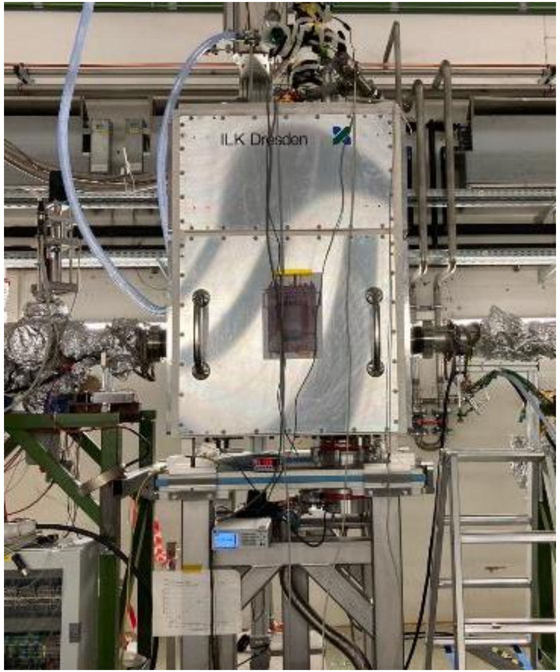
The Cryogenic Current Comparator at CRYRING@ESR

David Haider
Beam Diagnostics Group, GSI

On behalf of the CCC collaboration and the GSI-CCC team



CCC@CRYRING

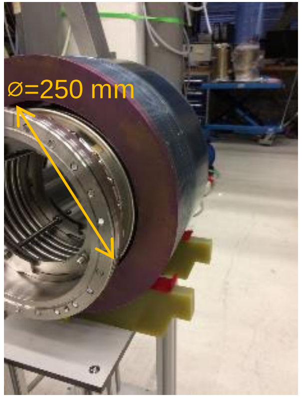
CCC team at GSI:

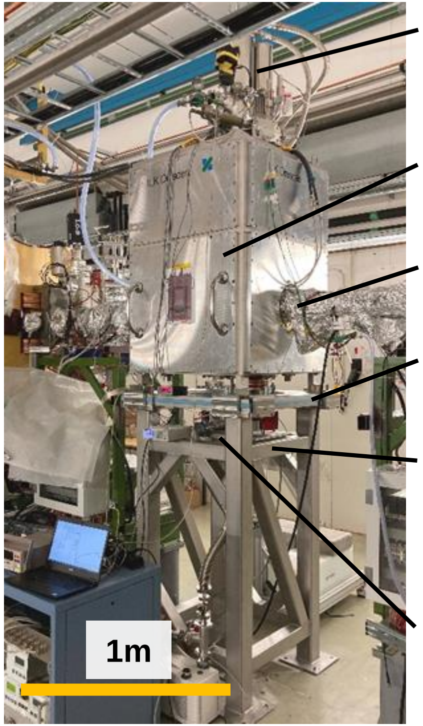
T. Sieber (project leader)

L. Crescimbeni (PhD student)

Cryogenic Current Comparator at CRYRING@ESR

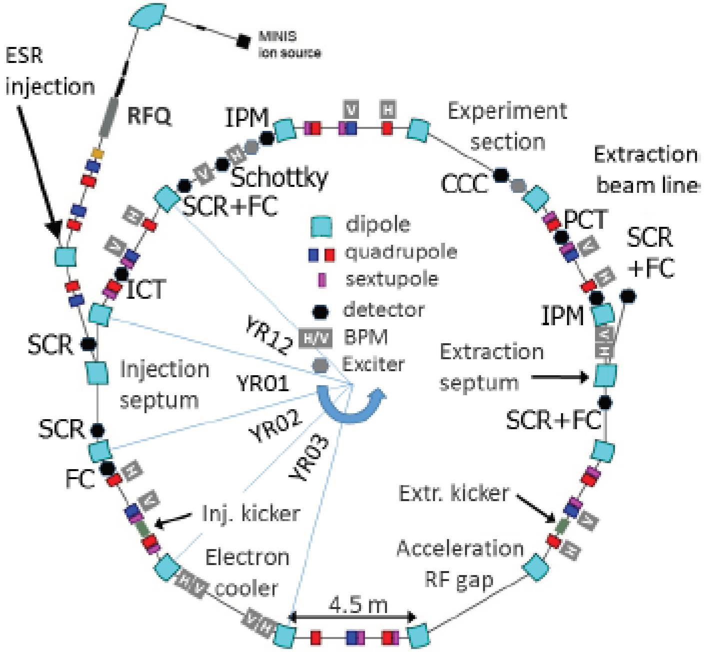
- 2020/9: Installation at CRYRING
- Operation between 2020/11 and 2021/05
  - Tested measurement range
    5 nA - 20 uA (DC – 100 kHz)





CCC@CRYRING

Motivation – Beam instrumentation at CRYRING@ESR



A. Reiter: Beam instrumentation at CRYRING

- Gap in <u>absolute</u> non-destructive intensity diagnostics below 1 μA

<u>DC beam</u>

- absolute: Parametric Current Transformer (PCT) > 5 μA
- relative: Ionization Profile Monitor (IPM count rate)

<u>AC beam</u>

- absolute: Integrating Current Transformer (ICT)
- relative: BPM & integrator, IPM count rate, CryRadio

Motivation

Advantages

- Non-interceptive
- Absolute calibration
- Independent of
  - Energy
  - Ion species
  - Beam structure (AC/DC beams)

GOAL

1 µA ⇨ 1 nA

expand operating limit

- Slow extraction (e.g. CBM)
- Stored coasting beam (e.g. CRYRING)

Beam Current Transformer

Limitations

- Thermal noise of load resistor $(U_{eff} = \sqrt{4\, k_B T\, R\, \Delta f})$
- Barkhausen noise of magnetic core material
- Magnetostriction
- External magnetic fields

Motivation

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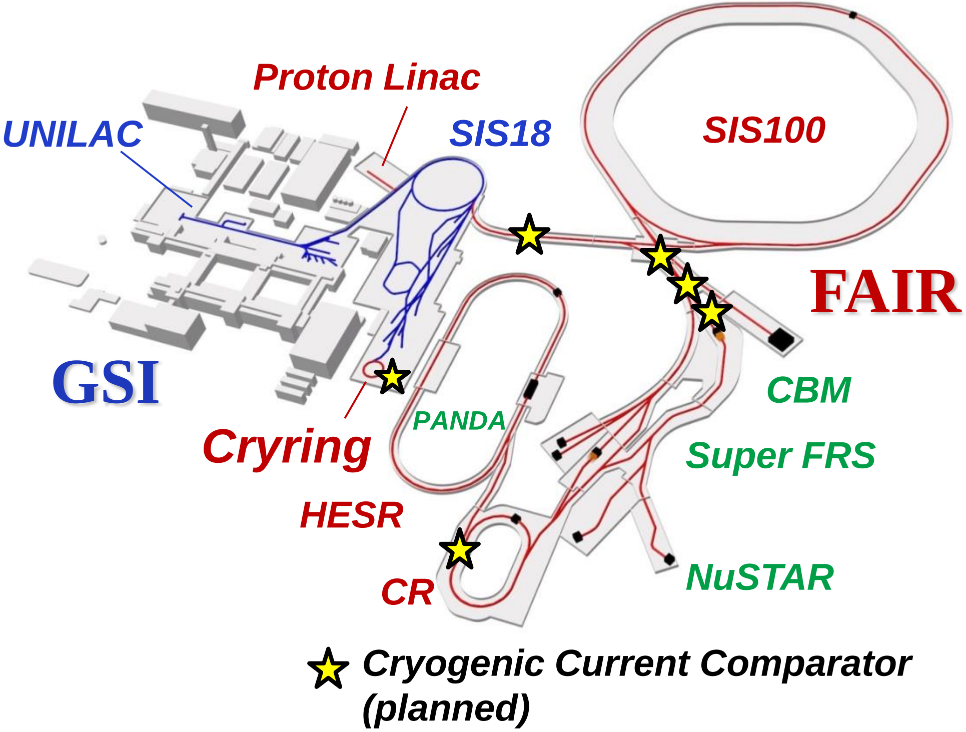
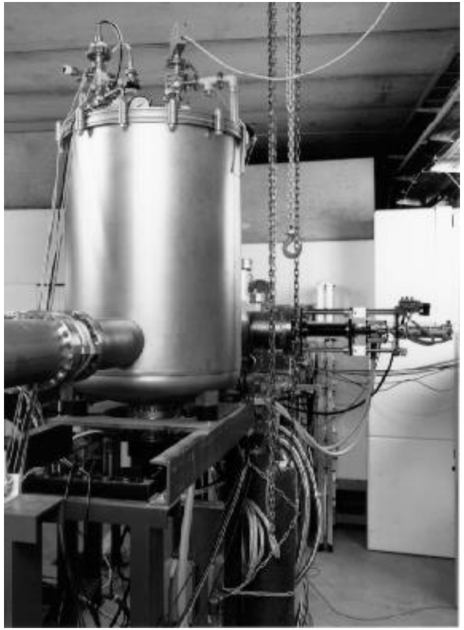


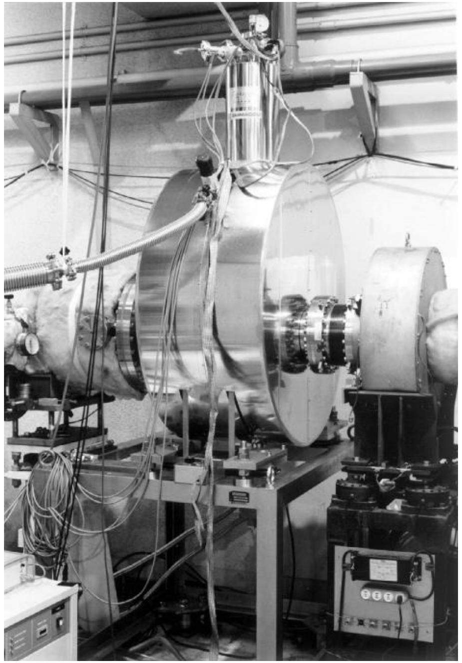
History – CCC detectors

I.K. Harvey:
CCC principle
(1972)

Antiproton
Accumulator,
Fermilab
(1985)



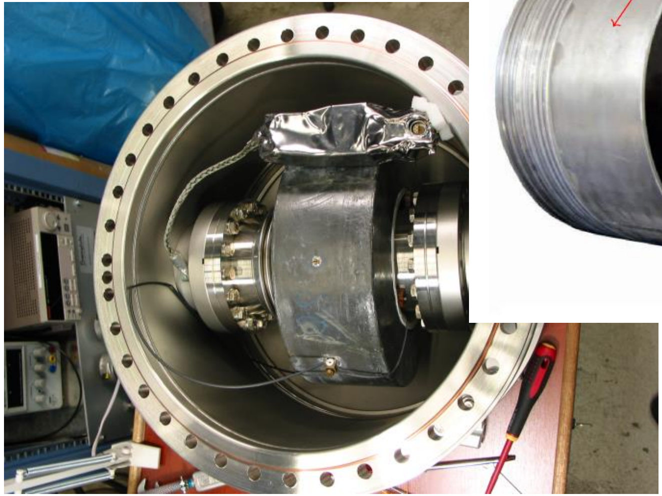
GSI (1996)



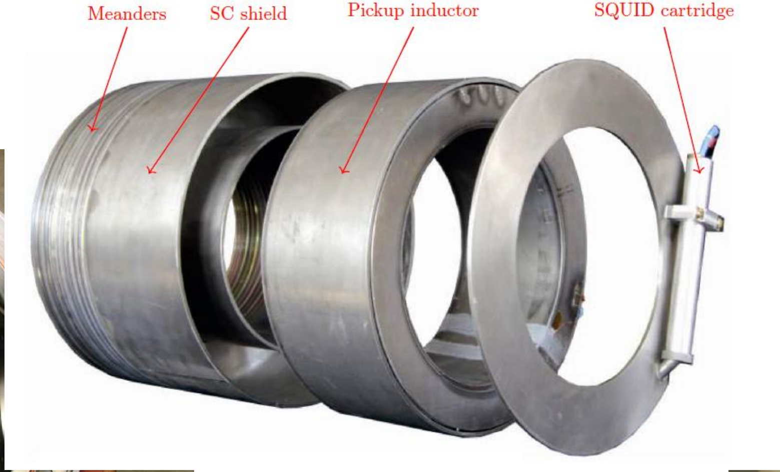
TARN II, Japan (1998)

AD CERN (2015)

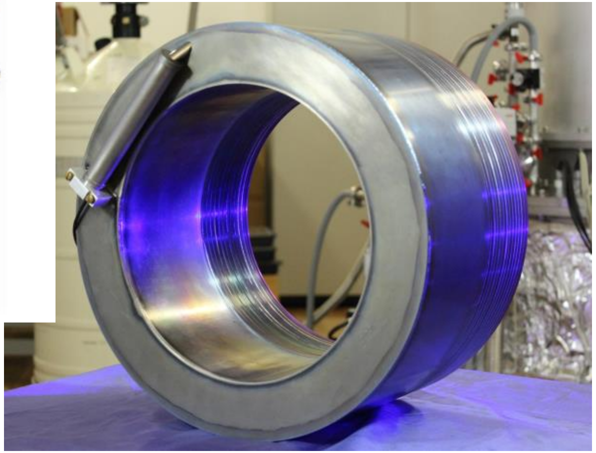
History – CCC detectors



GSI (1996)
⌀150 mm



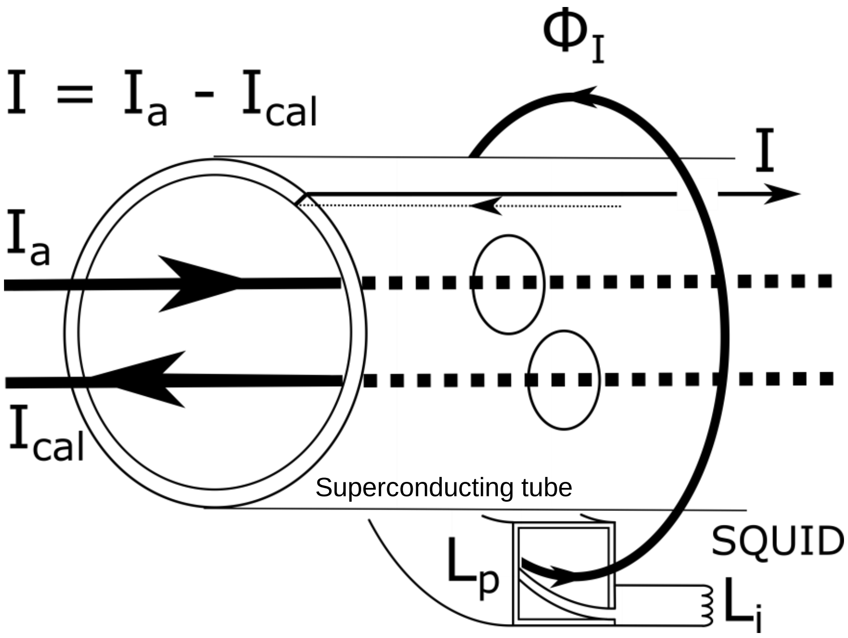
CERN (2015)
⌀185 mm



CRYRING/FAIR (2020)
⌀250 mm

Inner diameters

Metrological CCC (1972)

