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DARK CURRENT MEASUREMENT BY USING A CRYOGENIC CURRENT COMPARATOR

Contents:

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MOTVATION

The **performance** of our superconducting cavities is characterized by the q-value vs. gradient dependency, **measured** on a test stand (e. g. *CHECHIA*). But...

...unfortunately there is another (nasty) property: the **dark current** (vs. gradient), which we do not characterize today, but which may have an impact on the accelerator operation.

Dark current is caused by the emission of electrons in high gradient fields, when the forces of the applied external field are higher than the bounding forces inside the crystal structure. Potential **emitters** are [1]:

- High field gradients at **imperfections of the smooth cavity shape**, e. g. corners, spikes and other discontinuities.
- **Imperfections of the crystal matter**, e. g. grain boundaries, inclusion of "foreign" contaminants (Sb, In, Fe, Cr, Si, Cu,... microparticles) and other material inhomogeneous.

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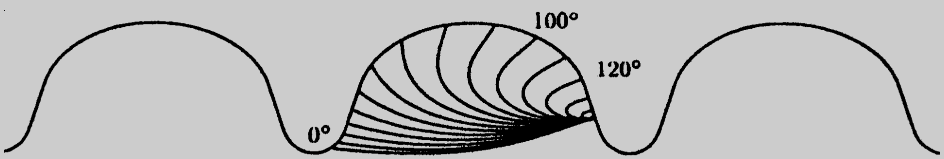
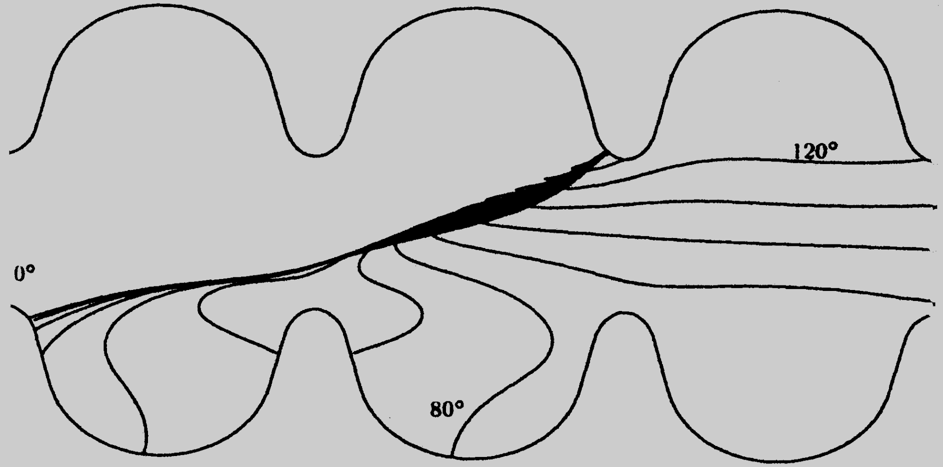


Dark current simulations [2]



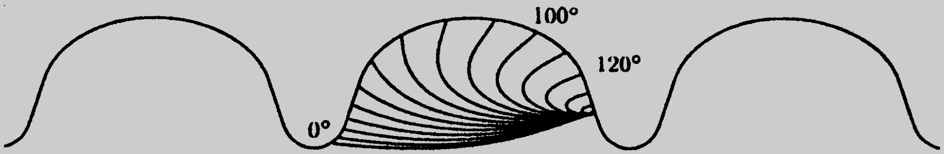
Dark current is an unwanted particle source which limits the accelerator performance. Two issues has been considered:

- **thermal load**
- propagating dark current (secondaries)

The heat load aspect is of main concern and limits the dark current of a TESLA 9-cell cavity to [3]

$$i_{\text{dark}} < 50 \text{ nA}$$

Further simulations show, that an avalanche effect due to a generation of secondaries (propagating dark current through the complete TESLA main linac) would show up only at extreme high gradients (> 150 MV/m); thus is of no concern.



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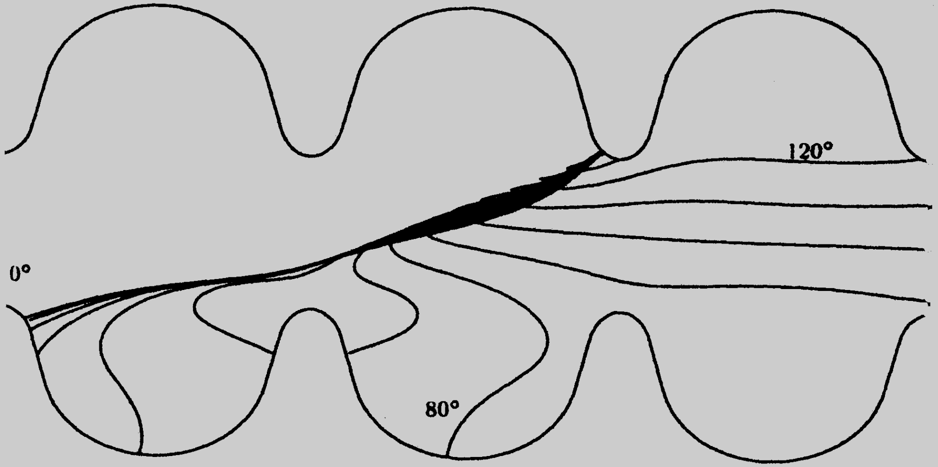

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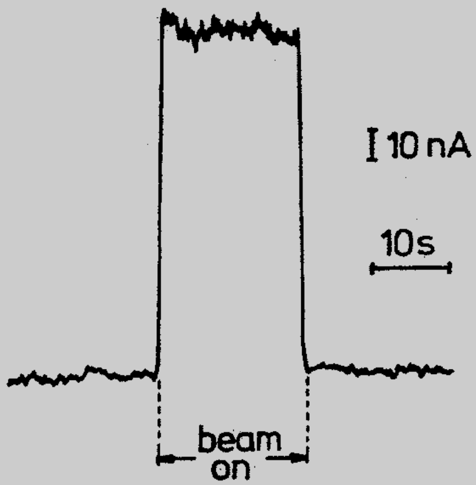
A *faraday cup* as dark current sensor will suffer from the high electron energies and low currents to be detected. While the capture of all secondary electrons in the stopper in case of a single 9-cell cavity test (*CHECHIA*, $E \approx 25...40$ MeV) is of no problem, it is challenging for a **module test stand** (12×9-cell cavity, $E \approx 350...560$ MeV).

A **cryogenic current comparator (CCC)** to characterize the dark current of the superconducting cavities has some advantages:

- high resolution (< 5 nA @ 1 kHz bandwidth)
- measurement of the absolute value of the dark current
- independent of electron trajectories
- absolute calibration with a wire loop
- the electron energies are of no concern



GSI (Darmstadt) has been made an impressive demonstration of the capabilities of a CCC to measure extracted ion-beams with a **resolution of 0.25 nA !** [4]

In collaboration with GSI and the Friedrich Schiller University (Jena) a CCC for the dark current measurement of the TESLA cavities is under construction. The proof of principle will be done in the *CHECHIA* test stand.

