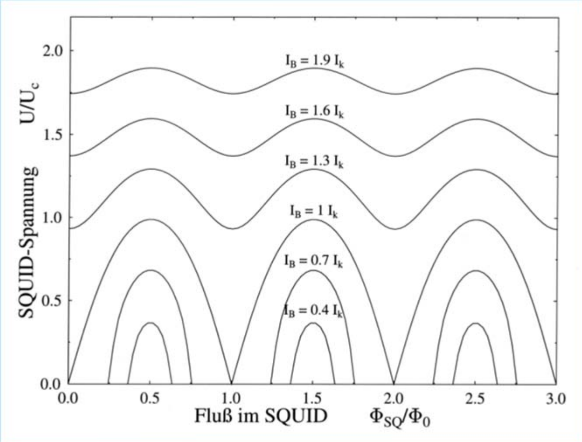
The working principle makes use of:

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

A dc SQUID consists of a superconducting ring with mostly two weak links (so-called Josephson tunnel junctions).



Simplified scheme of a dc-SQUID and a tunnel junction



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

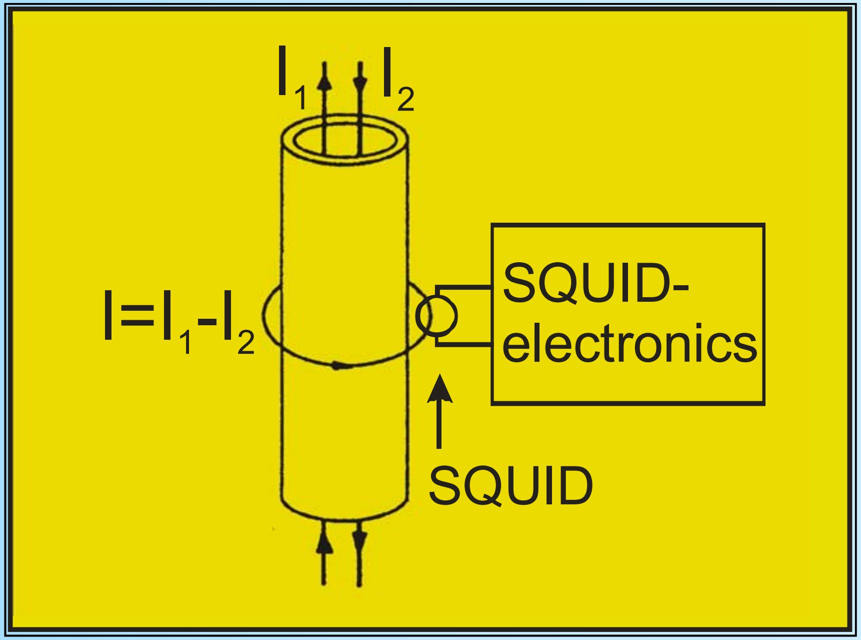
Main principle of the Cryogenic Current Comparator (CCC)

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*

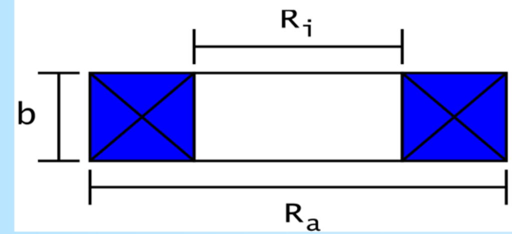
Resolution limits

Minimum detectable current I_s:

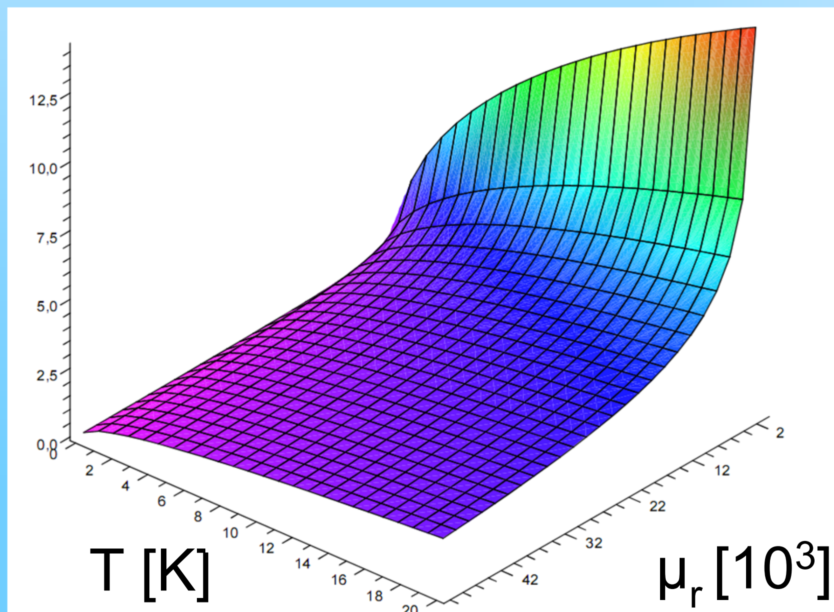
$$I_s = \frac{2\pi\sqrt{k_B T L}}{\mu_0 \mu_r f(R_a, R_i, b)} \Rightarrow I_s \propto \frac{1}{\sqrt{\mu_r}}$$

with: T = temperature
μ_r = relative permeability of core material
L = inductance of pick-up coil