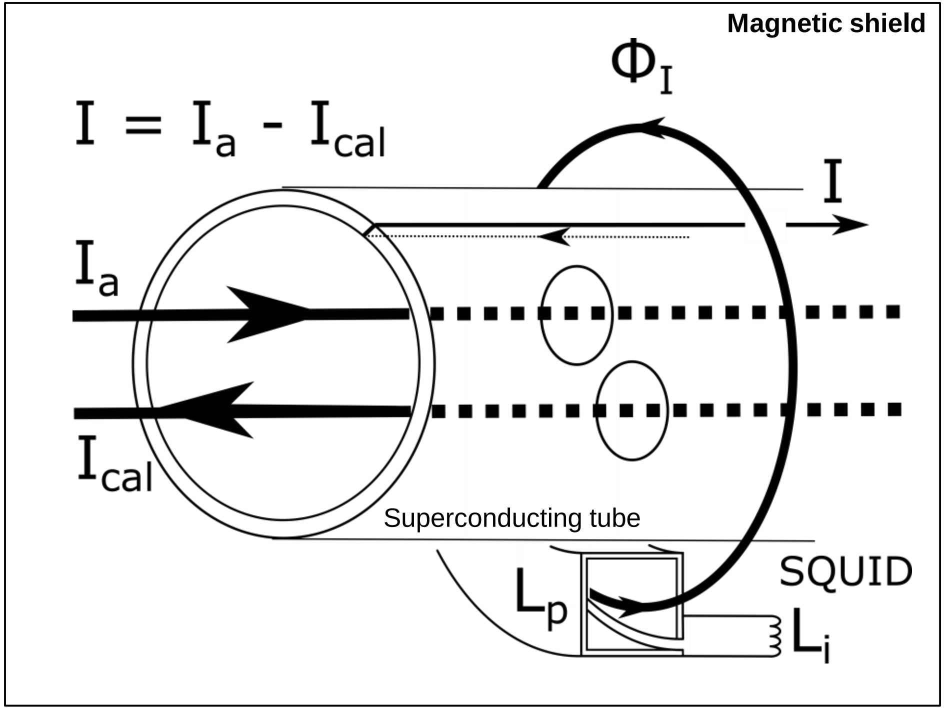


Cryogenic Current Comparator - Schematic

I.K. Harvey:
A precise low temperature dc ratio transformer, 1972
doi: 10.1063/1.1685508

DC-SQUID magnetometer
(Superconducting Quantum Interference Device)

Metrological CCC (1972)



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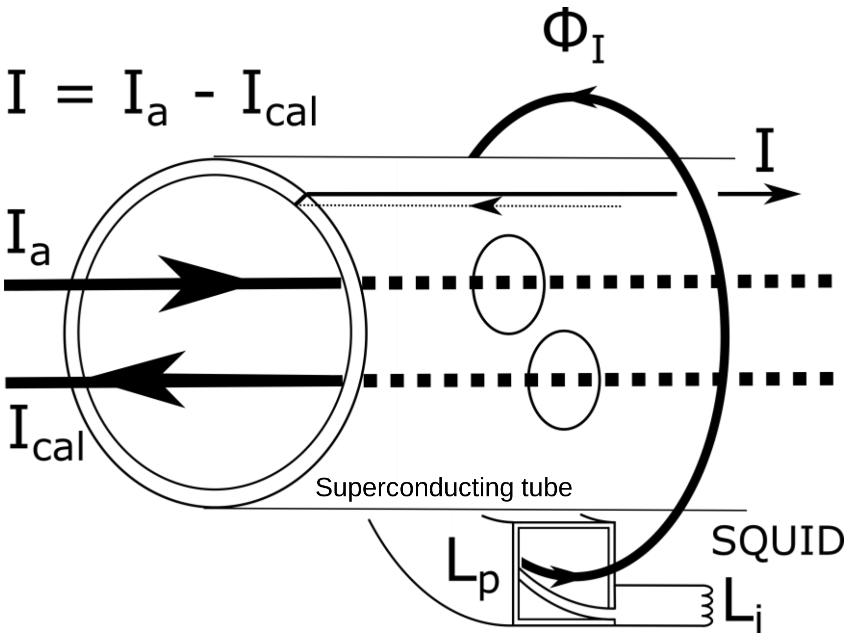
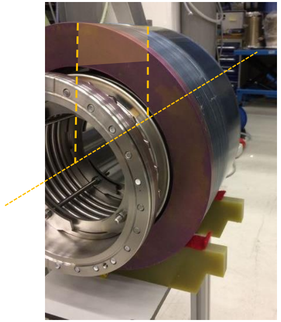
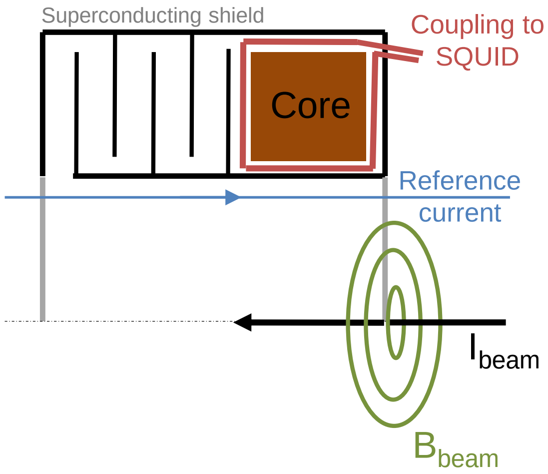
Motivation & operating principle



Cryogenic Current Comparator - Schematic



GSI-Nb-CCC-XD



K. Grohmann:
Field attenuation as the underlying principle of cryo current comparators, 1976

Challenge - Perturbations

MAGNETIC FIELDS

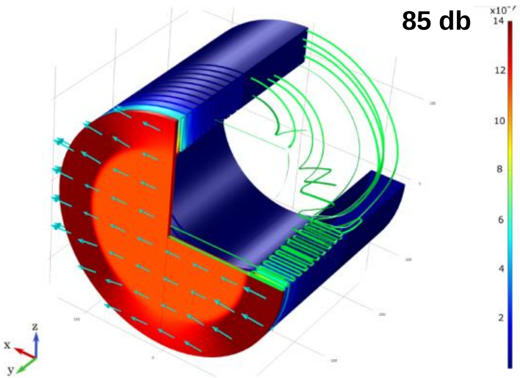
Static (Earth): **~50 μT**

Dynamic (Ramped dipole): **~10 μT**

much bigger than

Field of 100 nA ion beam: **~150 fT**
(10 cm distance)

field attenuation
85 db

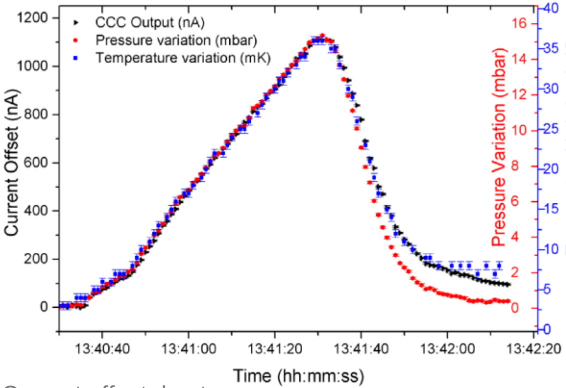


Simulation of field attenuation with Comsol Multiphysics® (F. Kurian)

TEMPERATURE/PRESSURE

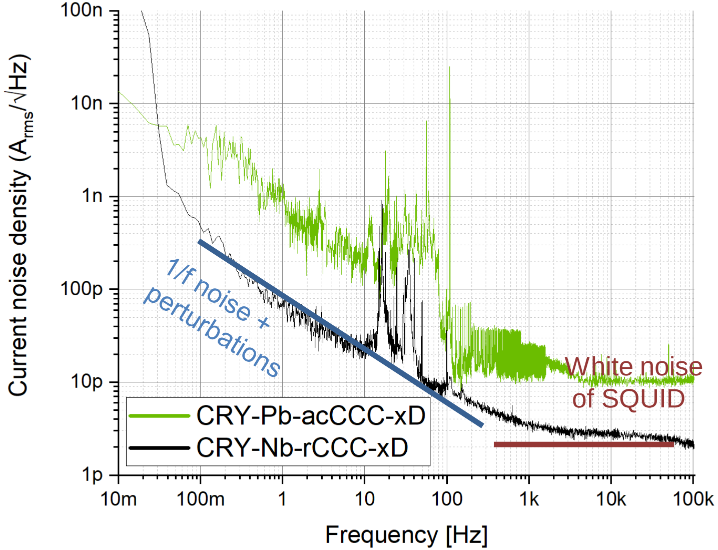
Drift of **73.7 nA/mbar**

33.5 nA/mK



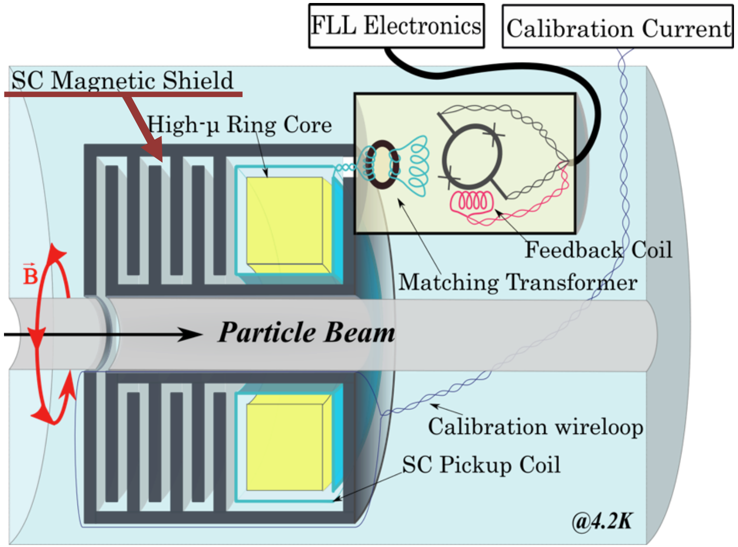
Current offset due to pressure and temperature variation.

ACOUSTIC/VIBRATIONS

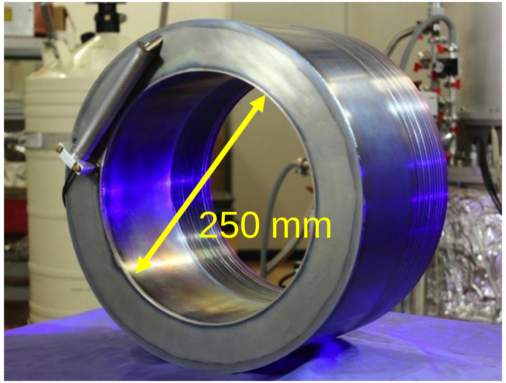


Current noise density of background measurement in the lab.

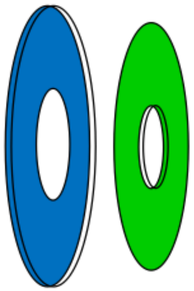
Operating principle – Superconducting shield

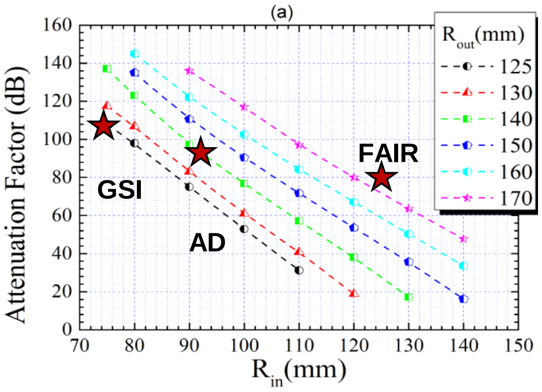


Drawing courtesy of F. Kurian (GSI)



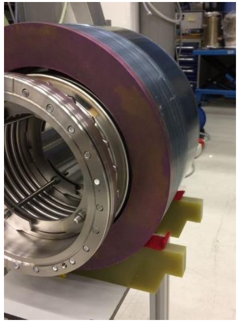
Niobium shielding for FAIR

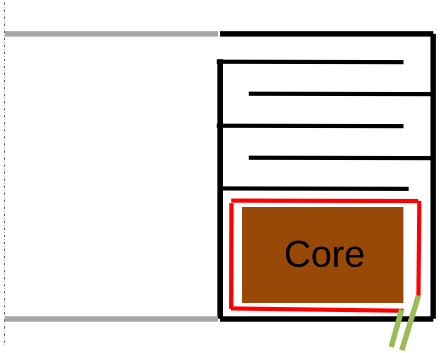




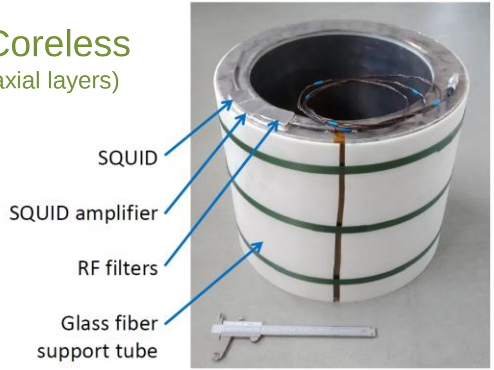
Development of CCC detector
Alternative design

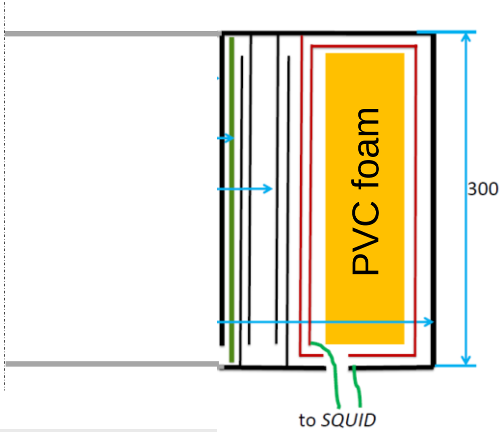
Classic
(radial layers)