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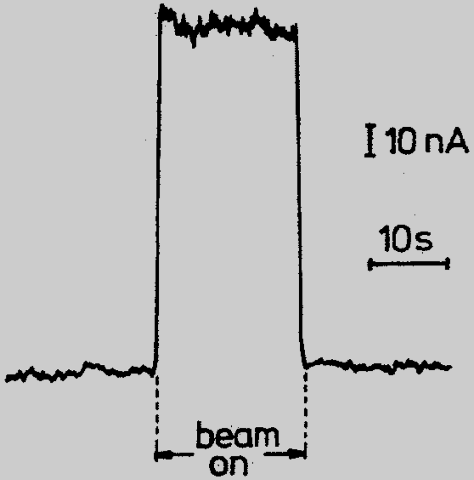

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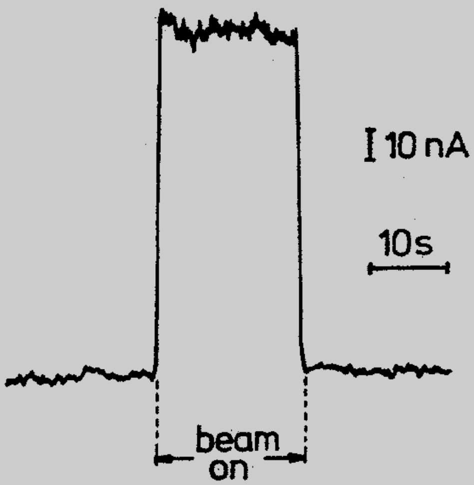

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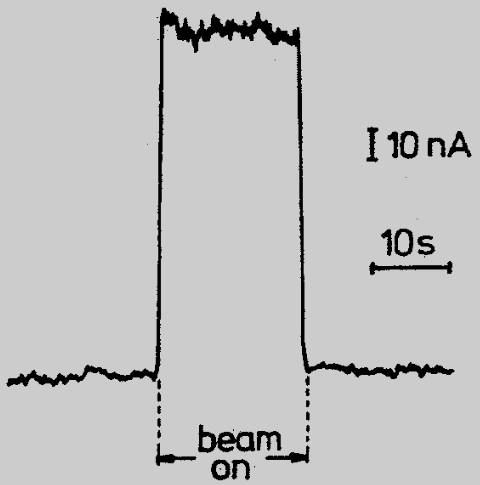

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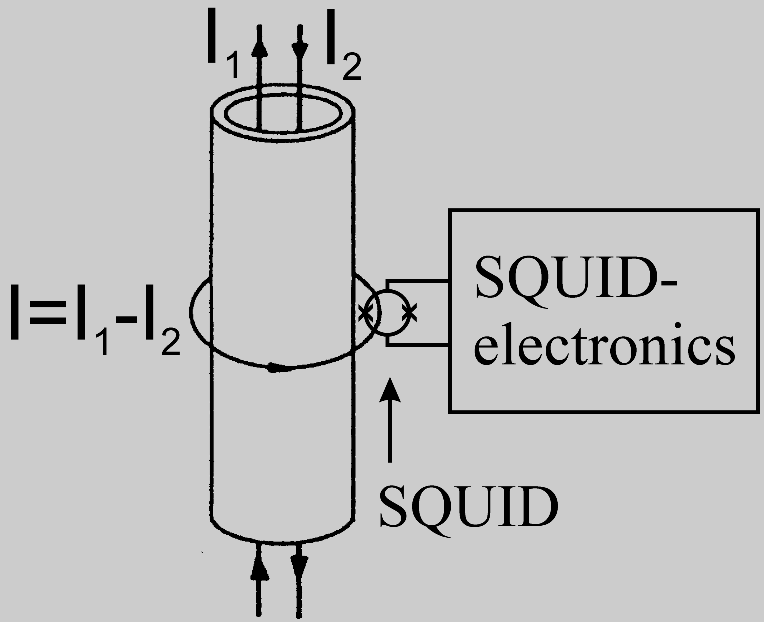
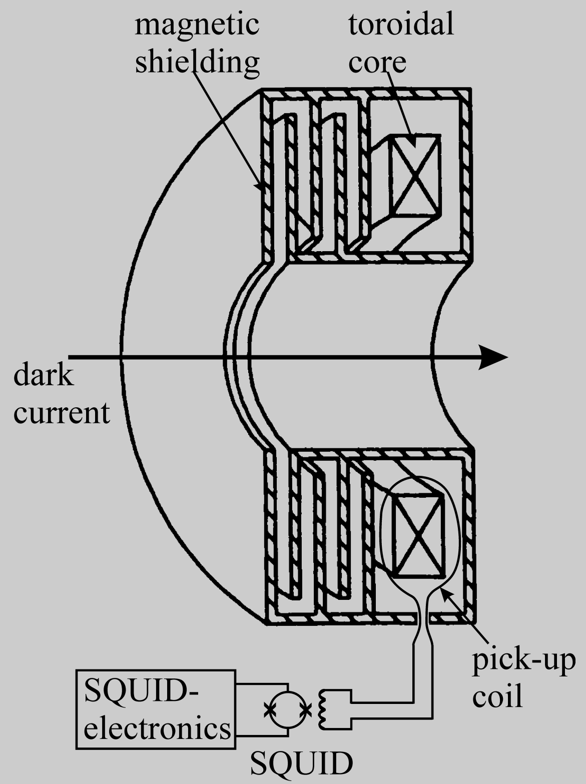
CRYOGENIC CURRENT COMPARATOR PRINCIPLE





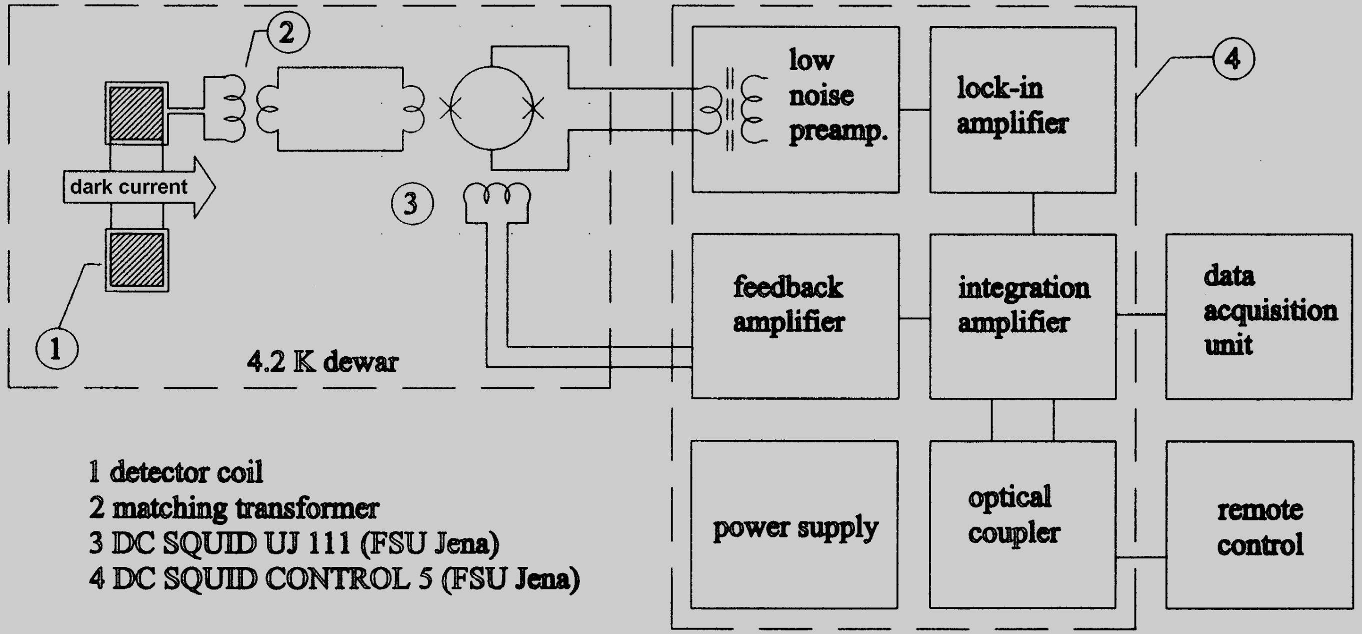
The CCC, first developed 1972 by Harvey, is composed of