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

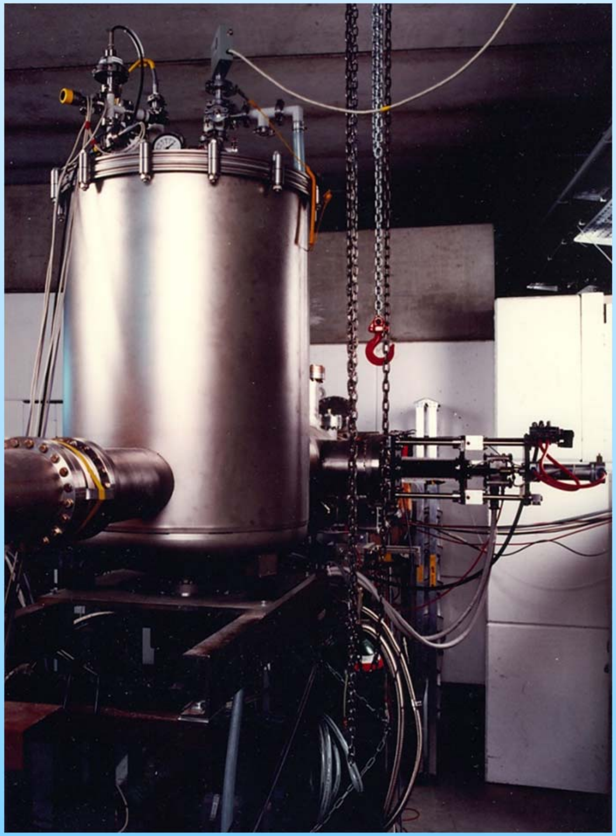


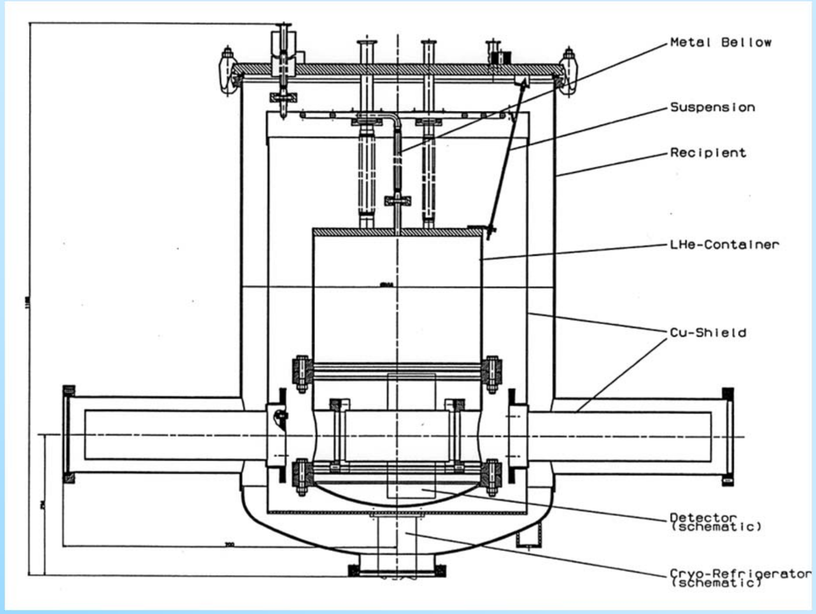
I_s [10^{-9} A]



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

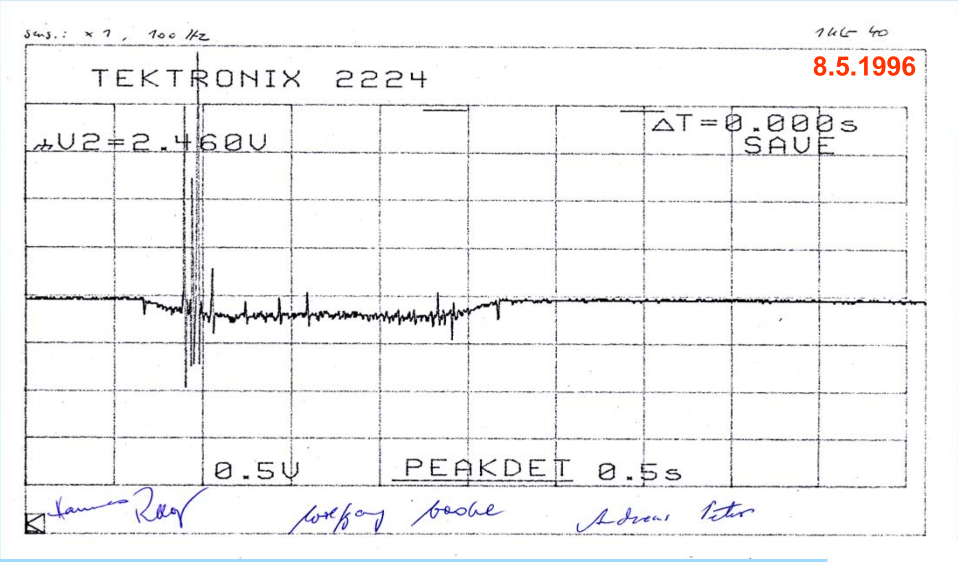
The CCC at GSI Darmstadt





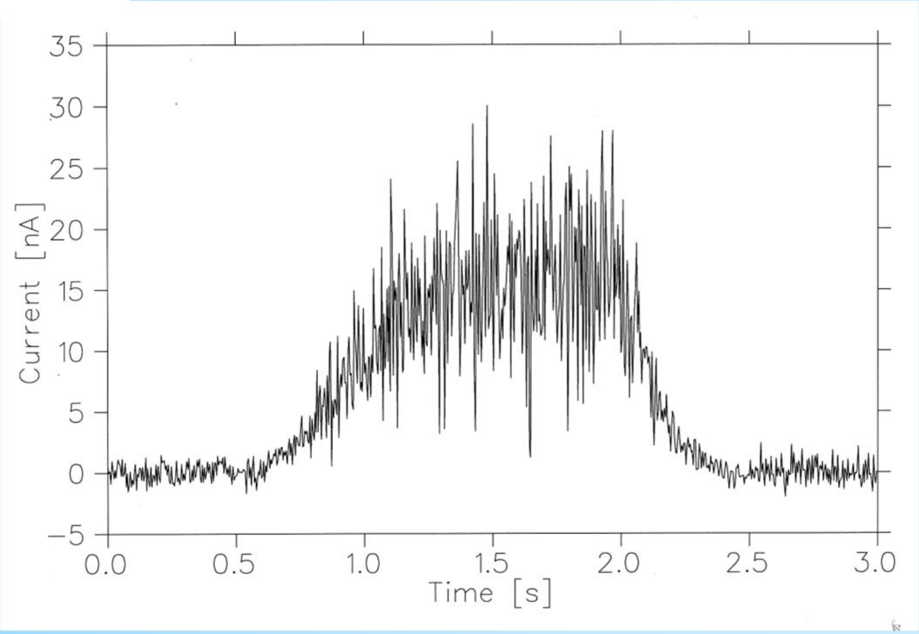
Photography of the CCC assembled in the beam line and some technical details.

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



Achieved current resolution:

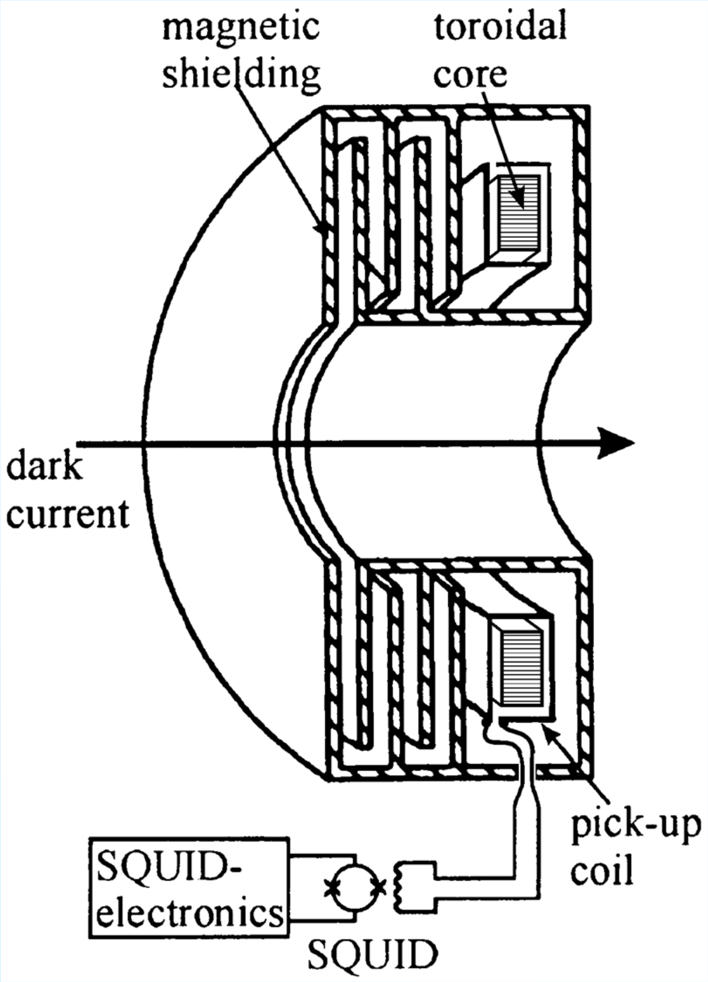
≤ 250 pA/√Hz



CCC at DESY Hamburg

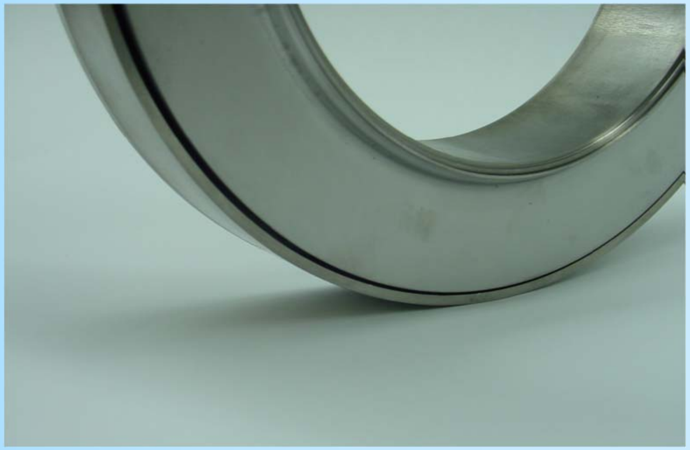
- The performance of superconducting cavities for accelerators is characterized, above all, by the Q-value vs. gradient dependency.
- The most important criterion is the so-called ***dark current***
- Dark currents are caused by field emission of electrons in high gradient electrical fields
- Dark currents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

Pickup coil with meander-shaped shield



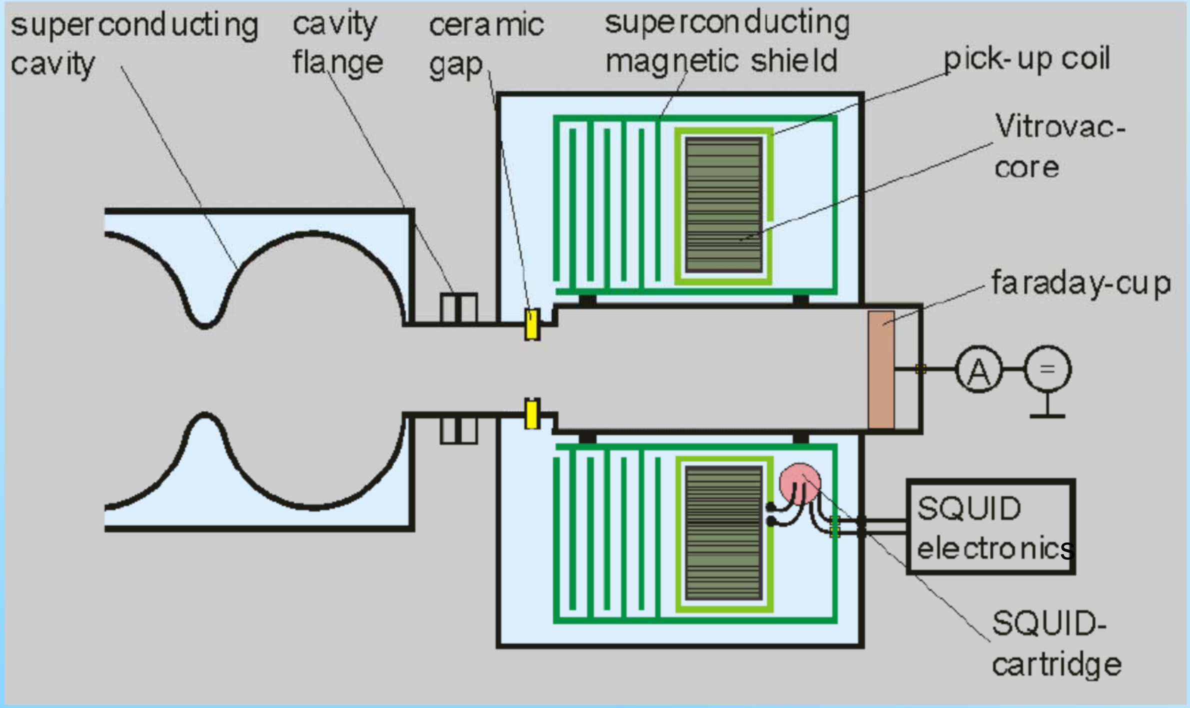
Schematic of the single turn superconducting pickup coil.

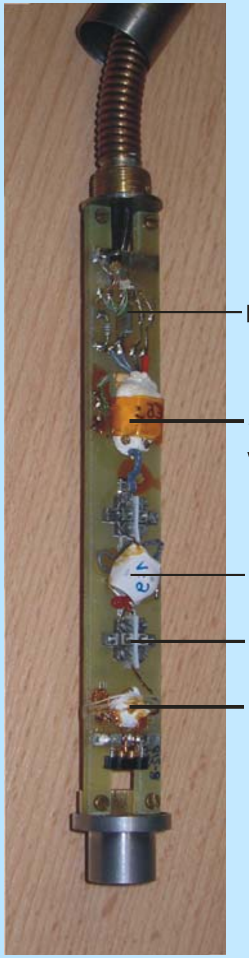
Toroidal core (VITROVAC 6025-F) housed in a VESPEL insulator.