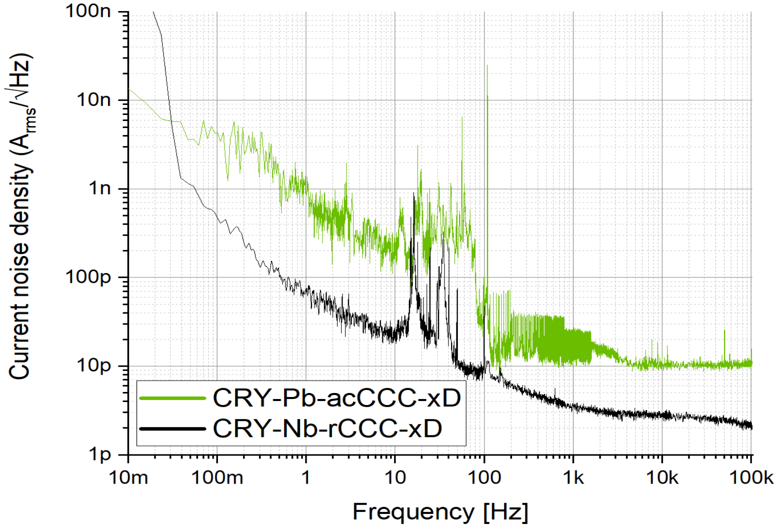




Coreless
(axial layers)

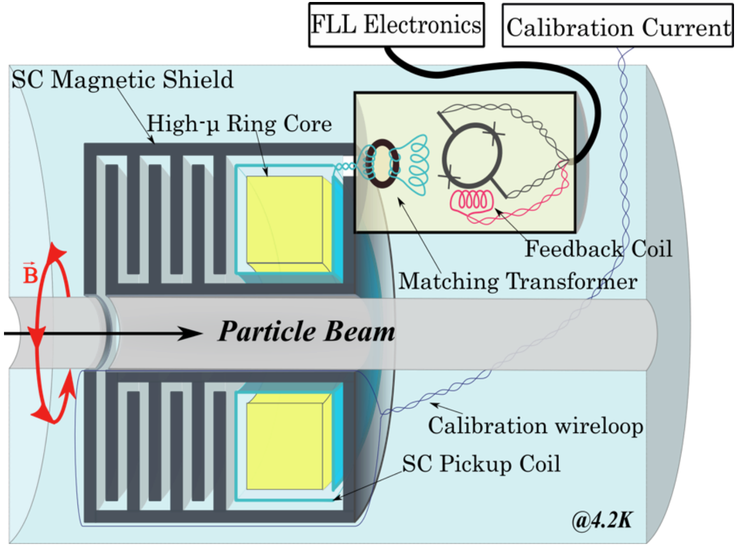




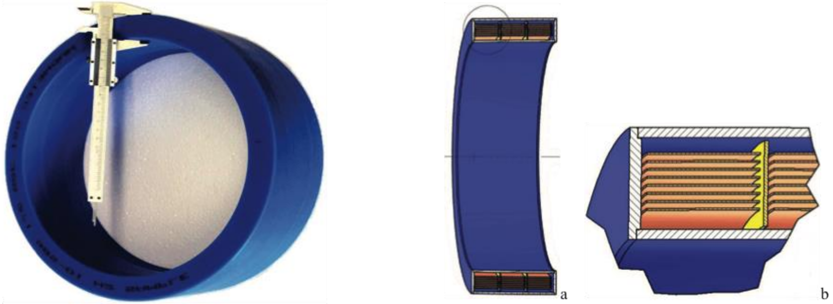


+ much higher shielding factor (>150 dB)
+ easy and cheap to build and prototype
+ eliminates (noisy) core
- still slighly higher noise figures

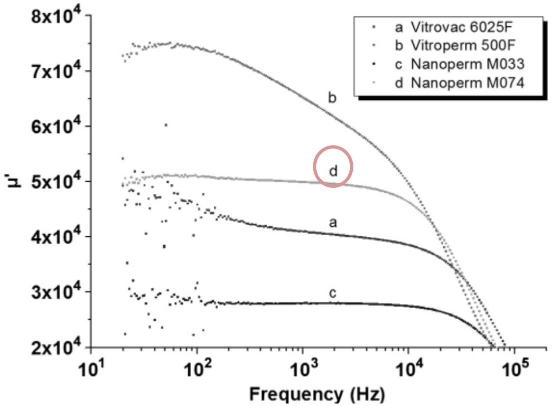
Operating principle – flux concentrator



Drawing courtesy of F. Kurian (GSI)



V. Tympel, Proc. IBIC16, Barcelona, Spain



R. Geithner et al., IEEE Trans. Appl. Supercond., vol. 21, no. 3, 2011

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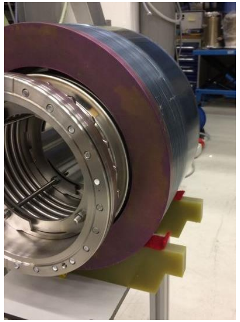

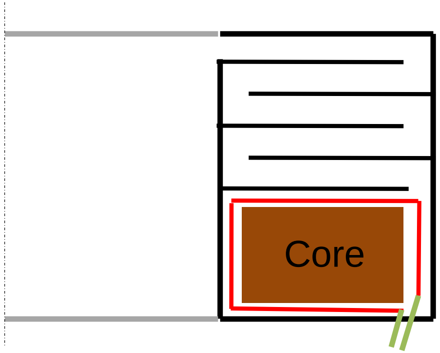

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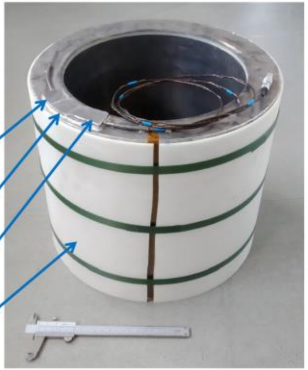
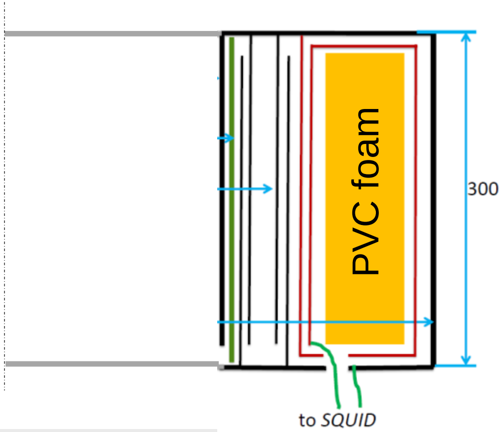
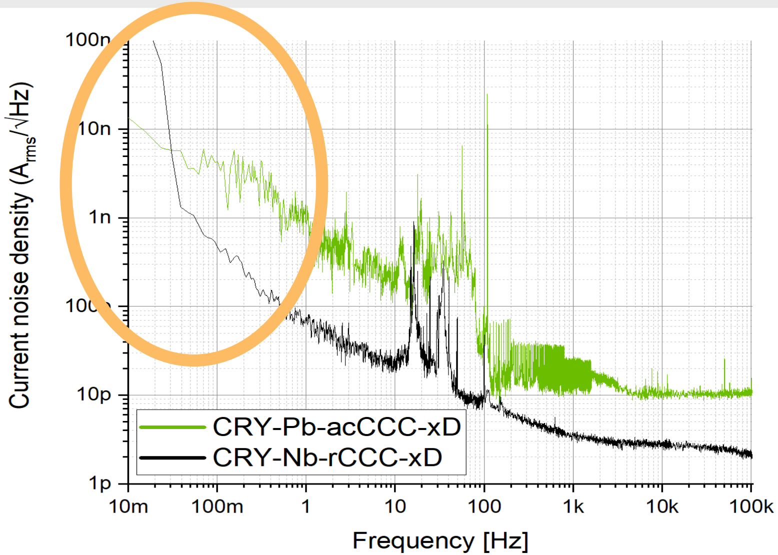
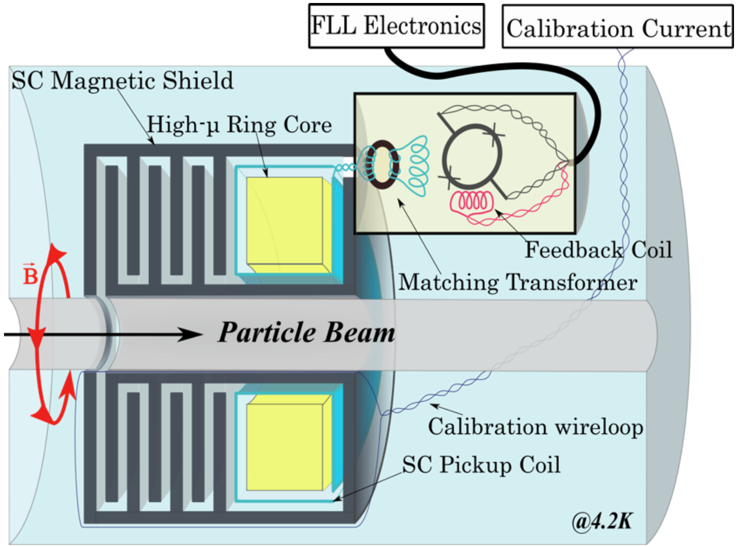




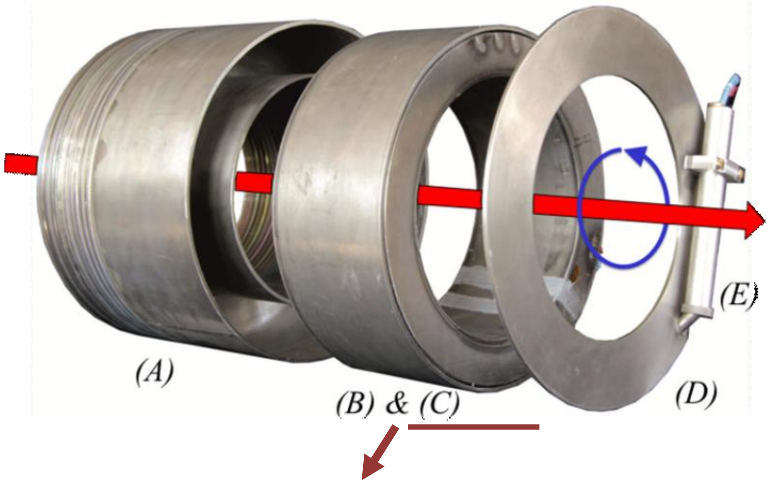


+ much higher shielding factor (>150 dB)
+ easy and cheap to build and prototype
+ eliminates (noisy) core
- still slighly higher noise figures

Operating principle – Pick-up

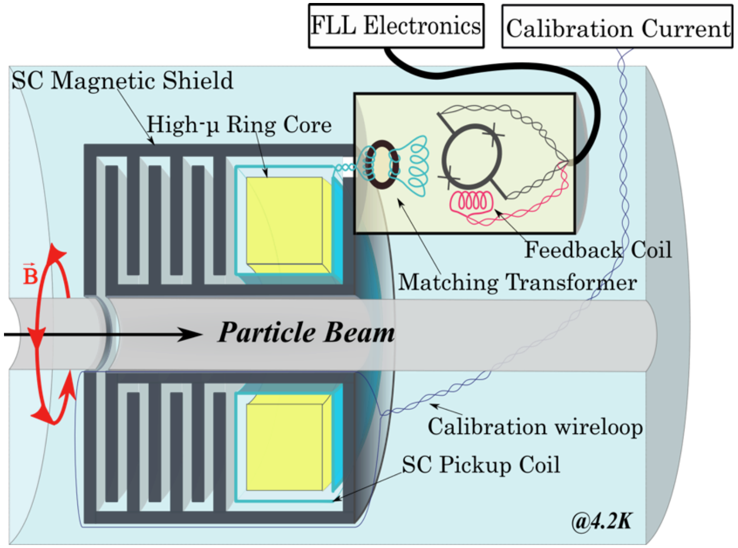


Drawing courtesy of F. Kurian (GSI)



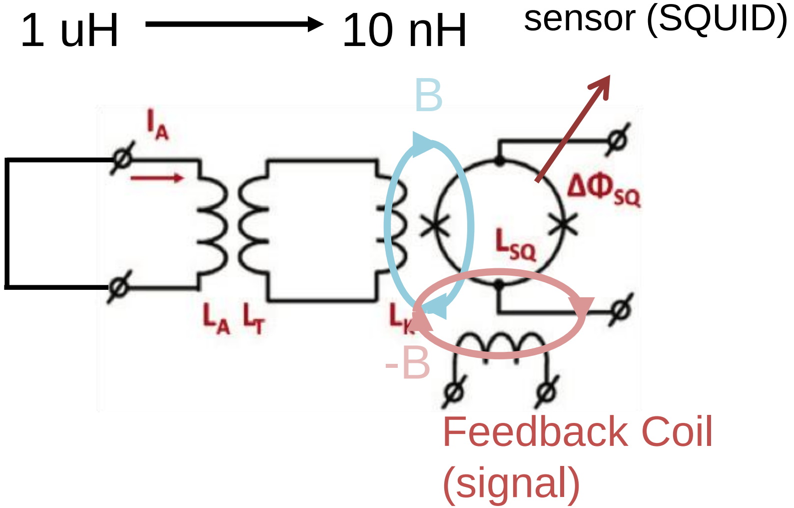
(B) High-μ ring core (inside)
(C) Pick-up coil

Operating principle – Flux transformer



Drawing courtesy of F. Kurian (GSI)

Matching transformer

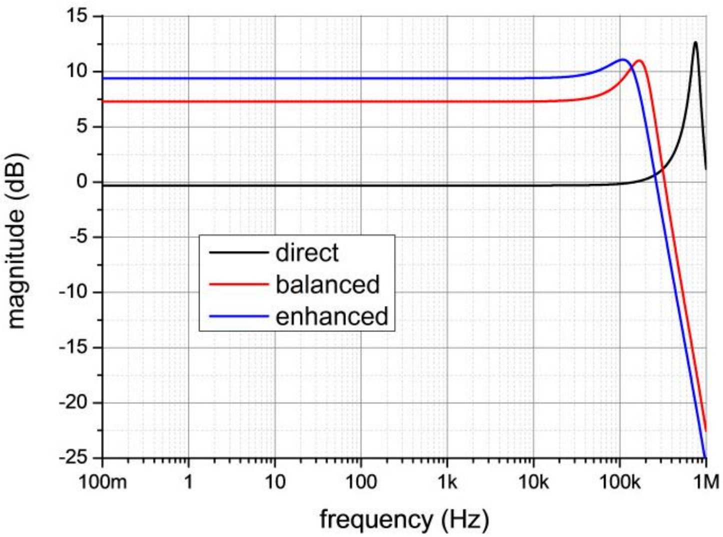


L ... inductance

ΔΦ ... magnetic flux variation

Operating principle – Flux transformer

Transfer function

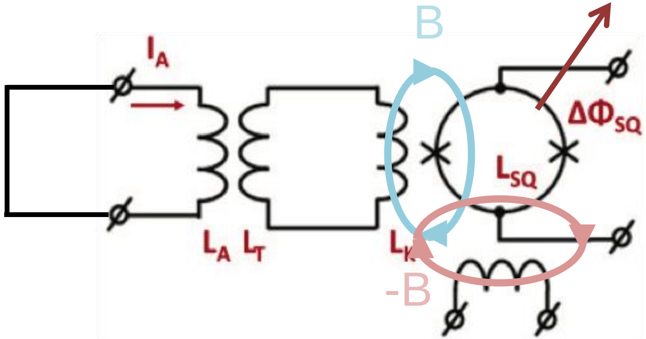


Maximum slew rate: ~ 0.16 A/s (@ 200 kHz bandwidth)