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

For the dark current measurement:

$$I = I_1 - I_2 = i_{\mathsf{dark}} - 0$$

the single turn, superconducting pickup coil is arranged on a toroidal core.



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

i_{dark} ⟶ **H-field** ⟶ **toroid** ⟶ i_{toroid} ⟶ **H-field**

↓

feedback ⟵ i_{SQUID} ⟵ **SQUID**

↓ ↑

electronics ⟶ i_{comp} ⟶ **H-field**

Superconducting QUantum Interference Device SQUID

A **DC-SQUID** is used to detect the magnetic field of i_{toroid}. It consists out of a superconducting ring with two weak links ("DC Josephson effect"), in which a quantization of the magnetic flux is observed by an **interference phenomenon**:

$$\Phi_{mag} = n \cdot \Phi_0 \qquad n = 0, 1, 2, ... \qquad \text{with } \Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}\ \text{Vs}$$

The characteristic of a *Josephson* junction is a solution of the affiliated wave-functions of *Cooper*-pairs tunnelling the barrier:

$$I(t) = I_0 \cdot \sin(\frac{2e}{\hbar} V_0 t + \varphi_0)$$

The current in the superconducting loop with two junction is (no voltage applied, $V_0 = 0$):

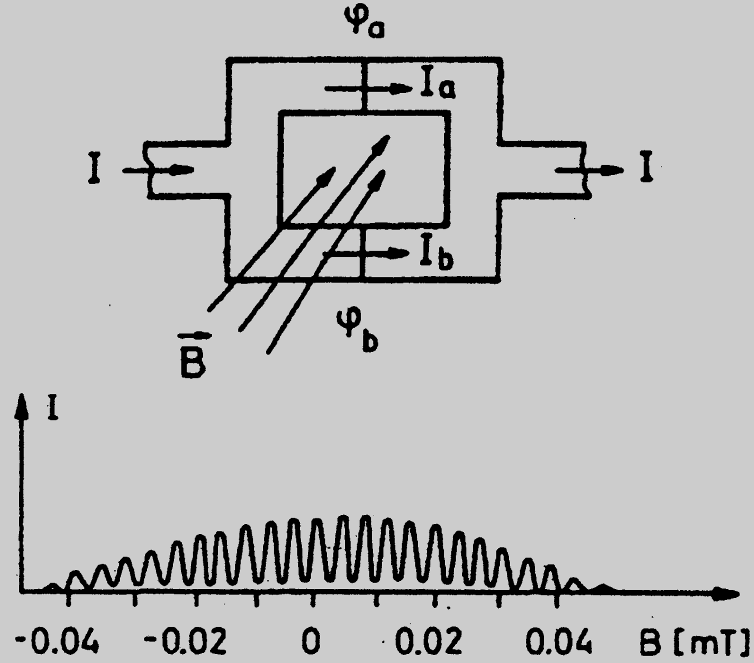
$$I = I_a + I_b = I_0 (\sin\varphi_a + \sin\varphi_b)$$

If a magnetic flux Φ_{mag} threads the area of the loop, the phases differ by:

$$\varphi_a - \varphi_b = \frac{2e}{\hbar} \oint \vec{A}\, \vec{ds} = \frac{2e}{\hbar} \Phi_{mag}$$

With $\varphi_0 = \varphi_a + \varphi_b/2$ the current I writes:

$$I = I_0 \cdot \sin\varphi_0 \cdot \cos(\frac{e}{\hbar}\Phi_{mag})$$



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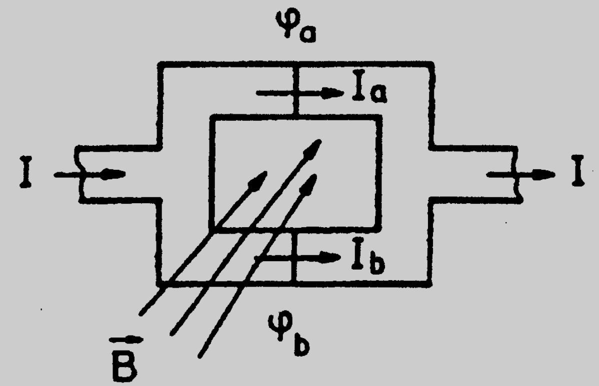
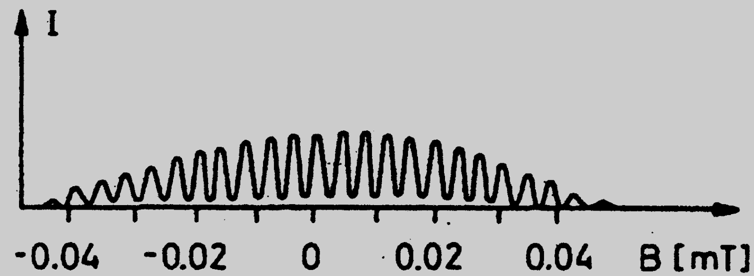
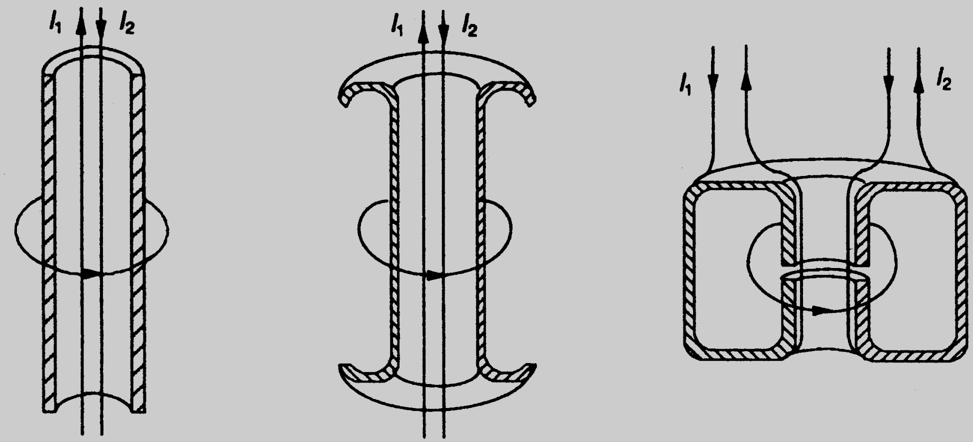
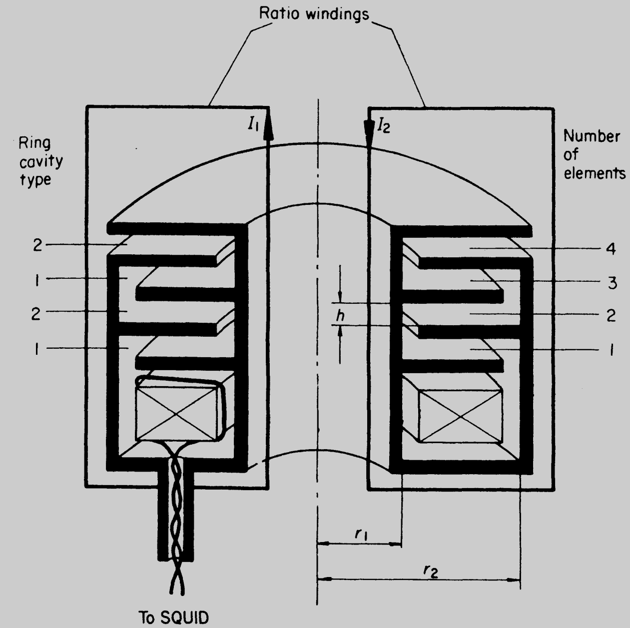