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

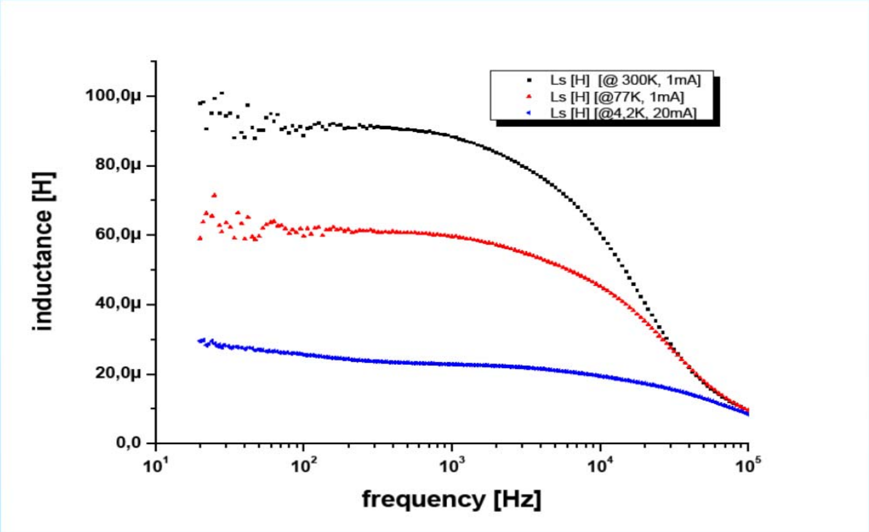
Schematic view of the CCC and LTS probe



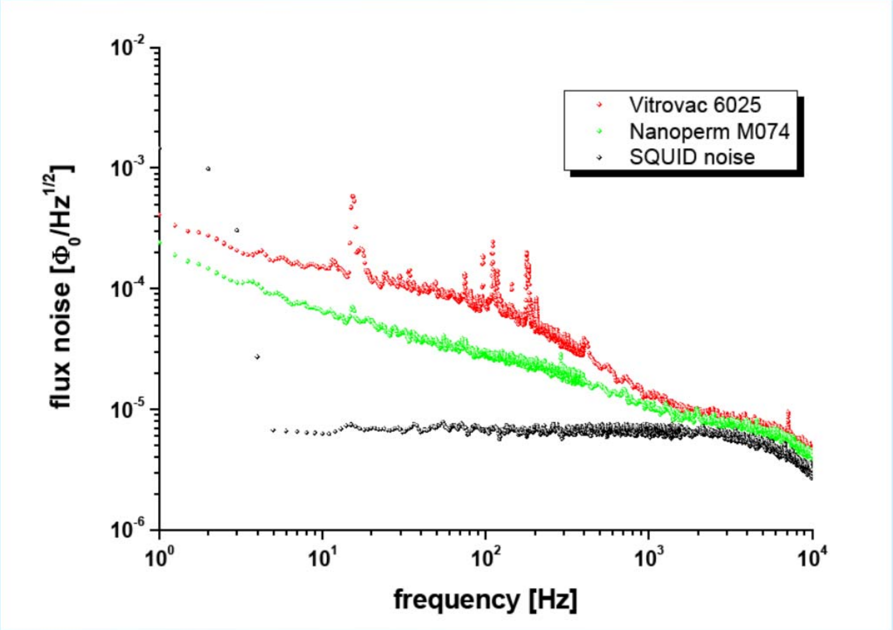


Low temperature probe with LTS SQUID, matching transformer and read-out circuit.

Experimental results

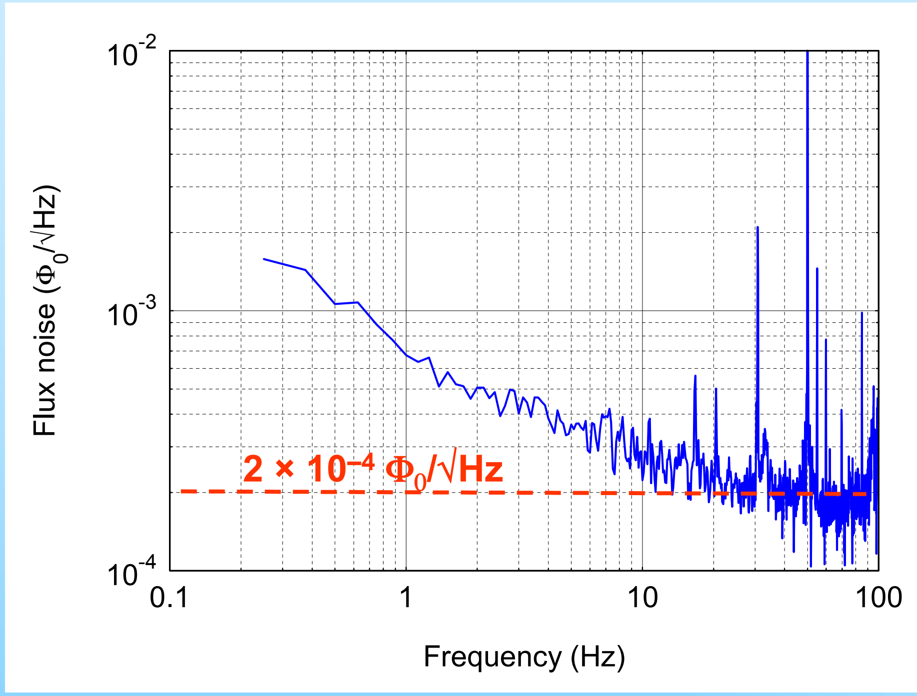


Inductance of the recent pick-up coil of the DESY-CCC in dependence of the frequency at different temperatures.