Matching transformer

1 uH → 10 nH

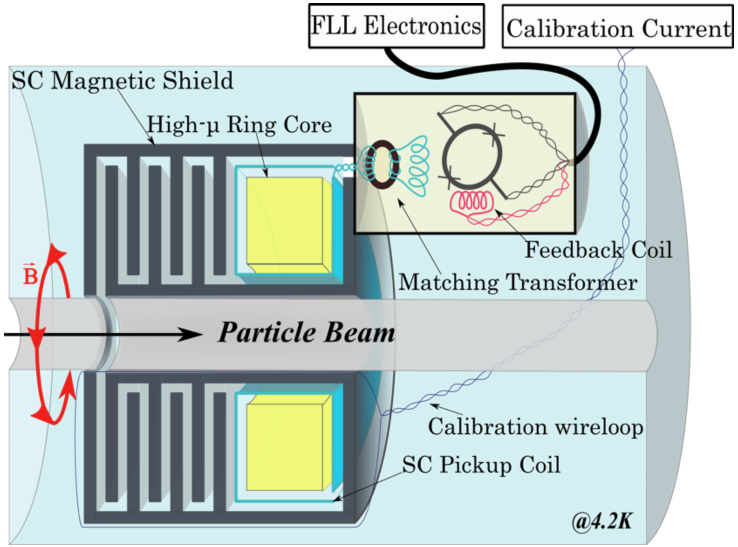
Magnetic field sensor (SQUID)



Feedback Coil (signal)

I_A … beam current
L ... inductances
$\Delta\Phi_{SQ}$ ... magnetic flux variation

Operating principle - SQUID



Drawing courtesy of F. Kurian (GSI)

(Superconducting QUantum Interference Device)

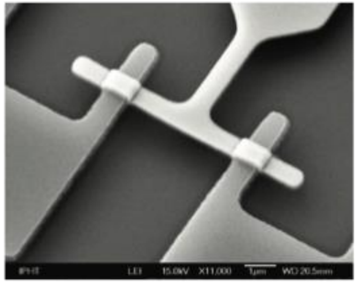
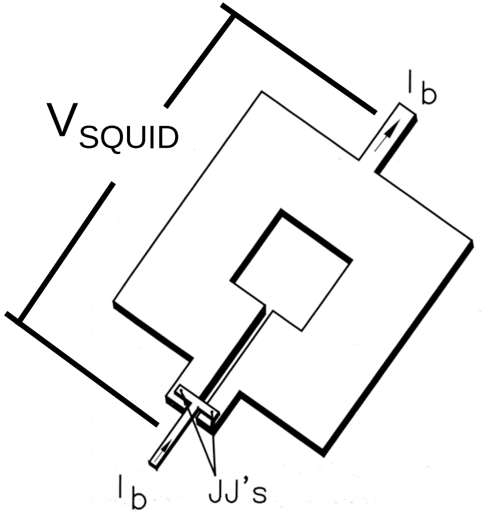


Image of a Josephson Junction (JJ)

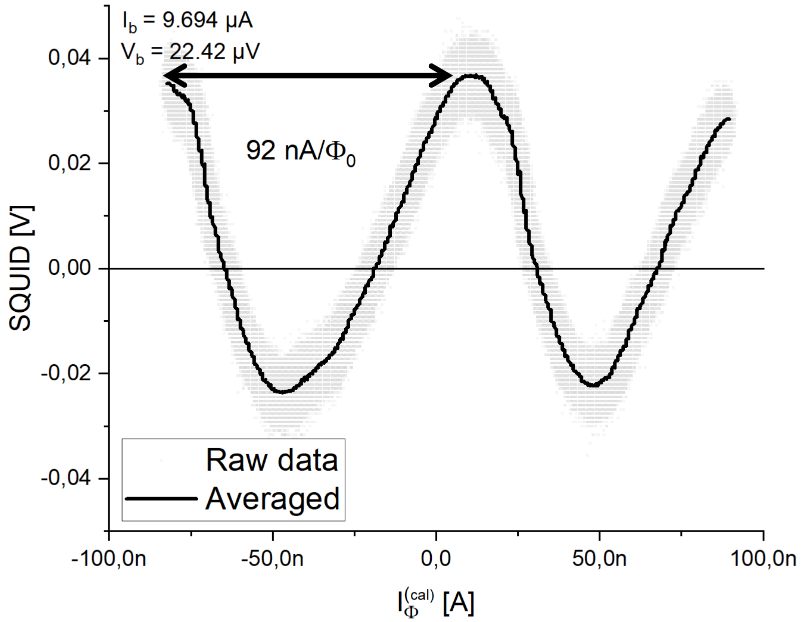


Simple DC-SQUID

Courtesy of TU Wien

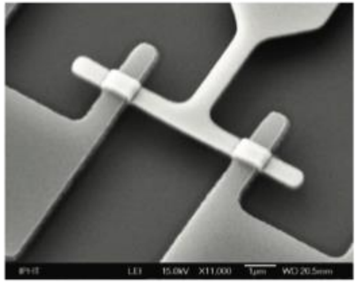
Josephson Junctions
(sc-nc-sc interface)

Operating principle - SQUID



→ no linear relationship

(Superconducting QUantum Interference Device)



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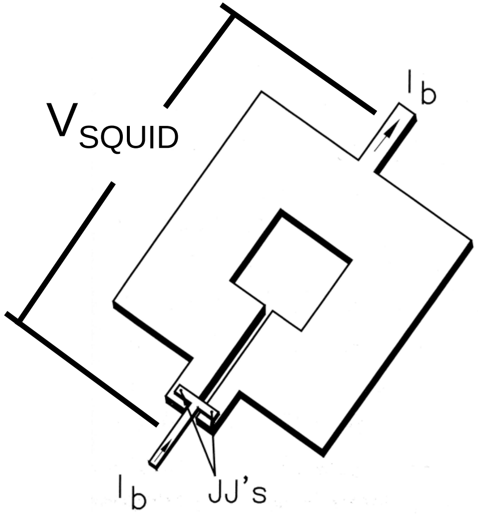
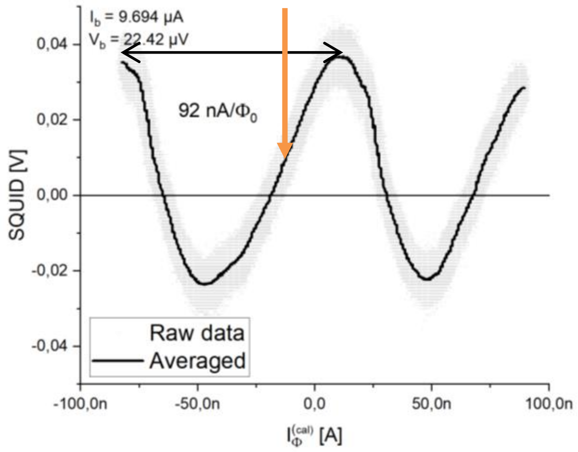


Simple DC-SQUID

Courtesy of TU Wien

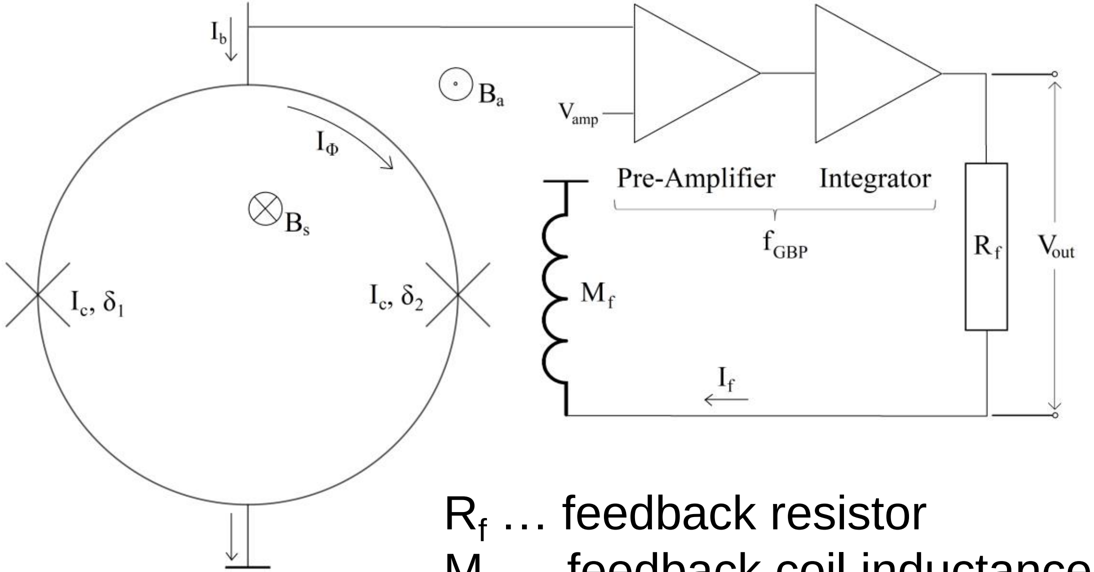
Operating principle - SQUID

select setpoint



→ no linear relationship

Flux Locked Loop (FLL) → linearization



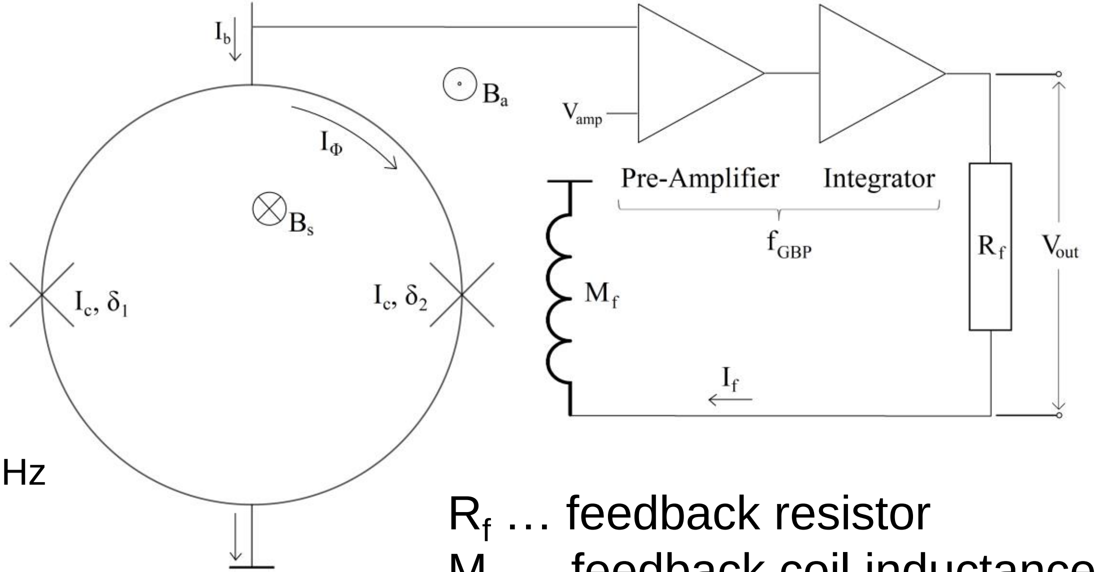
R_f … feedback resistor
M_f … feedback coil inductance

Operating principle - SQUID

Flux Locked Loop (FLL) → linearization

Rf [kΩ]	Sensitivity [nA / 1 V]	Range ±10V [μA]
0.7	3664.0	± 36
1	2564.8	± 25
10	256.5	± 2.5
100	25.65	± 0.25

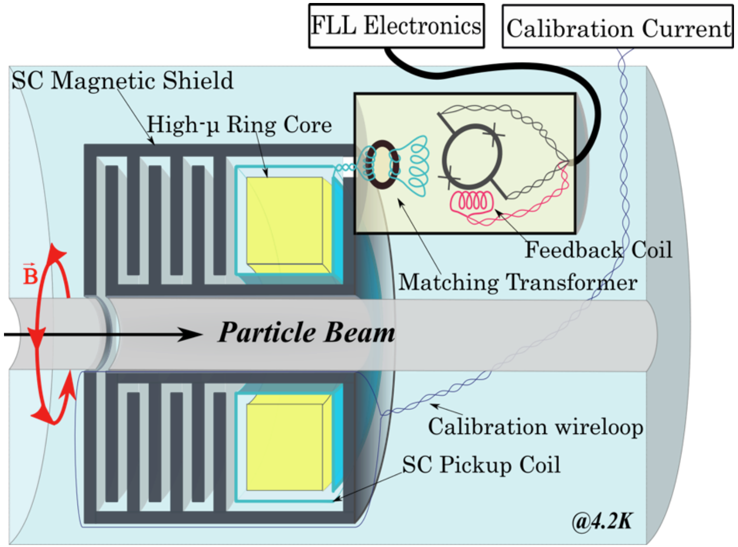
Gain-bandwidth-product (f_{GBP}): 0.23 – 7.2 GHz



R_f … feedback resistor
M_f … feedback coil inductance

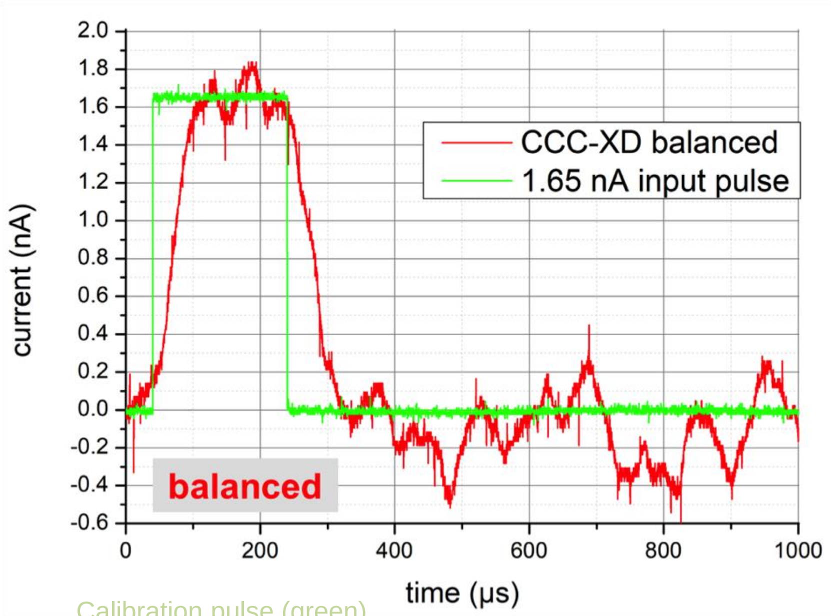
→ Stable feedback loop with slew rates below ~0.5 uA/ns (with 10 kHz filter)

Operating principle - calibration



Drawing courtesy of F. Kurian (GSI)

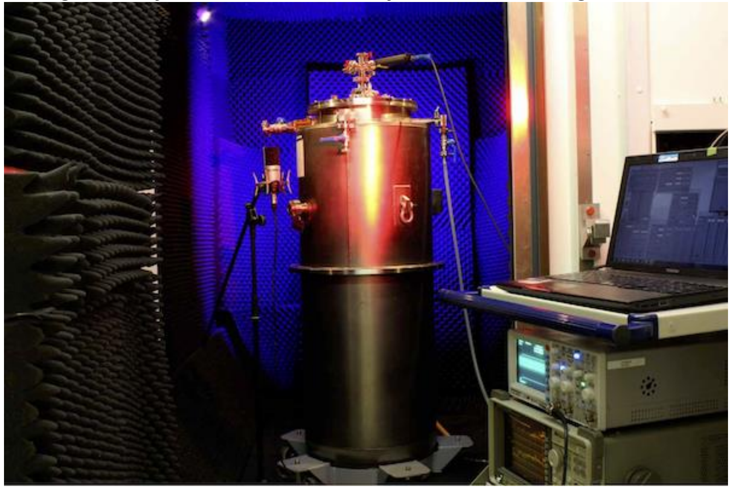
1.65 nA calibration pulse, 1 kHz low pass filter



Calibration pulse (green)
CCC output (red)

Operating principle - calibration

Magnetically shielded laboratory for CCC testing.