Superconducting Shielding

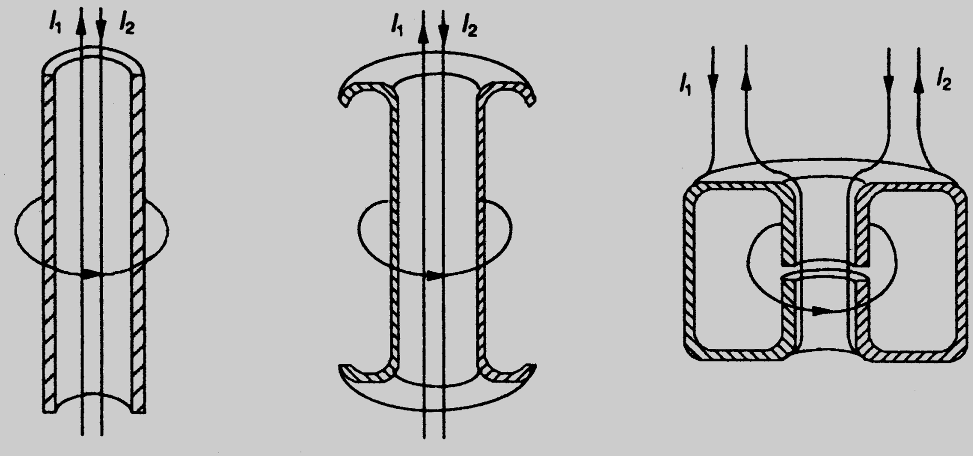


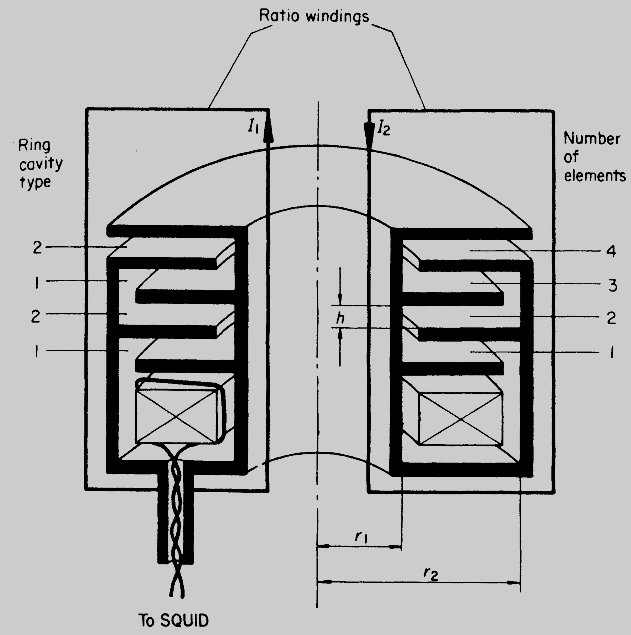


The resolution of the CCC is reduced if the toroid pickup coil operates in the presence of external magnetic fields. As this is in practice unavoidable, an **effective shielding** has to be applied [5], [6], [7].

- A circular, **meander-shaped shielding** geometry 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), which implies the vanishing of all normal components of the magnetic field at the superconductive surface.

Superconducting Shielding





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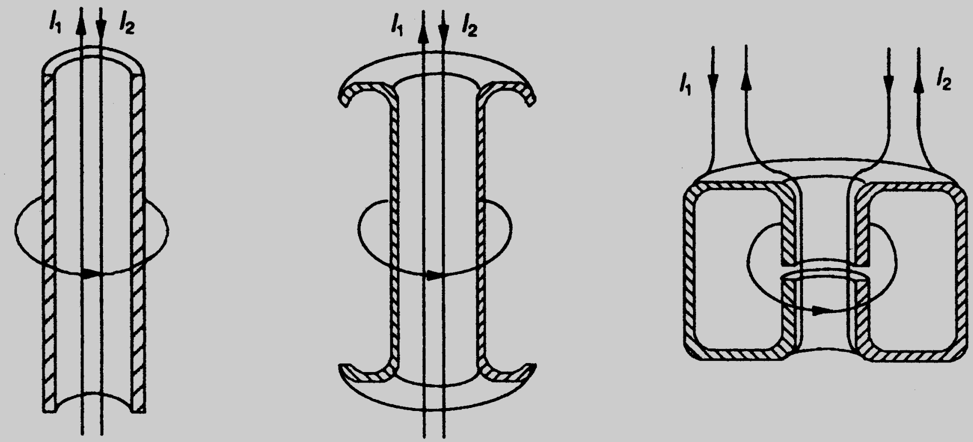