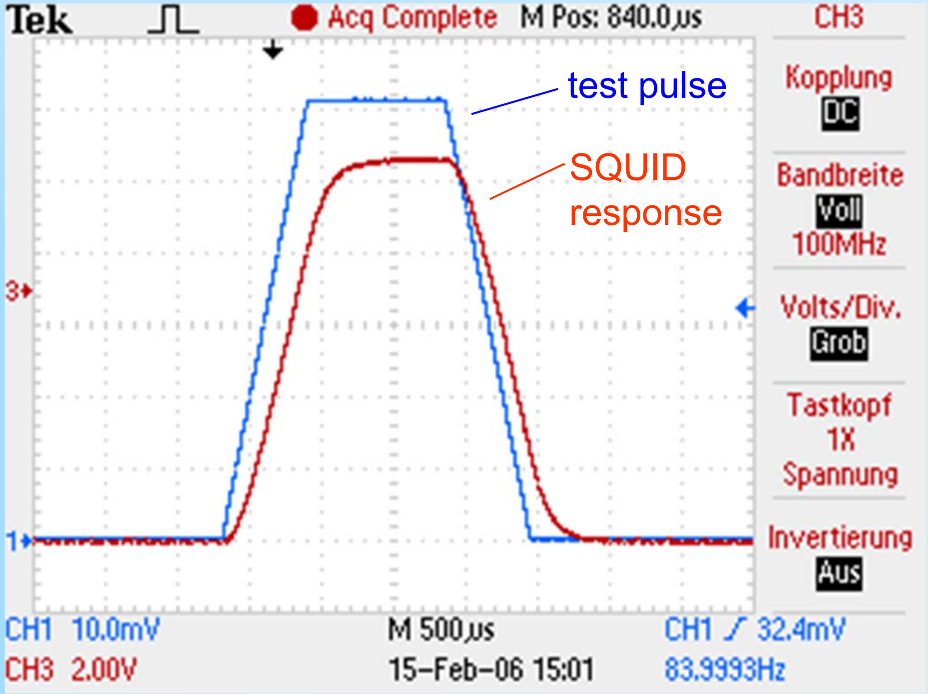


Spectral flux noise density of different core materials

Experimental results

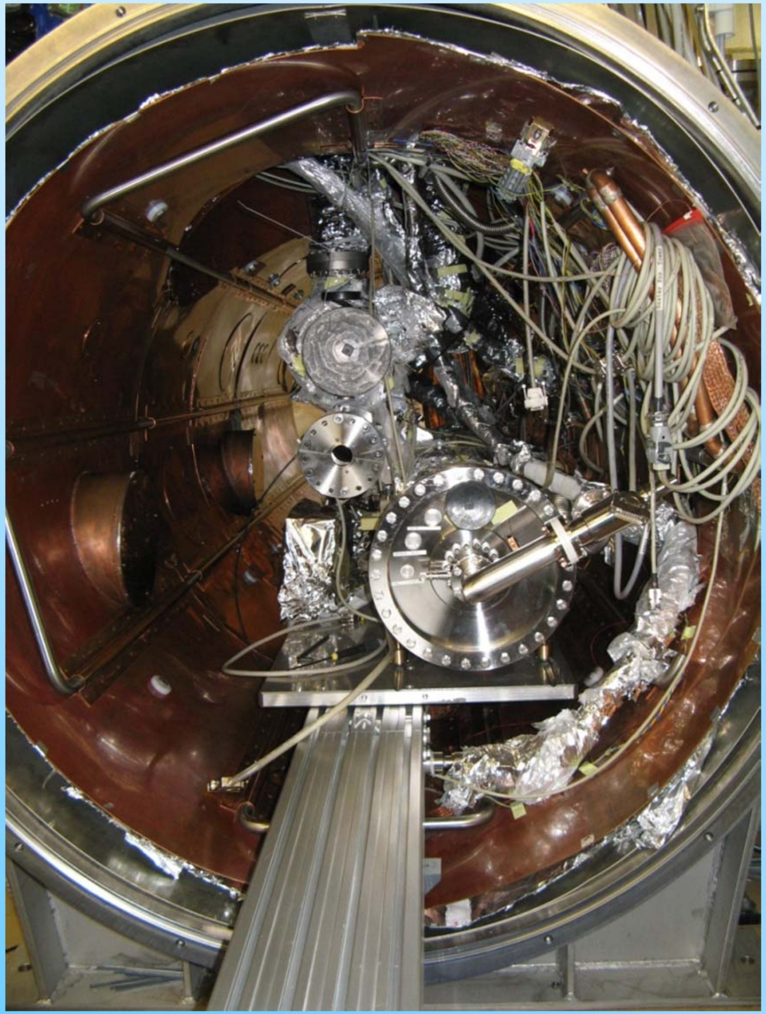


Spectral flux noise density of the SQUID system with connected pick-up coil.

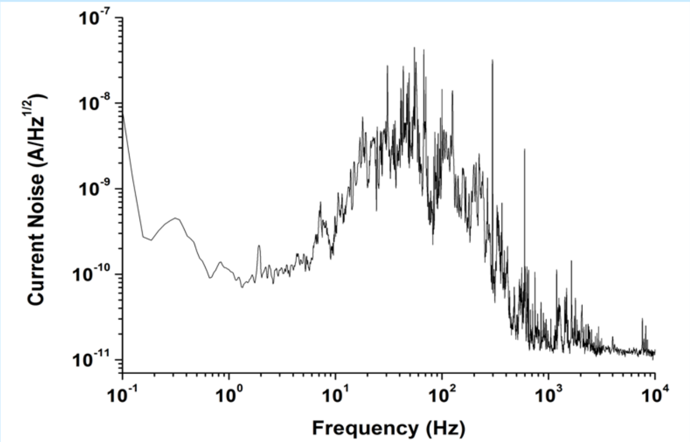


blue: test signal (1 ms current pulse)
red: SQUID system response

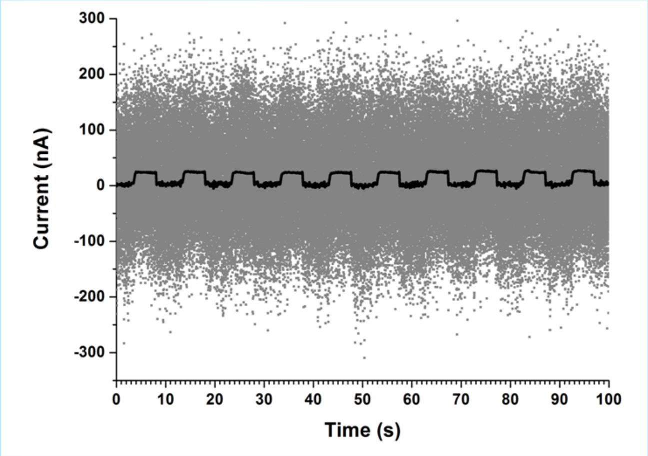
Application of the CCC in the test stand HoBiCaT
(in the noisy environment at BESSY)



View into the opened test stand "*HoBiCaT*" at BESSY



Spectral noise density



Unfiltered (grey) and filtered beam signal (low pass: 5 Hz)

W. Vodel, HI Jena

Measured performance of the DESY-CCC

- System bandwidth:	dc...70 kHz
- System sensitivity:	167 nA / Φ_0
- Flux noise (in the white noise region):	2×10^{-4} Φ_0 /√Hz
- Corresponding current noise:	40 pA /√Hz