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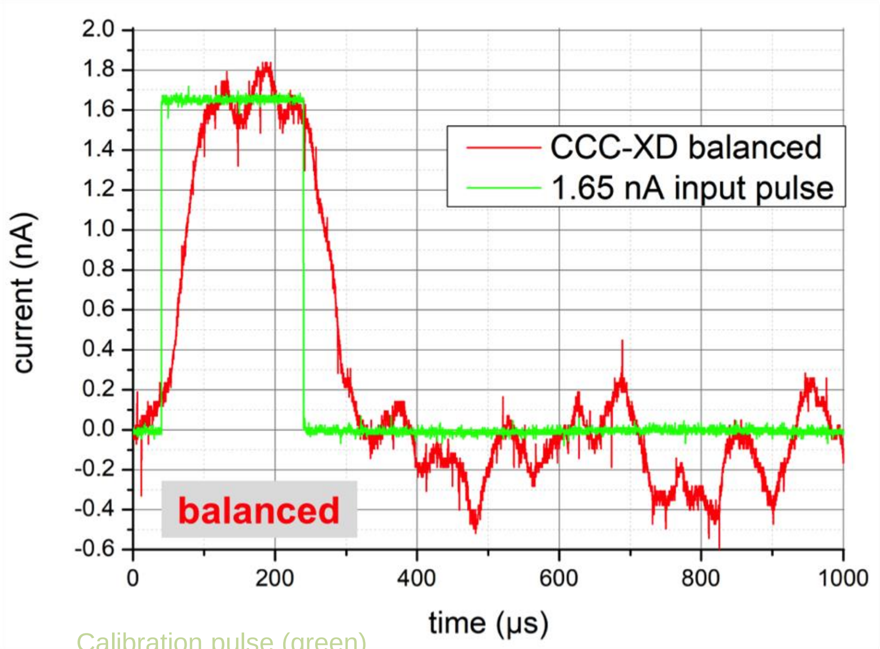
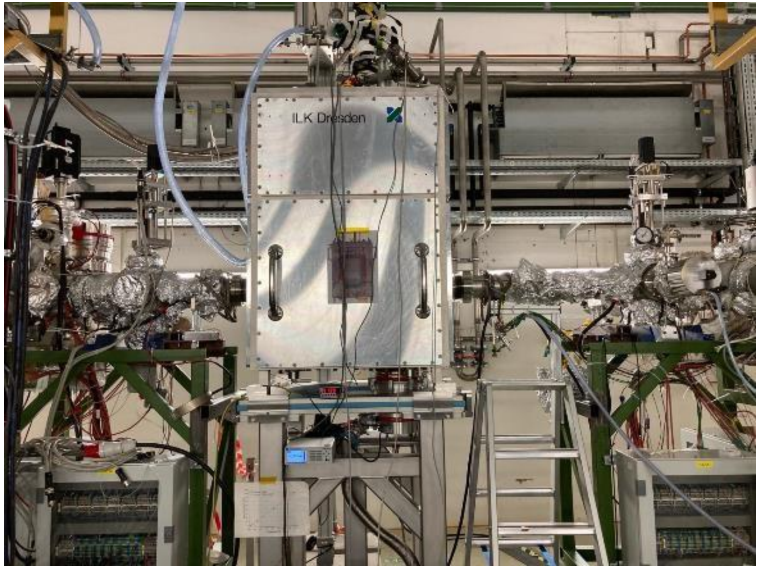
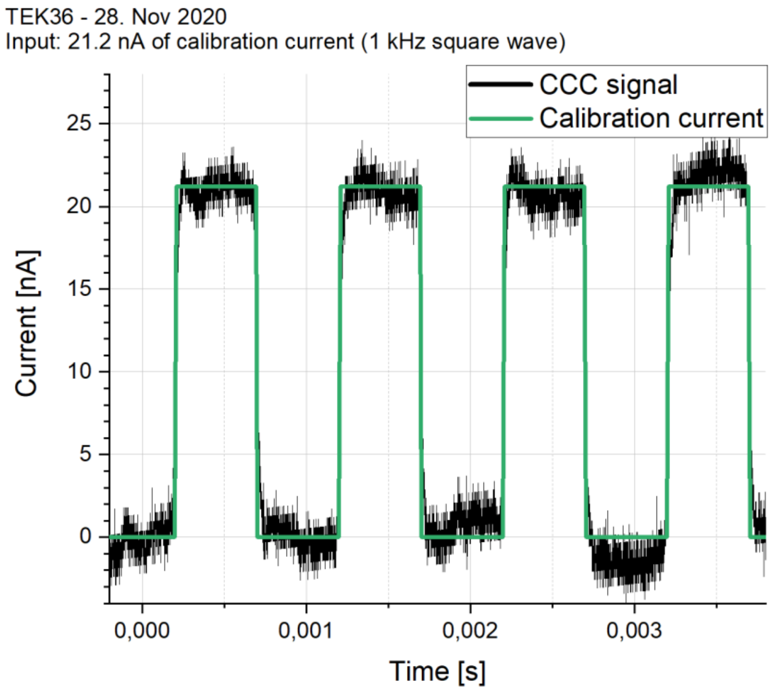


Calibration pulse (green)
CCC output (red)

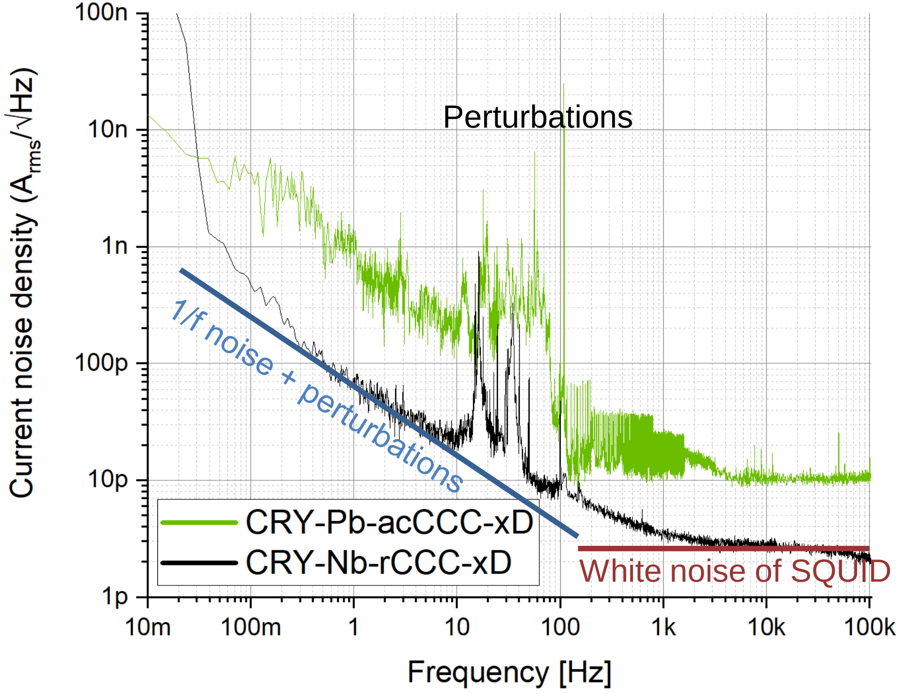
Operating principle - calibration



21.2 nA (1 kHz) calibration pulse, bandwidth of 200 kHz



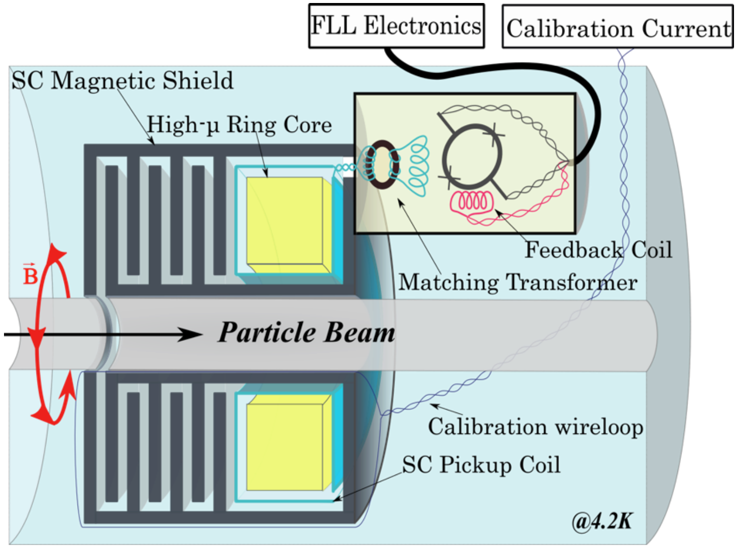
Current noise spectral density - laboratory



Noise (frequency range)	Lab [nA_{rms}]	CRYRING [nA_{rms}]
White noise (SQUID, thermal noise) (0 - 10 kHz)	0.05	2 (beam tube)
Acoustic, mechanical (0.1-100 Hz)	1	1-2
Temperature drift (<0.1 Hz)	0.5	0.5
Liquefier / Dipole	25 / 0	25 / 25

Measured in a clean lab environment

Data Acquisition



Drawing courtesy of F. Kurian (GSI)

Intensity signal
(analog, 100 kHz bandwidth)

SQUID (±10V) → U-f converter → Lassie / Experiments

→ Fixed measurement range

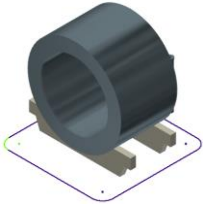
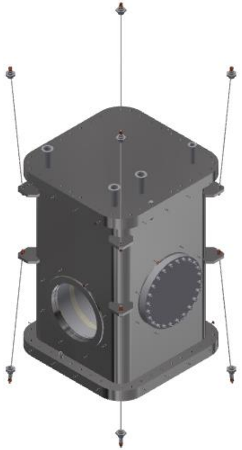
→ Offline baseline correction & filtering

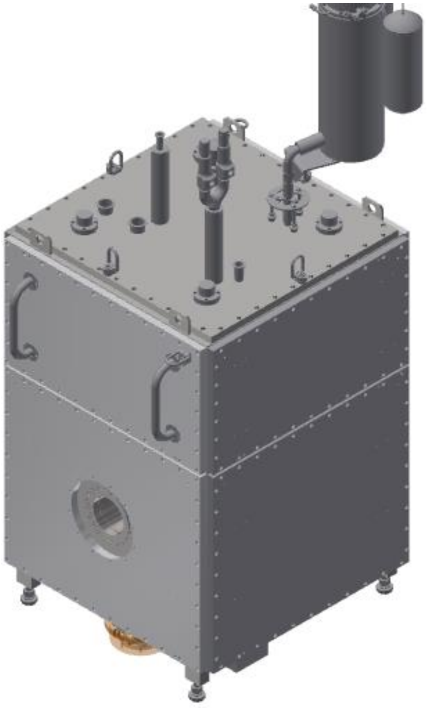
In preparation (components ready)

SQUID (±10V) → ADC (linux server) → FESA class

→ Selectable measurement ranges

→ Online baseline correction & filtering



Cryogenic support system

Design, production & installation

Challenge - Closed cryogenic system

Specifications of cryostat

Materials: Al, 316(Ti), 304, OFC, Ti6Al4V suspension, ceramic

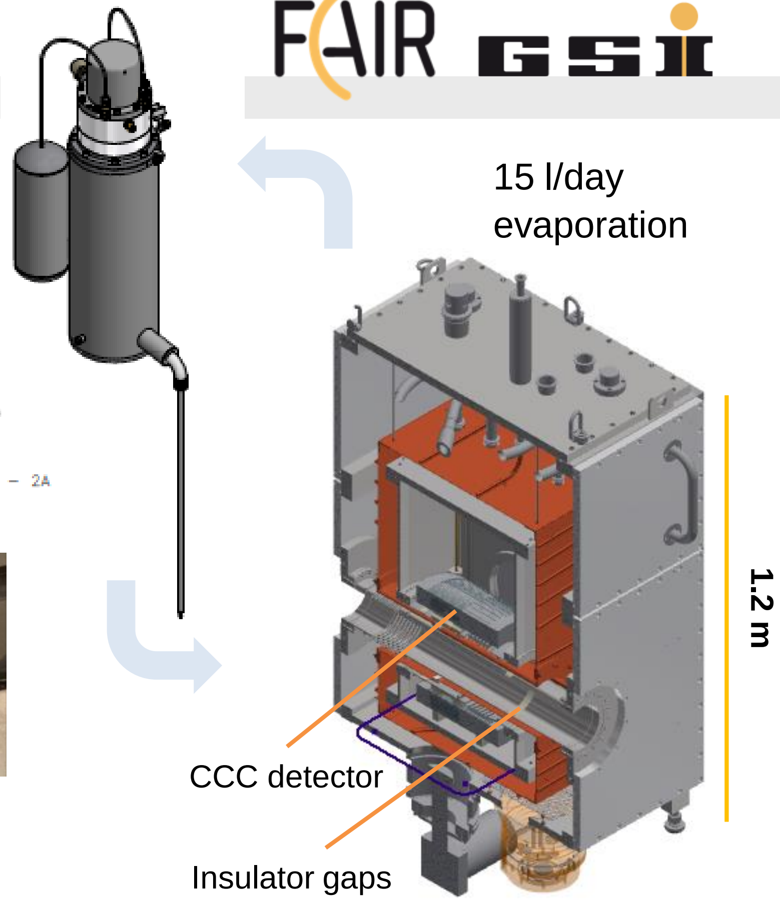
Dimensions: 850 x 850 x 1200 mm (~1.1 t)

Properties: UHV-beamline (bakeable), vibration damping, large maintenance windows