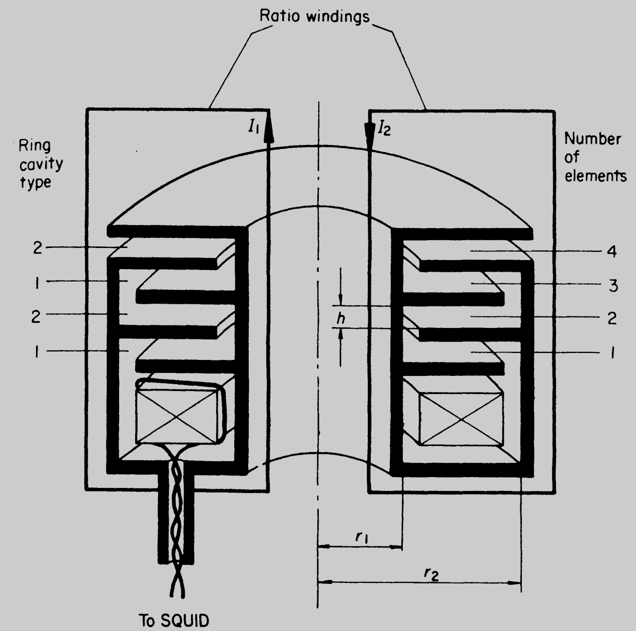

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