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

The Future (I): CCCs for FAIR

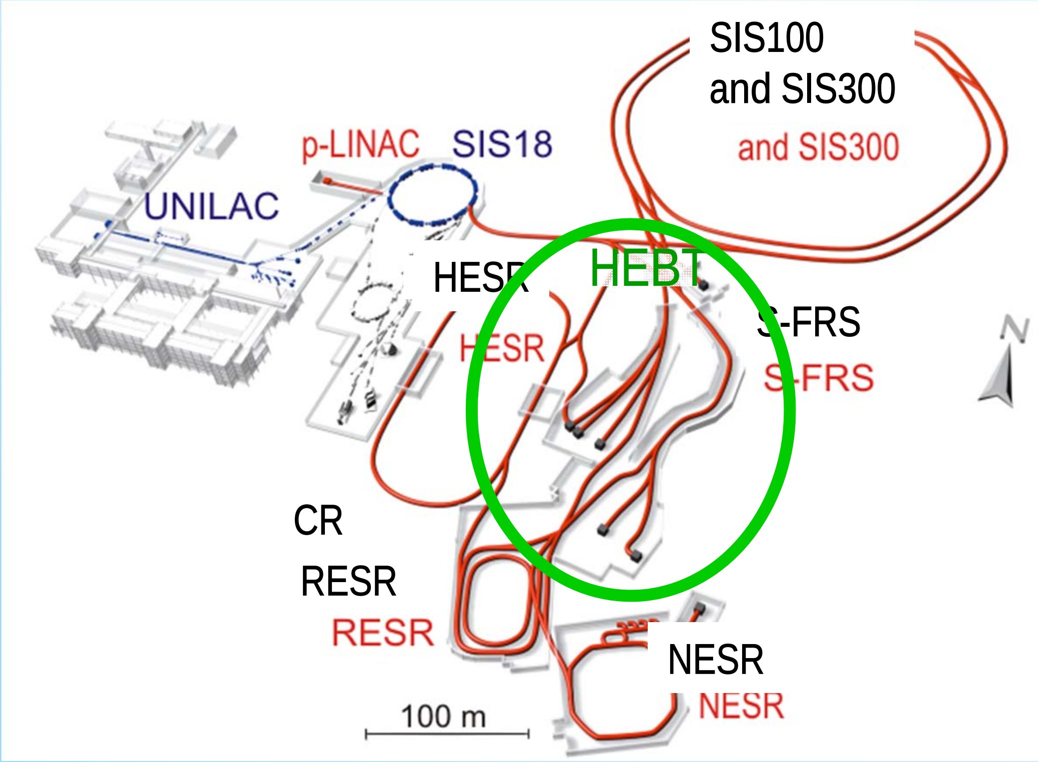
Goal of FAIR facility:
production of **'unprecedented' high intensity, high brightness ion beams**, beams of rare isotopes and antiprotons

High-Energy Beam Transport (HEBT) section requires a device 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 :

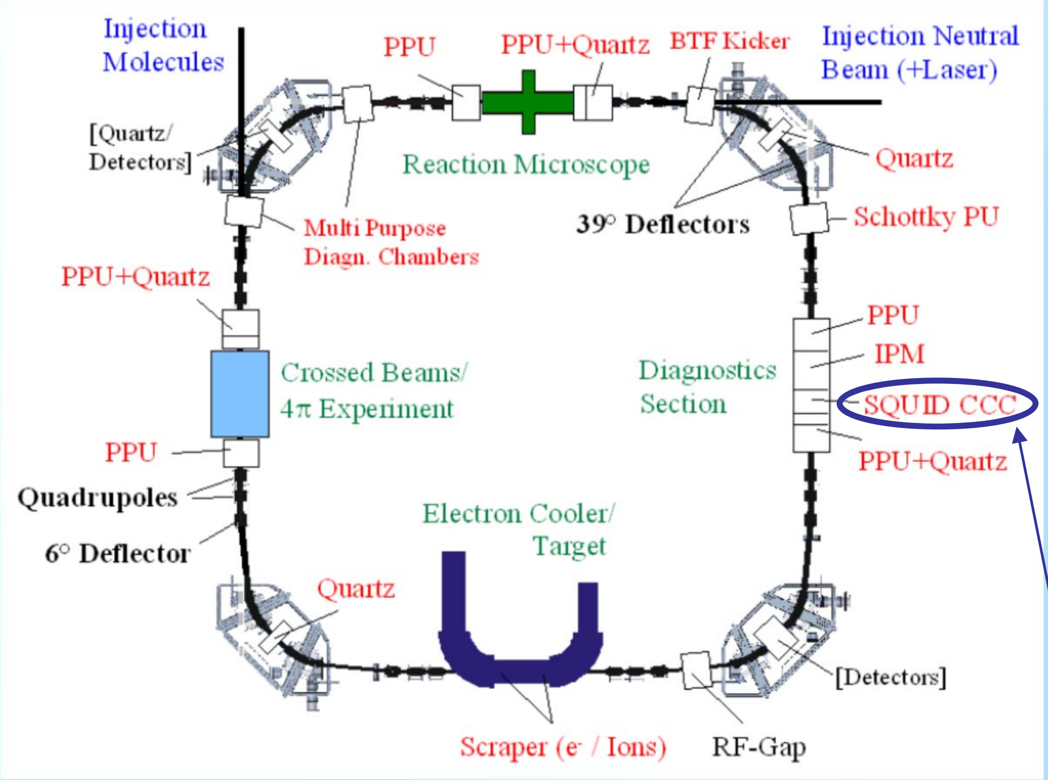
minimal Intensity: 10^4 pps

maximal intensity: 10^{12} pps

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

The Future (II): A CCC for CSR

Cryogenic Storage Ring CSR presently under construction at Max-Planck-Institute für Kernphysik / Heidelberg



(Figure courtesy T. Sieber, MPI-K Heidelberg)

CSR Key Features:

- Electrostatic ring
- 35 m circumference
- XHV vacuum system ~1E-13 mbar
- Operational temperature <10 K
- Particle energy: 10 - 300 keV
- Beam intensity: 1 nA – 1 μA

Current measurement device for:
- Lifetime measurements
- Determination of reaction rates / cross sections
- Pickup calibration

⇩

Below the sensitivity threshold of standard DC-Current transformers

⇩

A CCC for the Cryogenic Storage Ring as **prototype for FAIR CCC**

Outstanding advantages of a SQUID based CCC

- Non-destructive measurement method
- High resolution (< 1 nA/√Hz) – no alternatives
- 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 1995 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 HEB

Acknowledgment

Co-workers

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Friedrich-Schiller-Universität Jena

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- K. Knaack, K. Wittenburg DESY Hamburg
- T. Siebert, R. von Hahn MPI Kernphysik, Heidelberg

Thank you for your attention!

References

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[2] C. Stolzenburg, "Untersuchungen zur Entstehung von Dunkelströmen in supraleitenden Beschleunigungsstrukturen", (in German); Ph. D. Thesis, University of Hamburg 1996.

[3] R. Brinkmann, "Dark Current Issues"; Tesla Collaboration Meeting – CEA SACLAY, 4/2002.