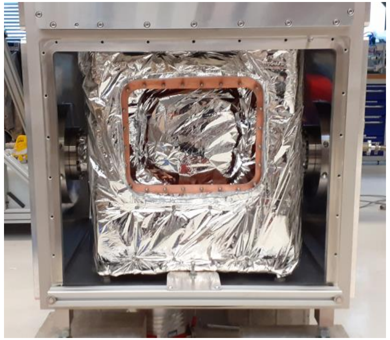
Cryogenics: Helium bath (80 l), gas cooled shield, stand-alone-system design

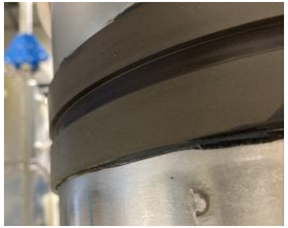
19 l/day liquefier

(CRYOMECH)




Damping bellow connecting liquefier

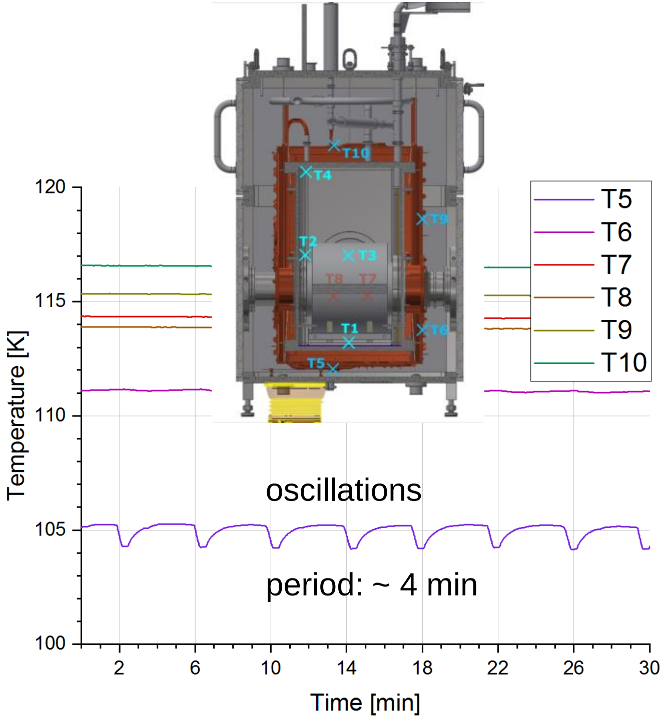

CF125 UHV beam tube through cryostat


Cryogenic polyimide insulator gap

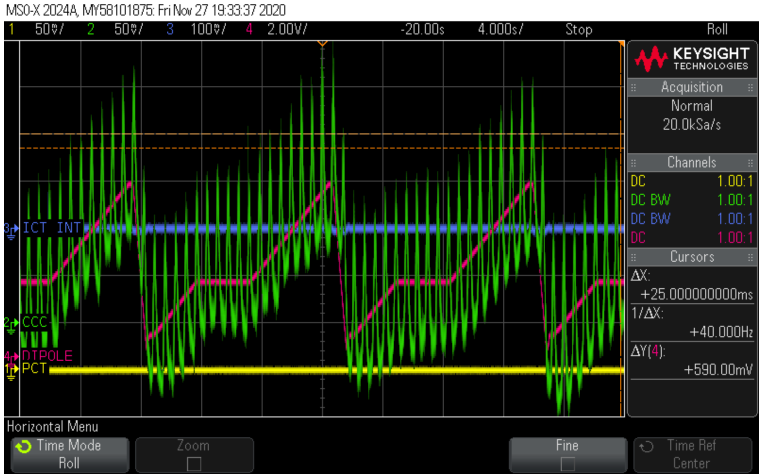
Cryogenic system

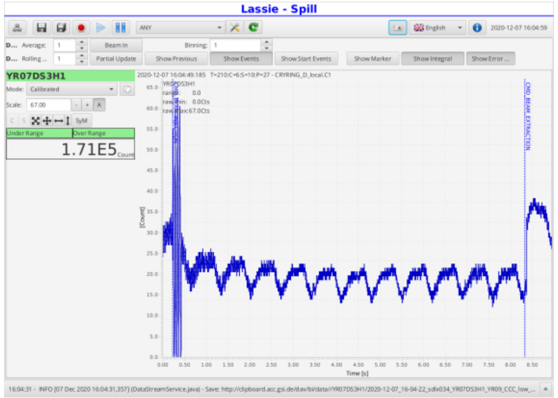
- Excellent vacuum and mechanical properties
- Detailed temperature monitoring
- Good mechanical decoupling from liquefier

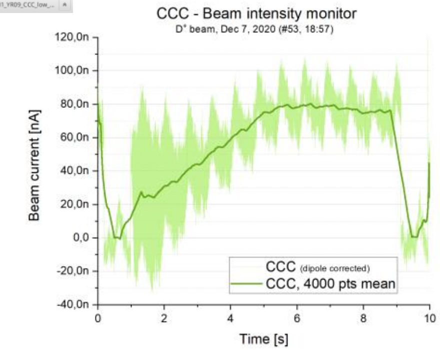
- Excessive helium loss in stand-alone operation (operating time of 1 week)
  - High flow resistance in exhaust line
  - Loss of gas through leaking safety valve



→ solved by a damping nozzle at the liquefier



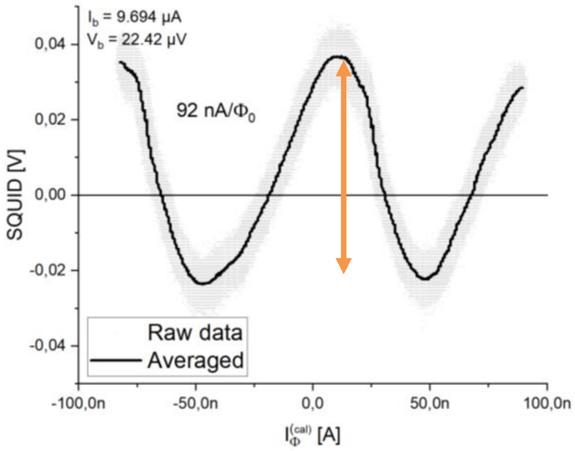




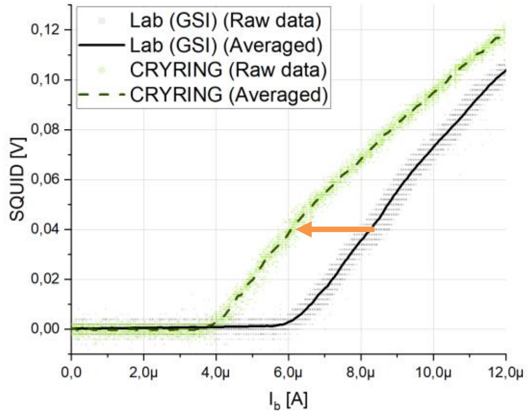
CCC – Current Monitor

Operation at CRYRING

From lab to accelerator

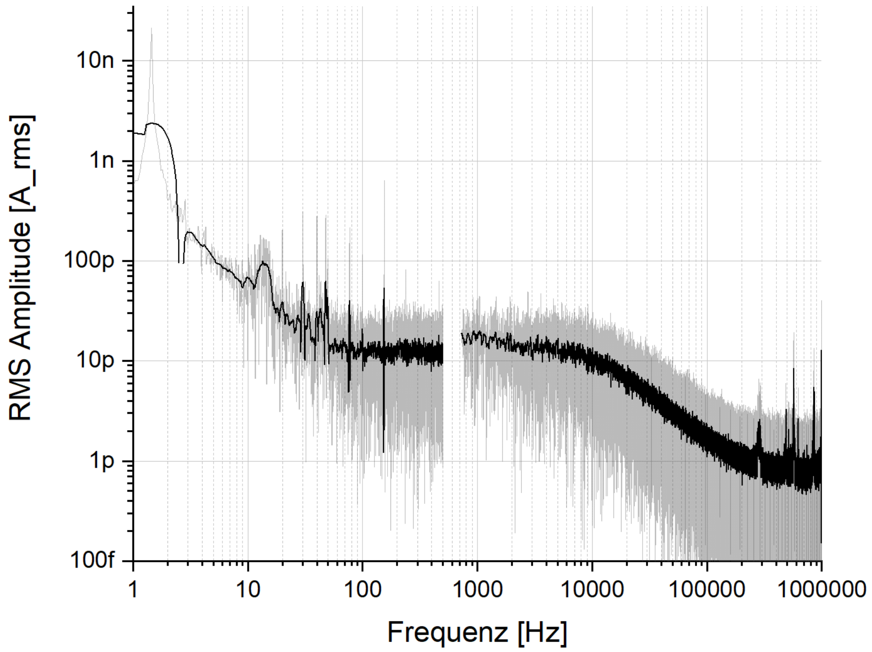


- Dynamic range of sensor cut in halve (RF interference, sensor deterioration?)
  - Maximum SQUID modulation in AMP mode (100 mV -> 60mV -> 30 mV)



- SQUID closer to normal-conducting state (pre-stressed)
  - I_{bias} of maximum SQUID modulation (10 uA -> 5 uA -> 3 uA)

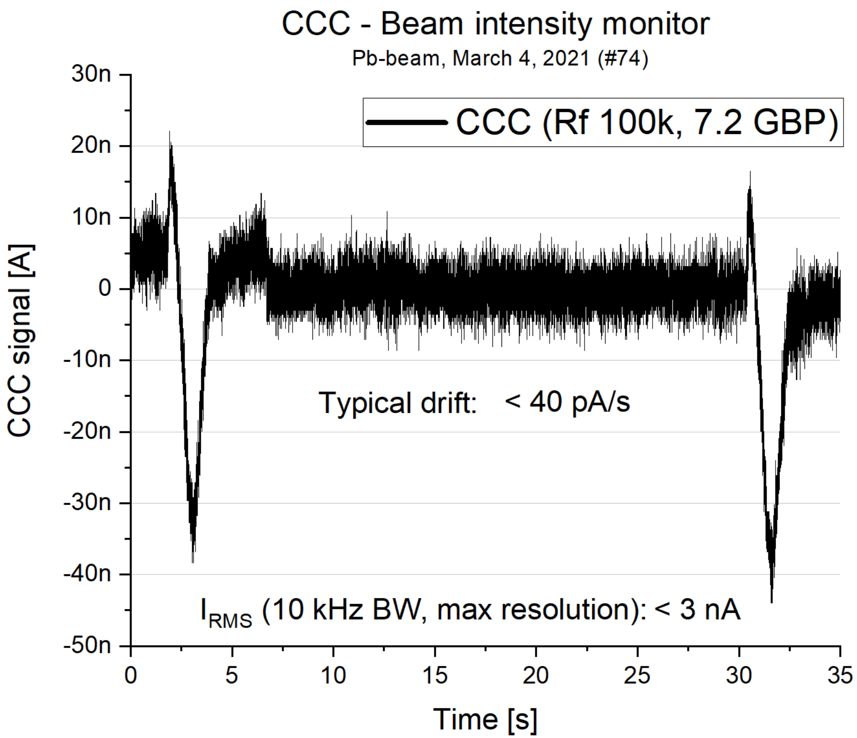
Current noise spectral density - CRYRING



Noise (frequency range)	Lab [nA_{rms}]	CRYRING [nA_{rms}]
White noise (SQUID, thermal noise) (0 - 10 kHz)	0.05	2 (beam tube)
Acoustic, mechanical (0.1-100 Hz)	1	1-2
Temperature drift (<0.1 Hz)	0.5	0.5
Liquefier / Dipole	25 / 0	25 / 25

Drift and noise figure

liquefier switched off



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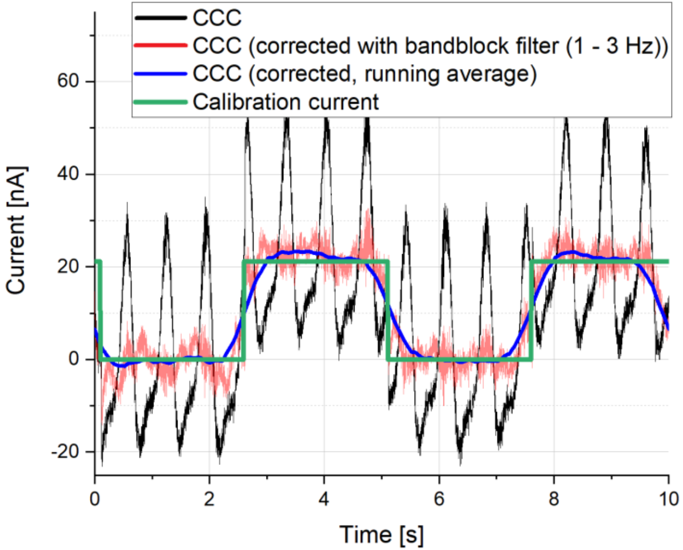
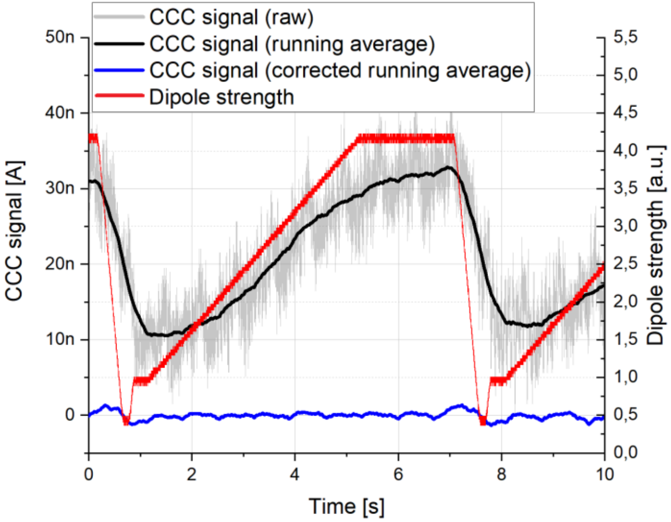
Perturbations - Filters



Helium liquefier

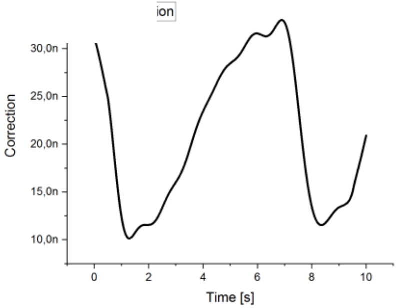
fixed frequency (1.4 Hz):
use bandblock filter