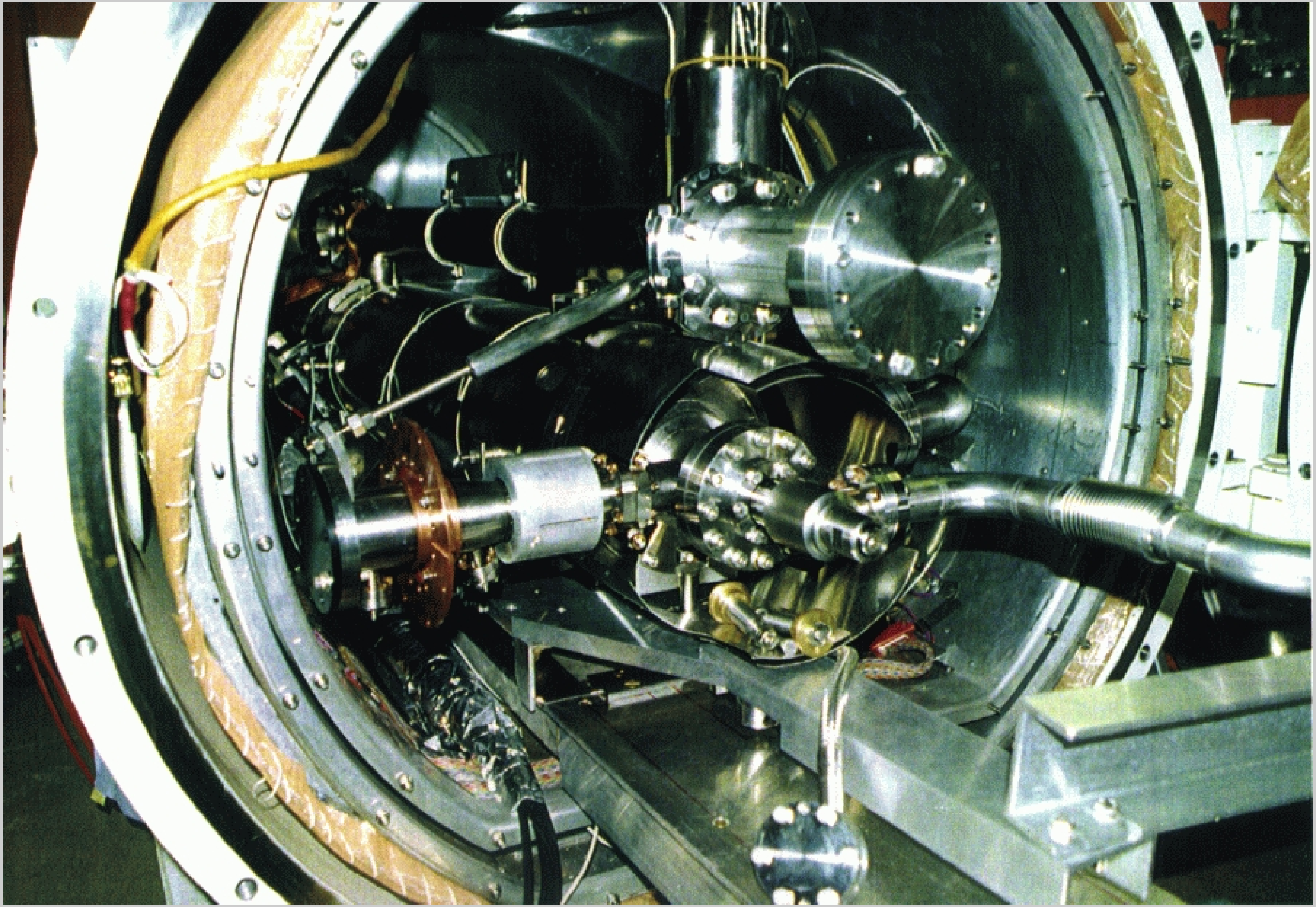
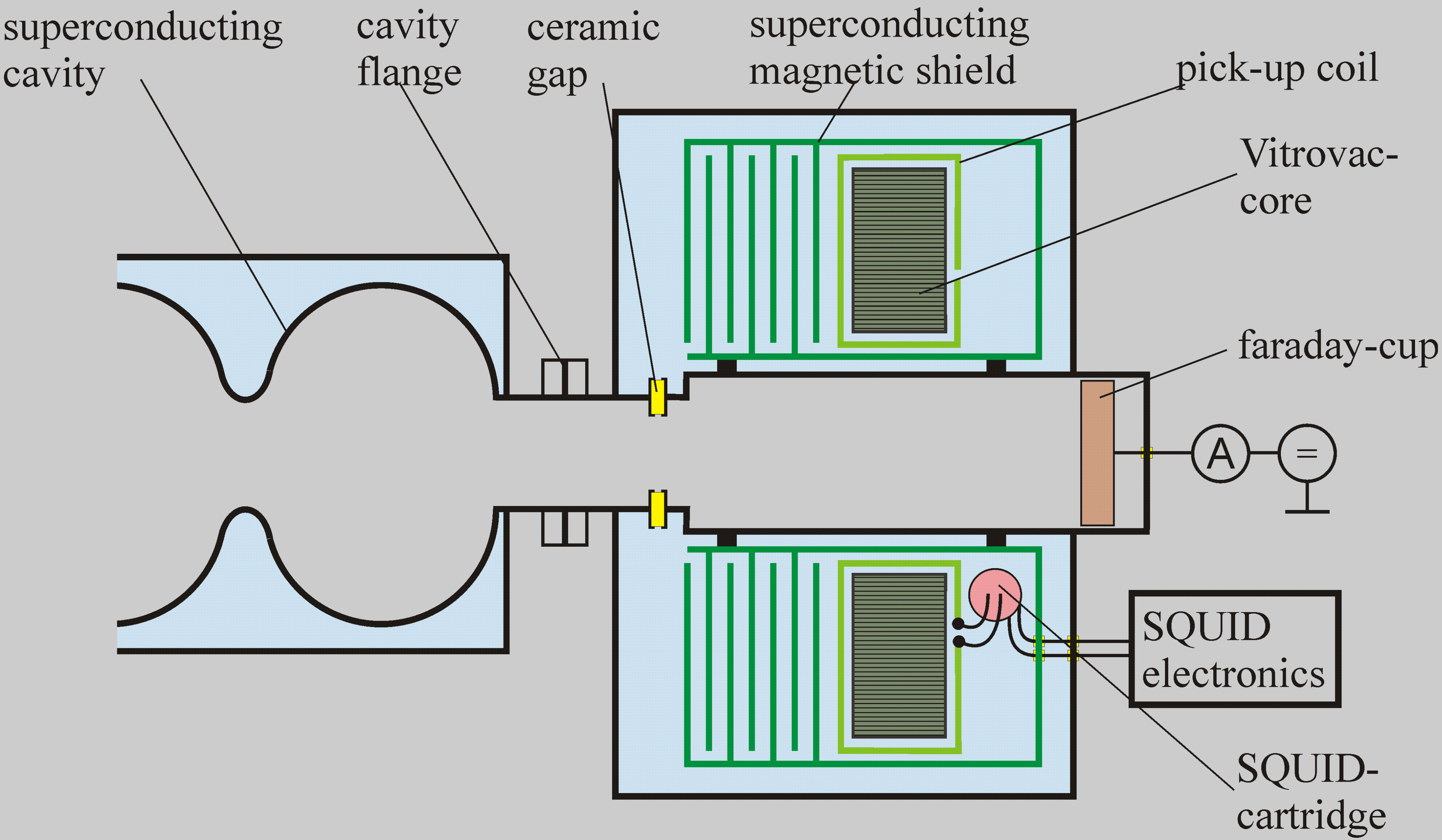
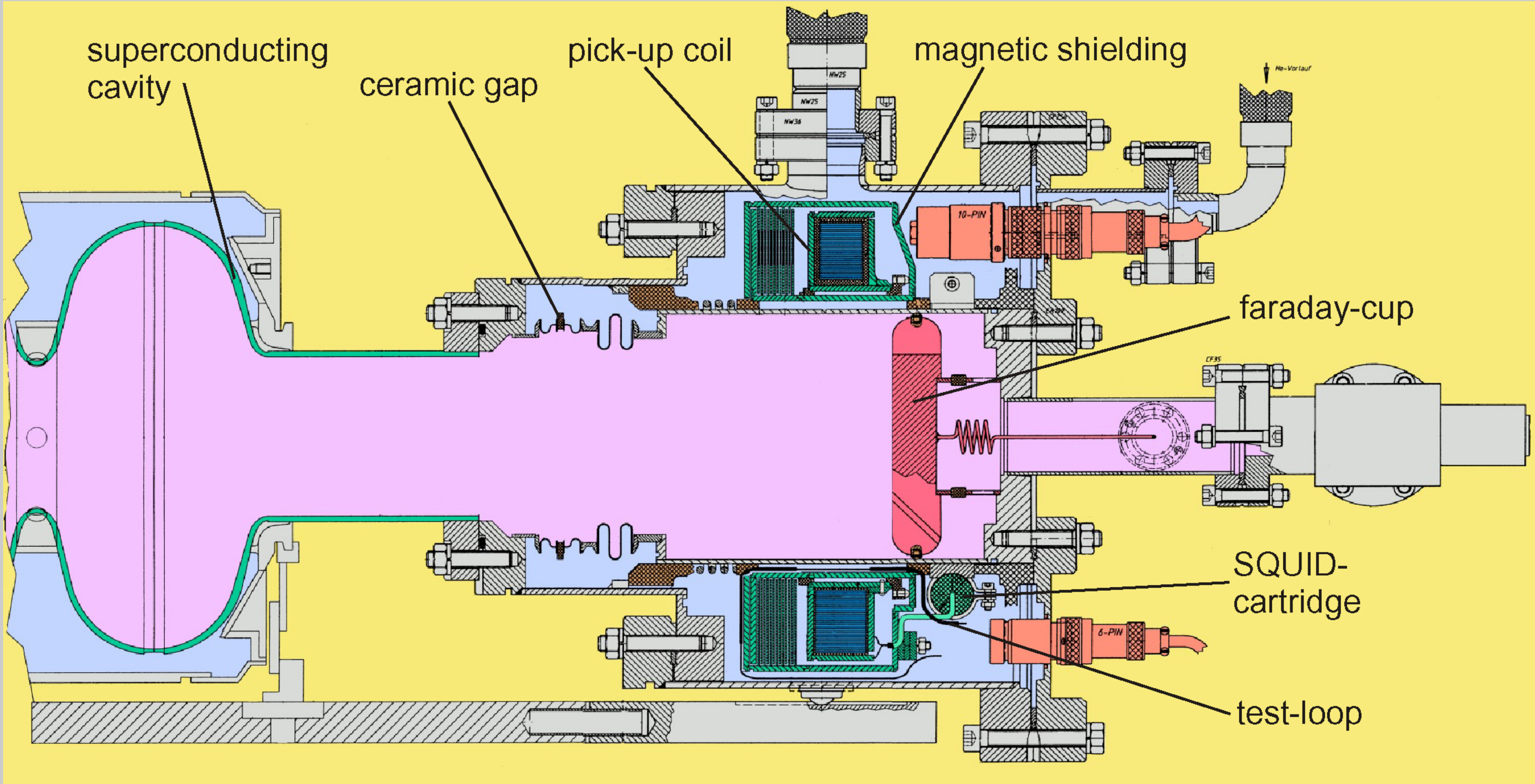