[4] A. Peters, et al., "A Cryogenic Current Comparator for the Absolute Measurement of nA Beams"; Proc. of the 8th BIW, Stanford, 1998, AIP Conf. Proc. 451, pp.163-180

[5] K. Grohmann, et al.; CRYOGENICS, July 1976, pp.423-429

[6] K. Grohmann, et al.; CRYOGENICS, October 1976, pp.601-605

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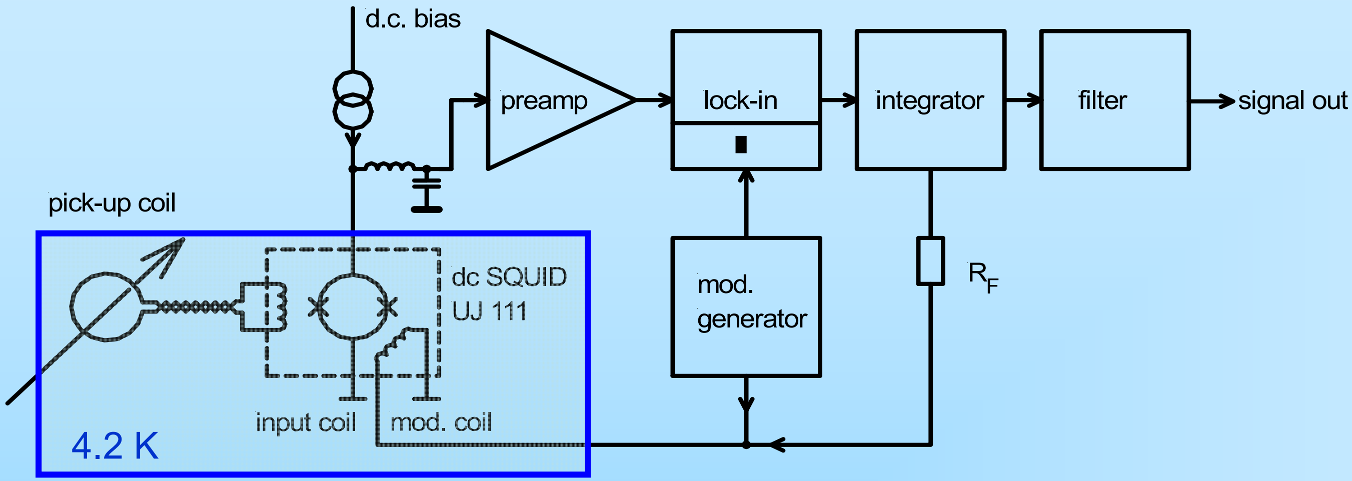
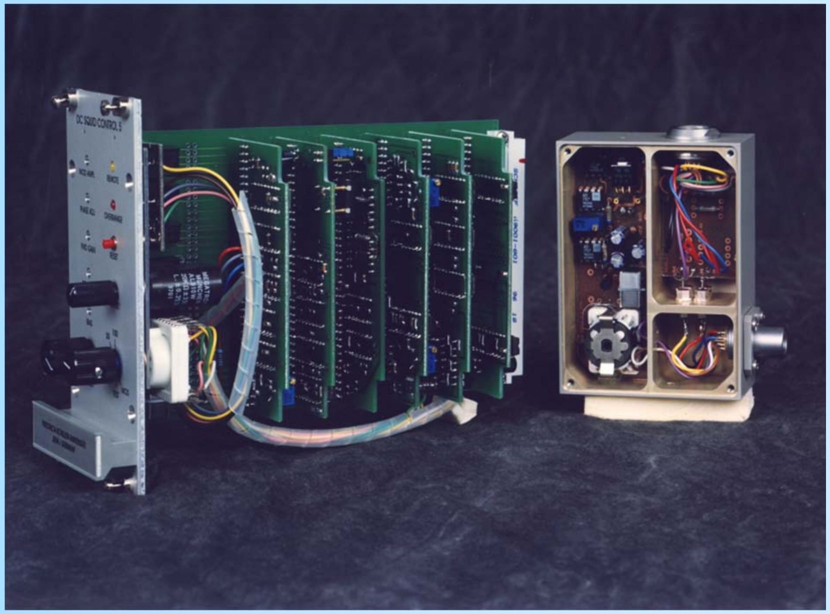
[8] K. Knaack, et al., "Cryogenic Current Comparator for Absolute Measurements of the Dark Current of Superconducting Cavities of TESLA"; Proc. of the DIPAC 2003, Mainz 2003

The *dc SQUID system 5*



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



1 channel of the *dc SQUID System 5*

Magnetic material

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

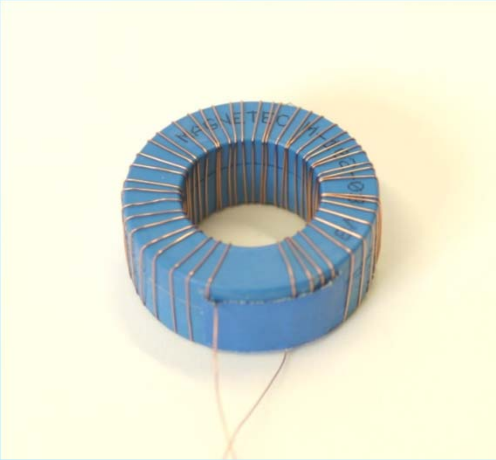
Magnetec Langenselbold

•Nanoperm

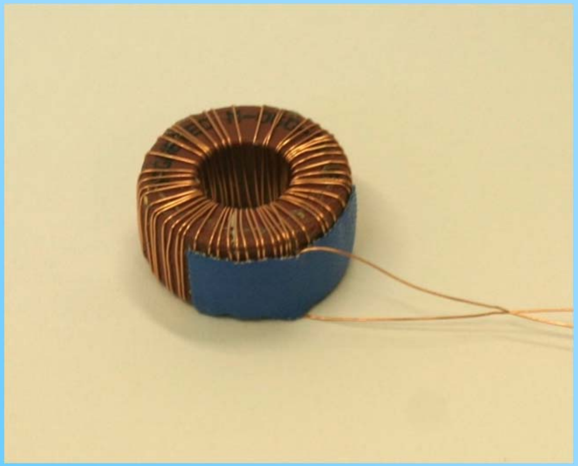
toroidal tape wound cores in plastic cases in different dimensions with μ_r from 25.000 to 100.000 at 300 K

Nanoperm- magnetic cores

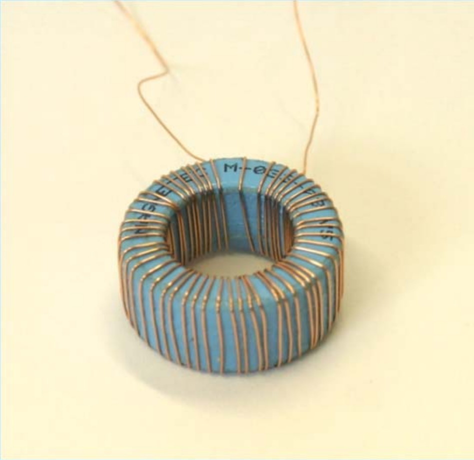
Nanoperm-toroidal tape wound cores



Nanoperm-toroidal tape wound cores
M074 (50 windings)