Dipole ramp

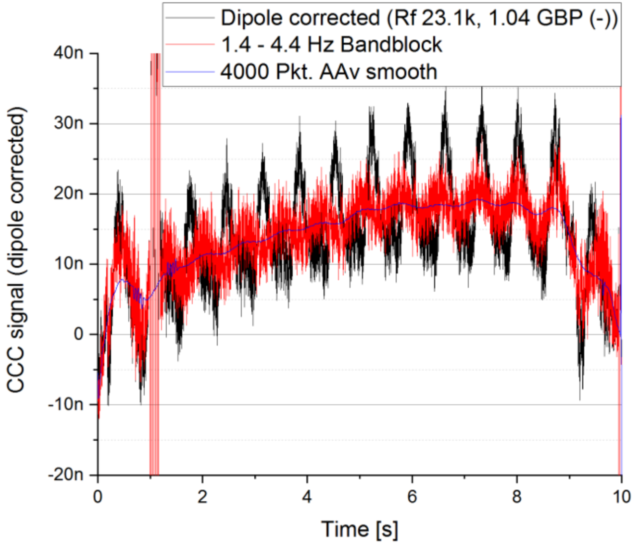
deterministic:
subtracted using averaged background measurement

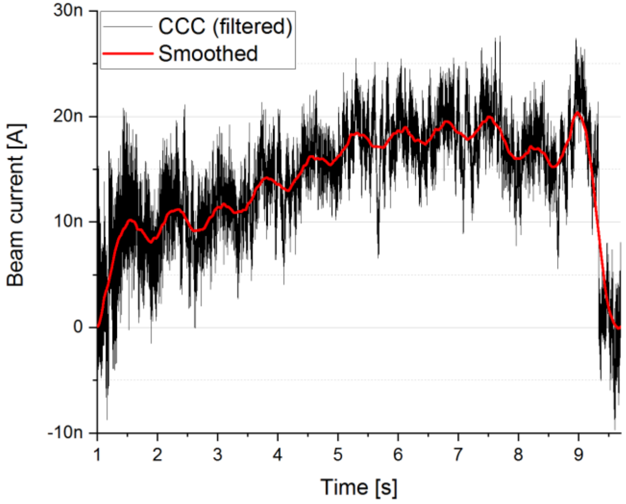
correction function



Application – Weak currents

- Limited by external perturbations (liquefier, dipole) → improve filters

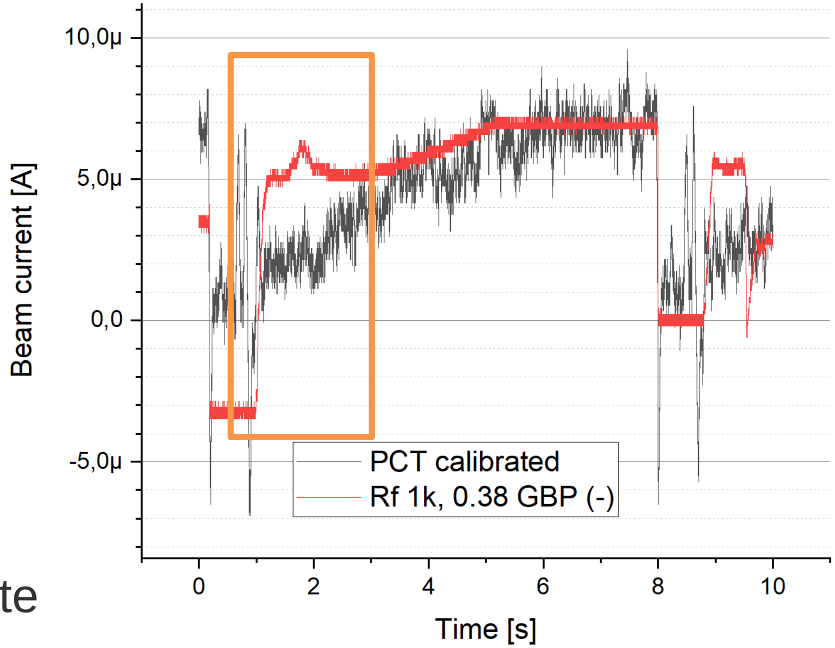




Application – High currents

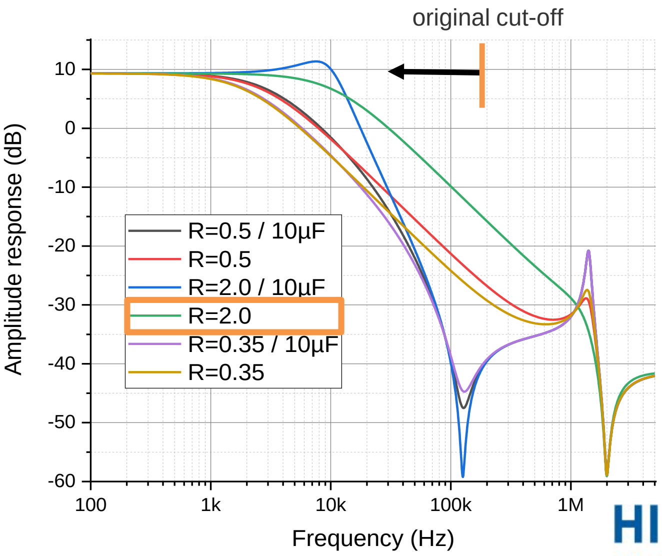
- Limited by ADC
- High slew rates at injection
  → loss of signal lock
- Threshold around 200 nA of D^+

→ Add low pass filter to reduce slew rate

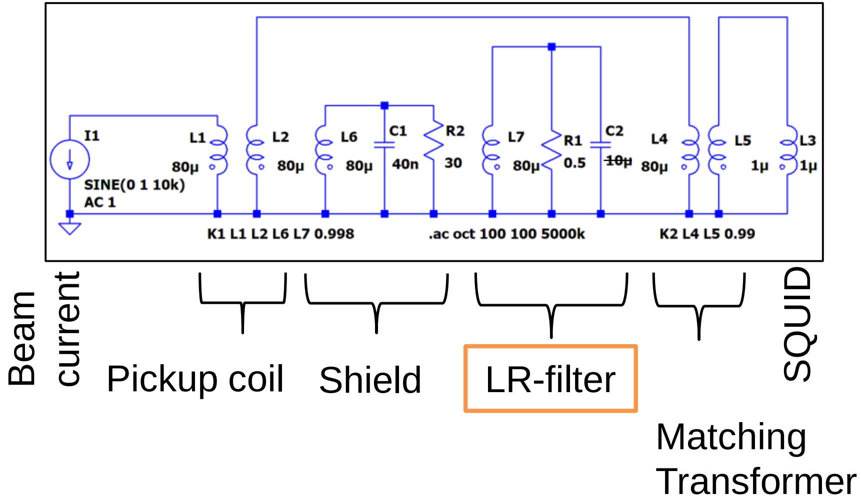


Modification – low pass filter

- Create low pass with internal calibration loop



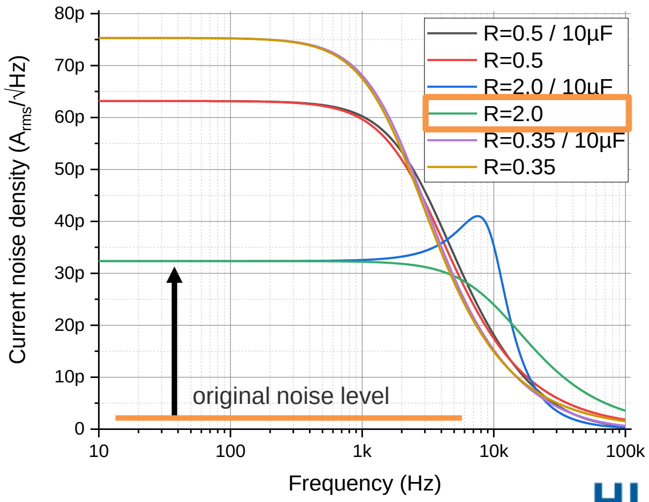
V. Tympel (HIJ)



- R1 = 1.94 Ohm
  - Frequency cut-off moved (200 kHz to 10 kHz)

Modification – low pass filter

- Create low pass with internal calibration loop



V. Tympel (HIJ)

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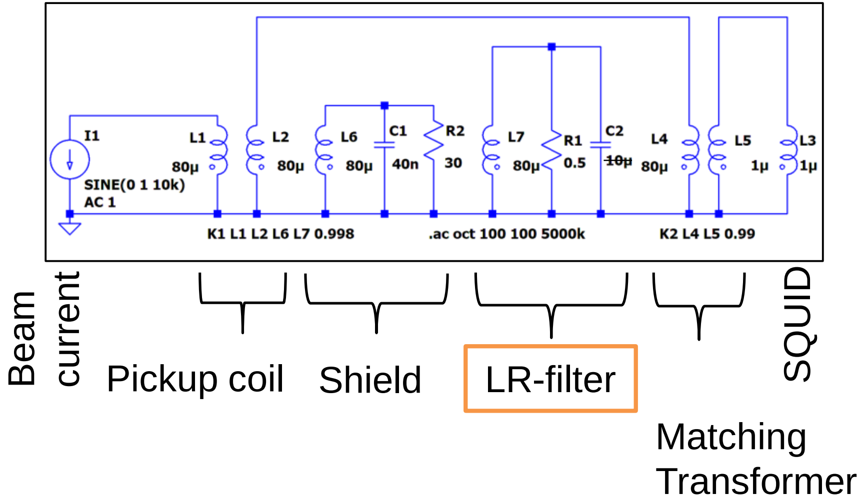
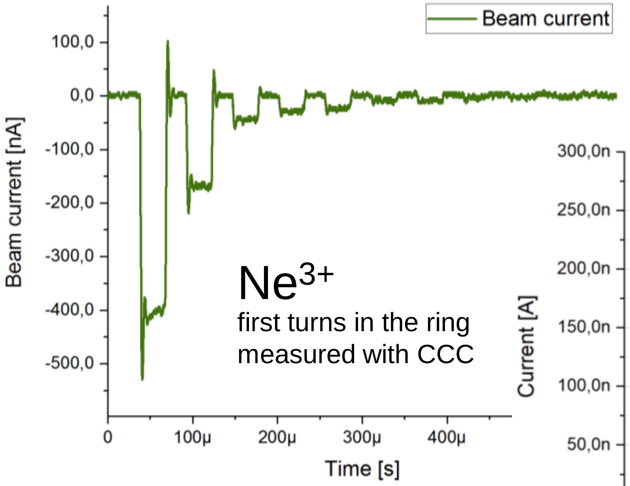


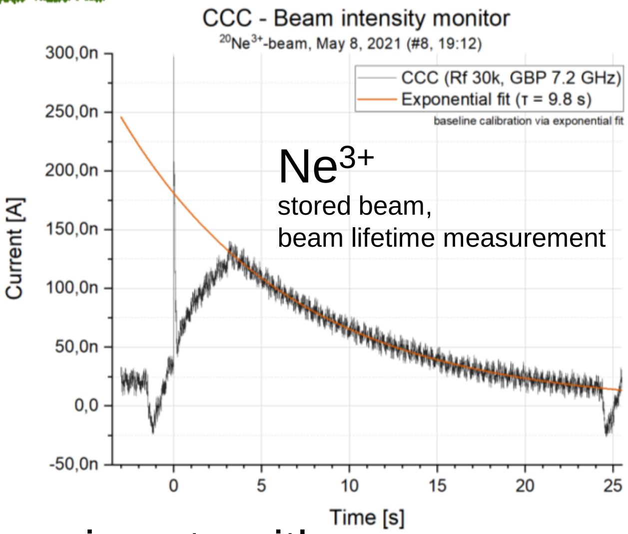
- R1 = 1.94 Ohm
  - Thermal noise level increased (about 10 x)

Highlights - Beam time @ CRYRING



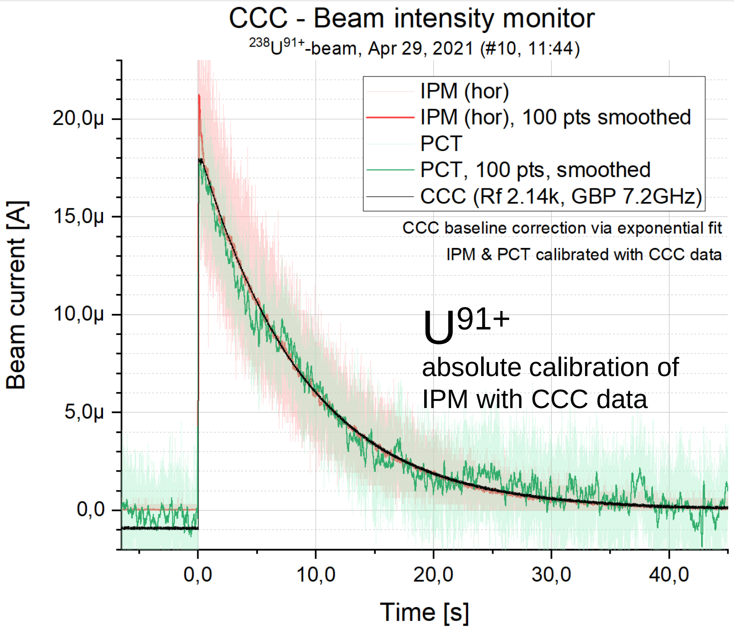
Commissioning

non-destructive measurement
up to ~100 kHz bandwidth



Experiments with weak beams

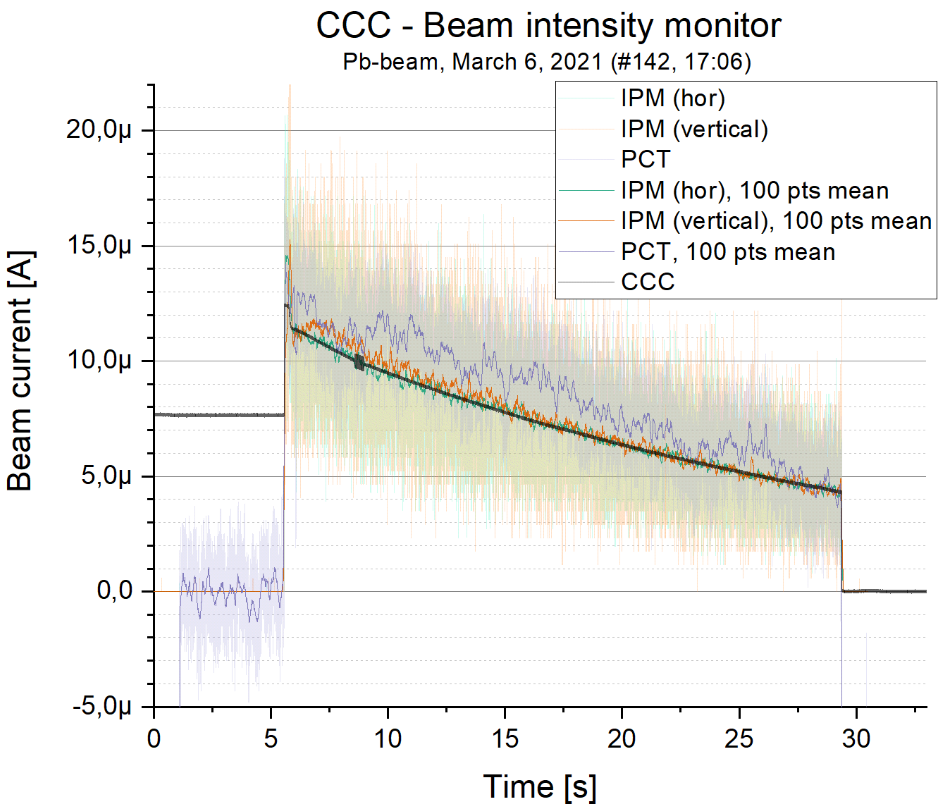
absolute intensity
resolution of a few nA