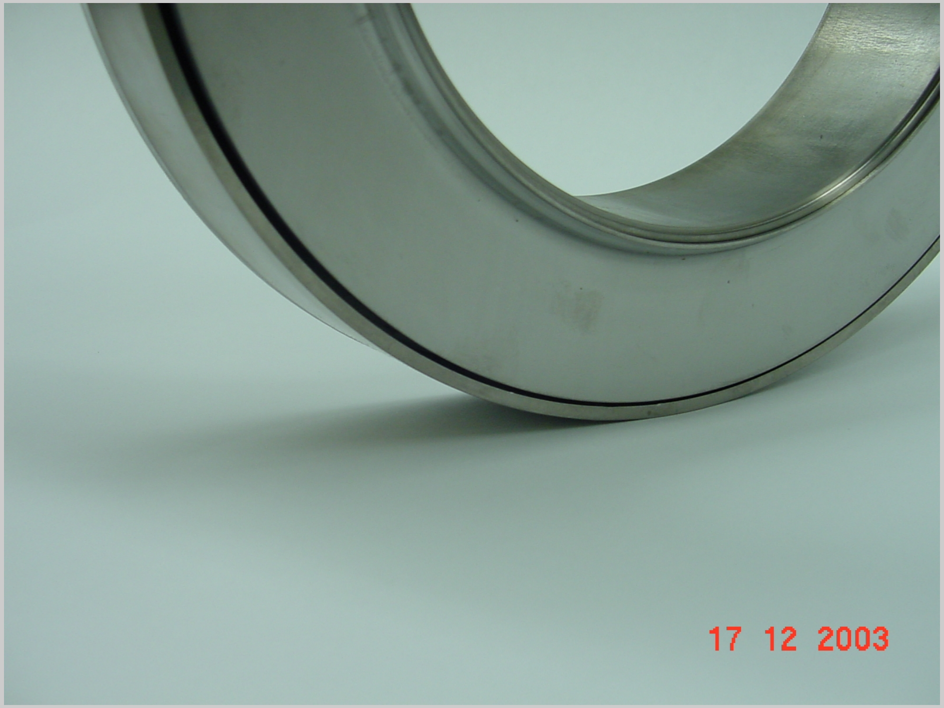


Schematic view of the CCC for *CHECHIA*

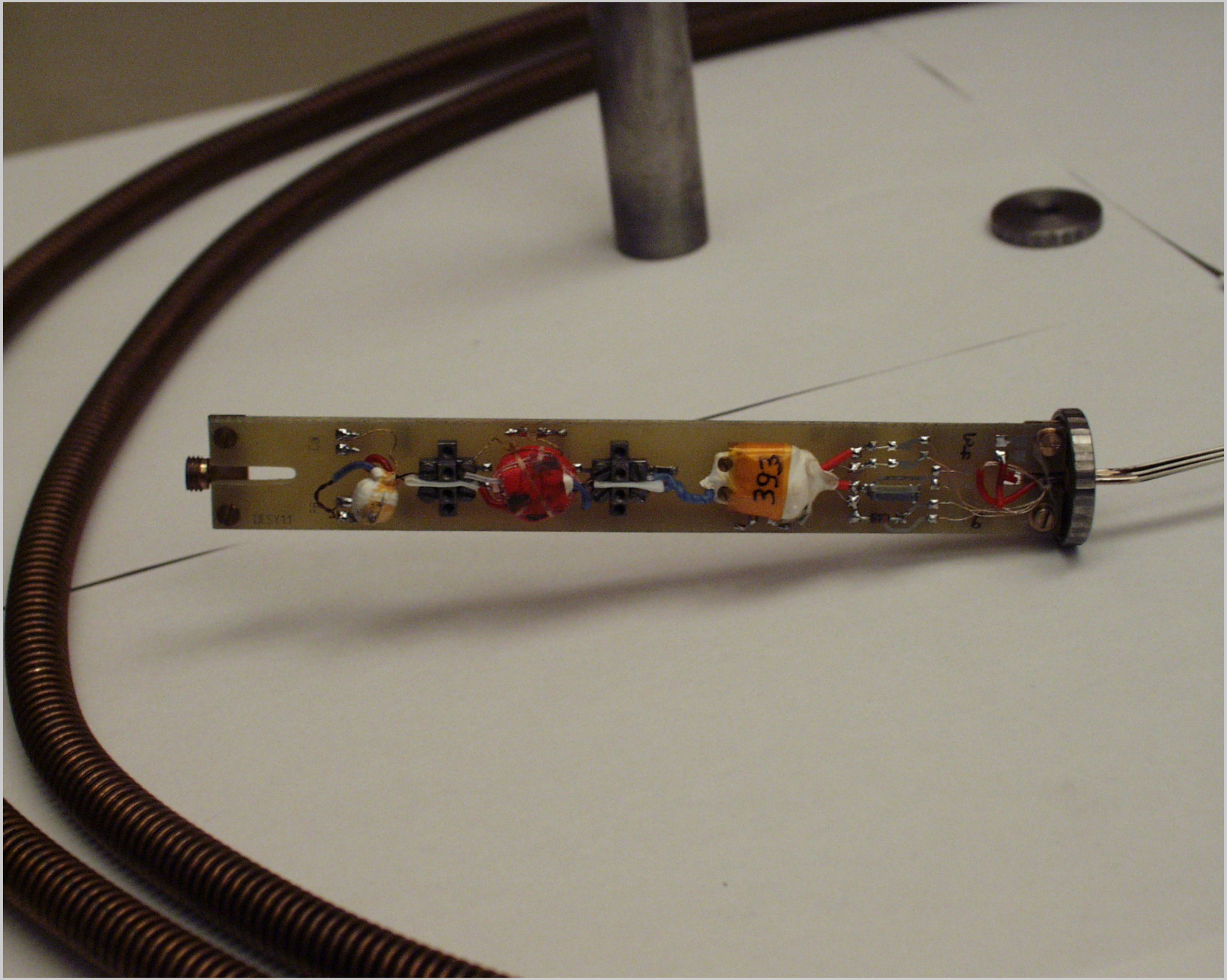


Construction details of the CCC dark current hardware

Toroid core made of *VITROVAC 6025-F* (*Vakuumschmelze GmbH*, Hanau), housed in a *VESPEL* insulator. The *VITROVAC* material is proven to provide high permeability and low noise levels even at liquid helium temperatures.

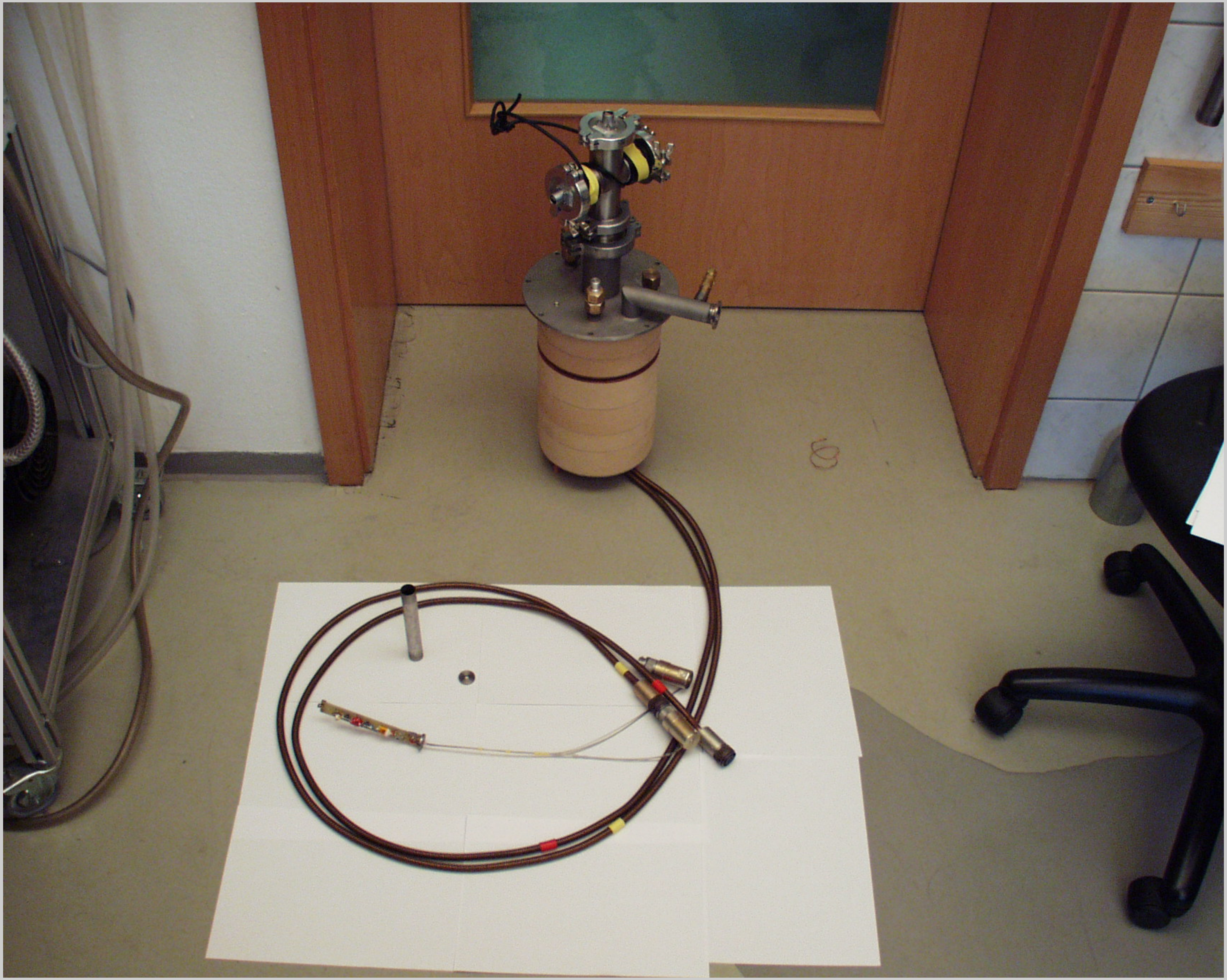


Completed toroid pickup with single turn niobium "coil".