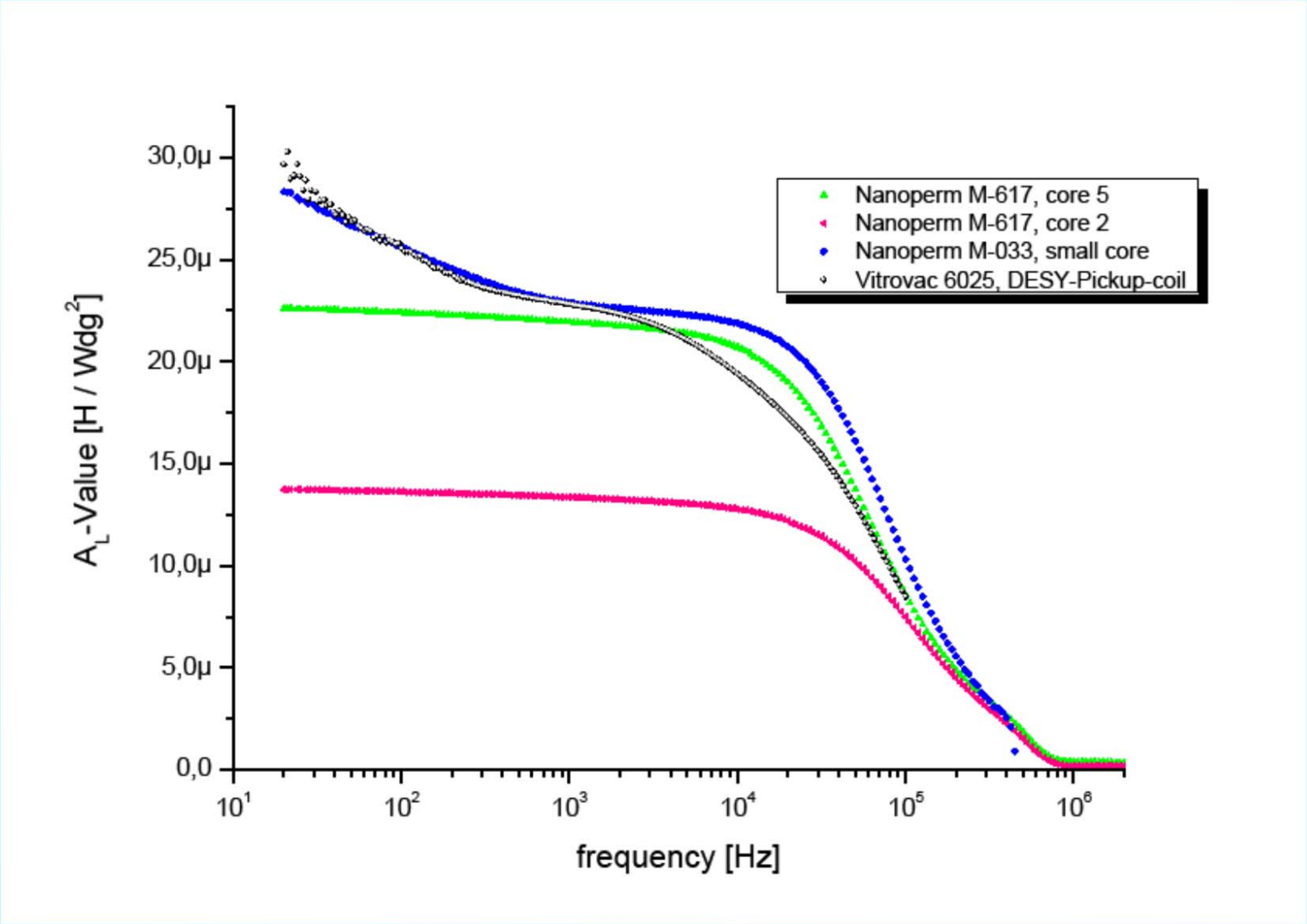


Nanoperm-toroidal tape wound cores M060
(50 windings)

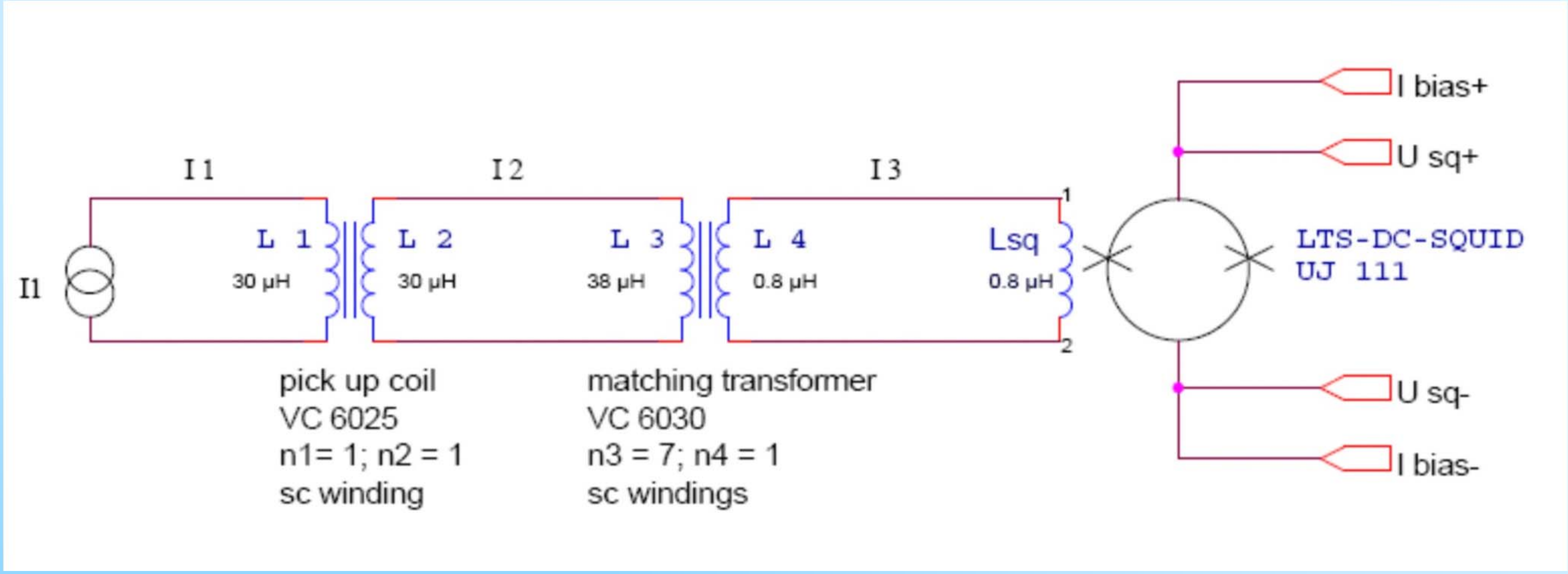


Nanoperm-toroidal tape wound cores M033
(50 windings)

Frequency dependence of A_L-values of magnetic materials at 4.2 K



Electrical Scheme of the input circuit



Total current gain:

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