Open SQUID cartridge and read-out electronics keeping the *UJ 111* DC-SQUID (FSU Jena)

SQUID electronics, custom made for DESY (FSU Jena)



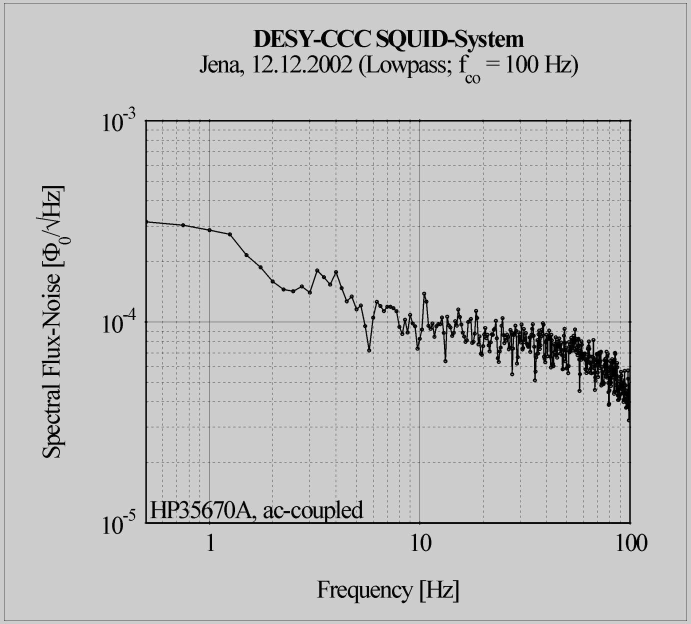
Test arrangement for a SQUID performance check (FSU Jena)

Measured performance of the SQUID system [8]:

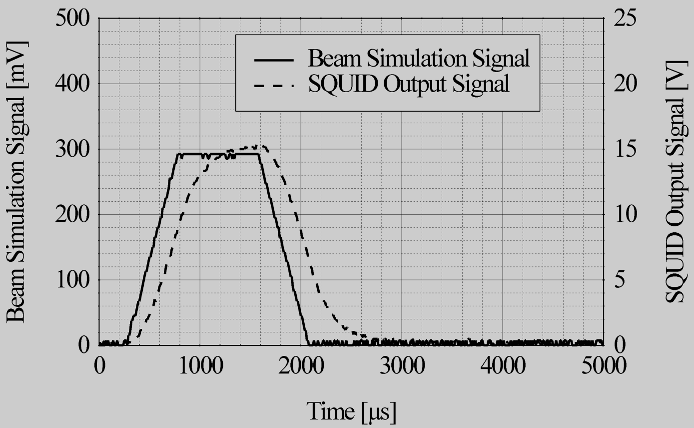
max. system bandwidth:	DC...70 kHz
system current sensitivity:	167 nA/Φ_0
flux noise (in the white noise region):	$8\times10^{-5}\ \Phi_0/\sqrt{\mathrm{Hz}}$
corresponding current noise:	13 pA $/\sqrt{\mathrm{Hz}}$

The current resolution of the final system will decrease by approximately one order of magnitude (!) due to the additional noise contribution of the *VITROVAC* core of the pickup coil.

A system bandwidth of 500...1000 Hz is sufficient to acquire the AC-contents of the dark current due to the 950 μs rf-pulse duration. This will give a 3...4 nA dark current resolution of the final CCC system.



Spectral noise densisty



SQUID system response to a 1 ms test pulse signal

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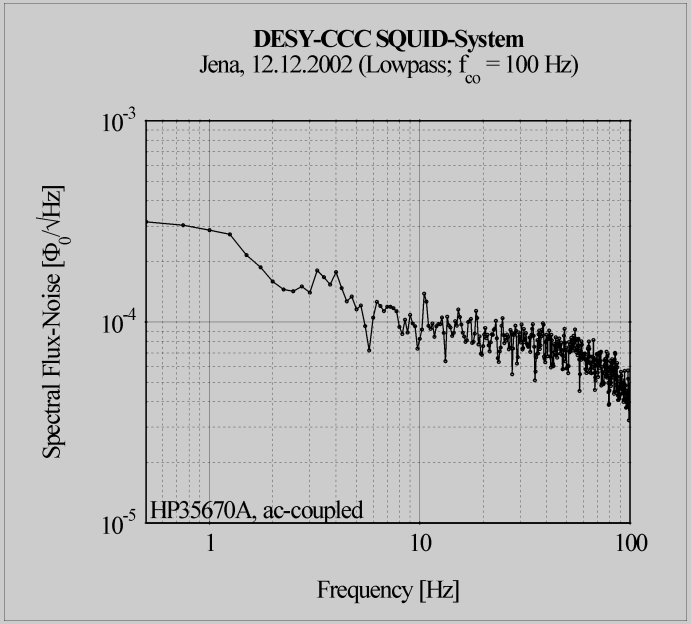

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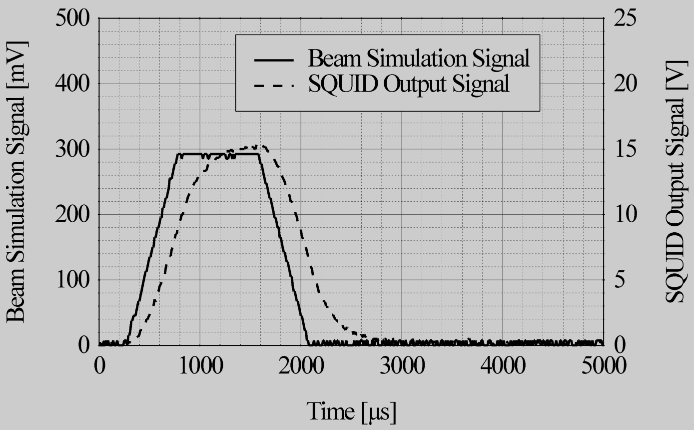

SQUID system response to a 1 ms test pulse signal

OUTLOOK

Superconducting Shielding

- Analytical and numerical analysis promise a damping of external magnetic fields of 94 dB (DC and low frequencies) and $>$ 200 dB (!) for high frequencies ($>$ 1 GHz) [8].
- Already at the beginning of the fabrication process of the shielding structure a couple of problems showed up. Tolerances in the order of 0.1 mm will give further trouble in manufacturing of niobium and electron beam welding for this sophisticated $14\times$ meander-shaped shielding...
- Another system test, including pickup coil and shielding, is waiting for the shielding to be completed.

Faraday Cup

A **faraday cup** with HV-screen has been included in the CCC construction to be able to compare the CCC dark current measurement in the *CHECHIA* test stand. It will be completed by some detection electronics to measure the cup-to-ground current flow.

References

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[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.*; CRYYOGENICS, July 1976, pp.423-429

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

[7] *K. Grohmann and D. Hechtfischer*; CRYYOGENICS, October 1977, pp.579-581

[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, to be published