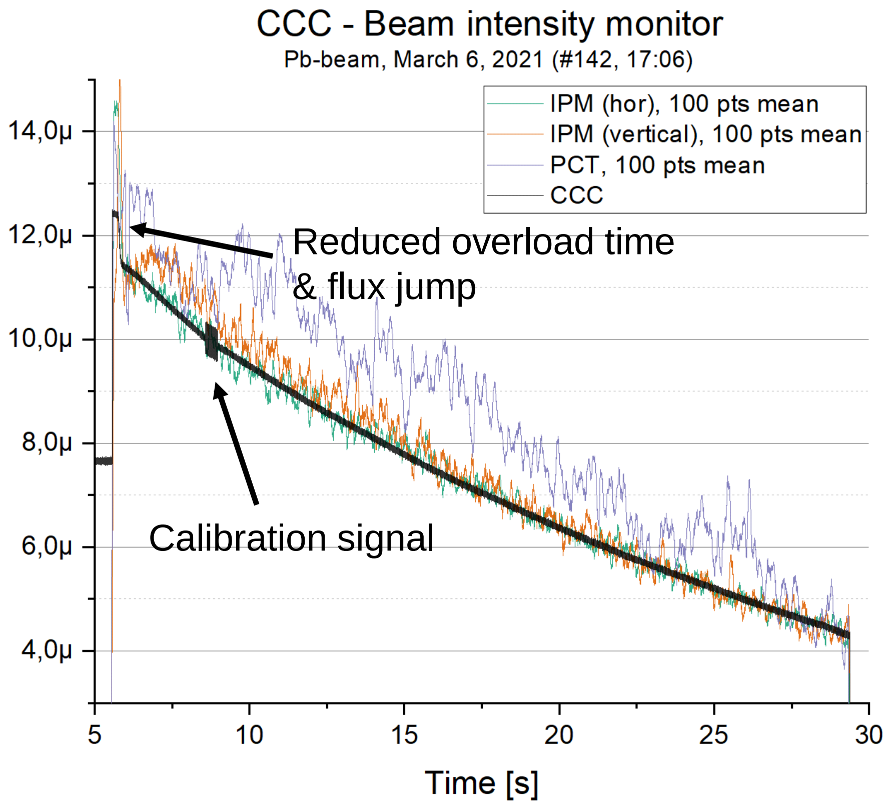


Instrument calibration

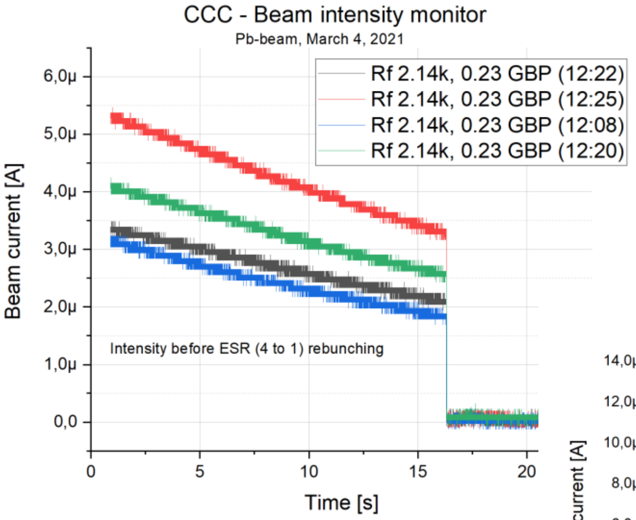
increase absolute
accuracy of existing diagnostics

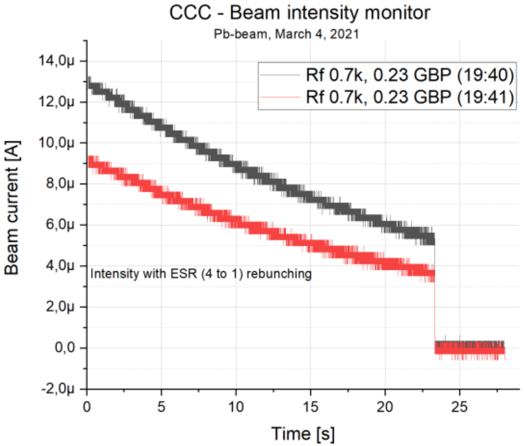
High currents - Comparison of intensity monitors

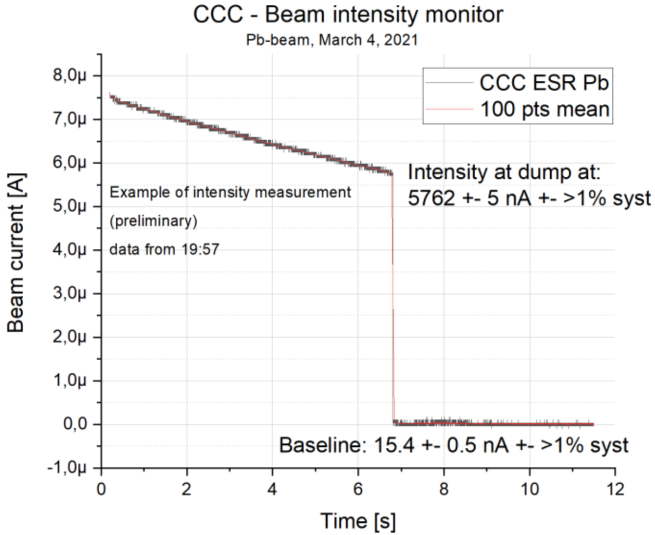




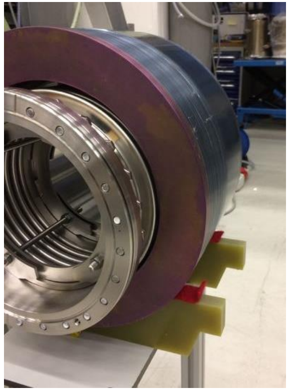
CRYRING – Pb^{78+} (intensity monitoring)





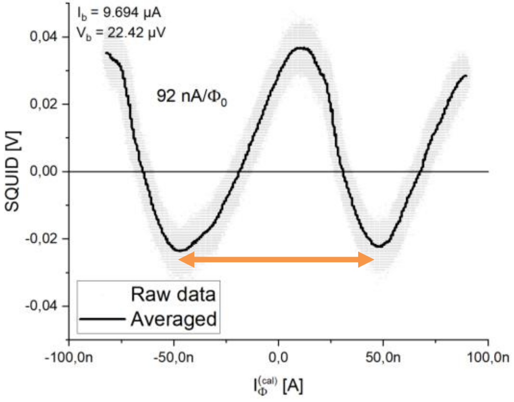


Development of CCC detector



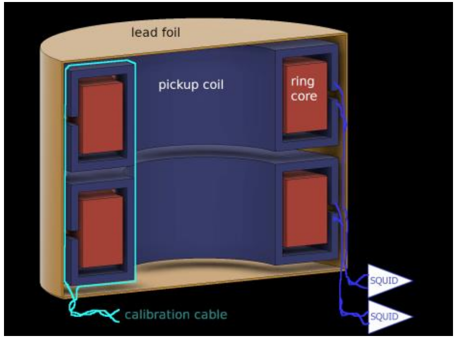
Development of CCC detector

- Increase slew rate



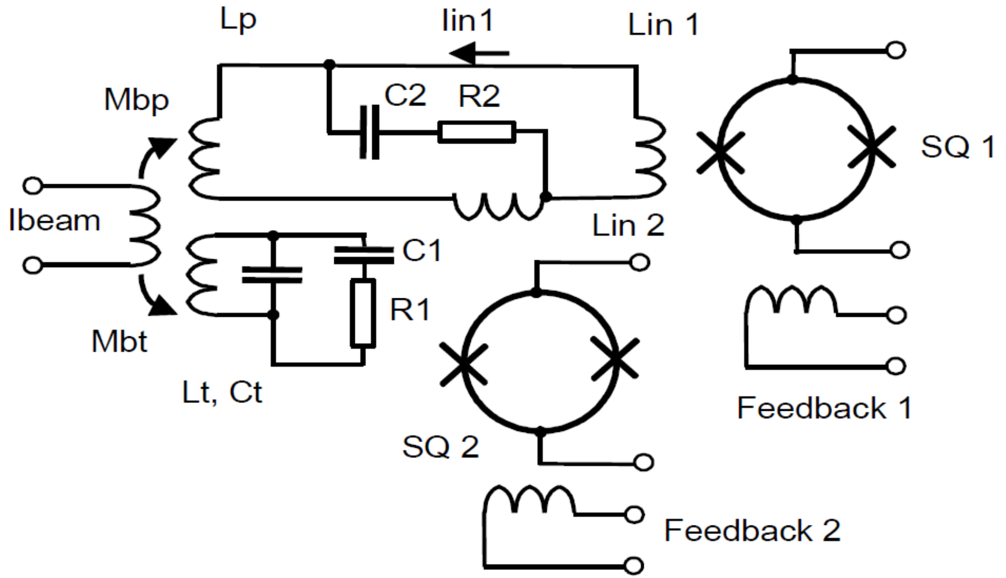
→ increase to 80 µA/Φ_0

- Decrease influence of noise



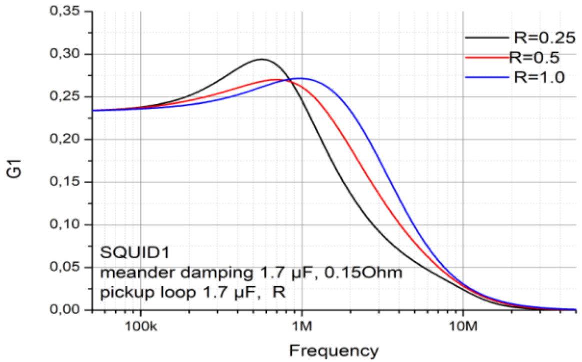
Development of CCC detector – slew rate increase

- Two (cascade-)SQUID system

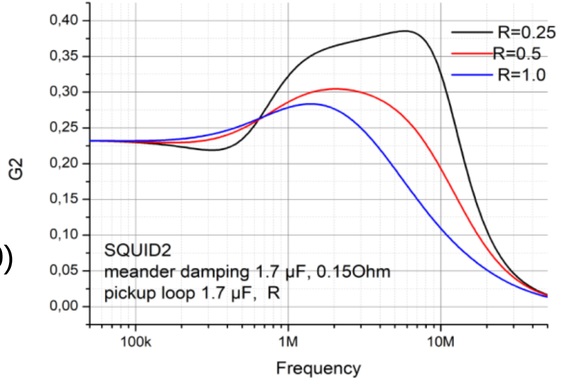


Transfer functions

SQ1
sensitive



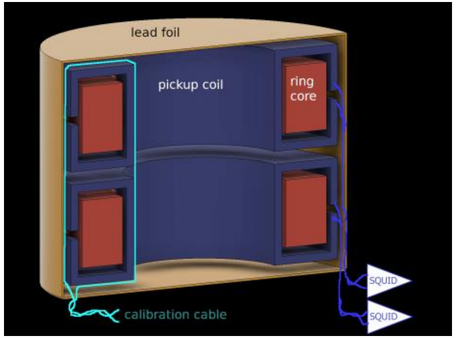
SQ2
reference
(80 uA/phi0)



Development of CCC detector
Challenges - Perturbations

- Filter
  - Mechanical vibrations
  - Thermal and pressure effects
  - External fields

Multiple ring core CCC (Dual-CCC)



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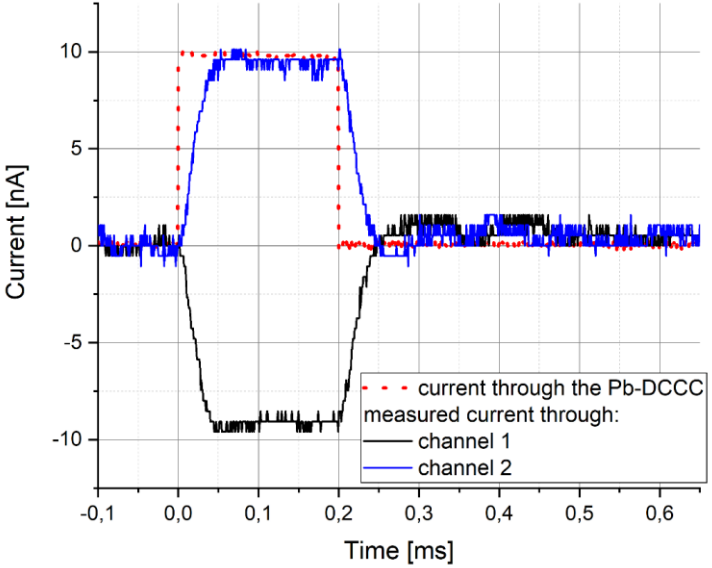
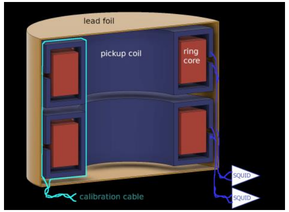
V. Tympel, M. Stapelfeld

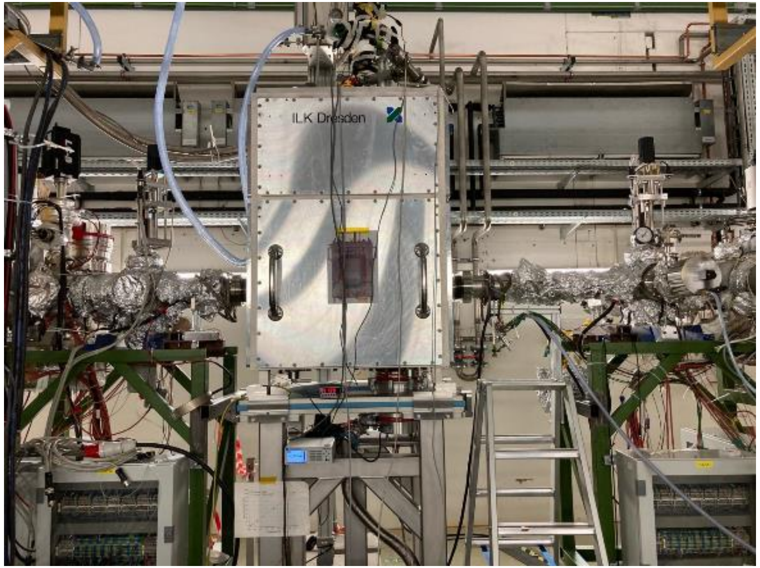


CCC - Further developments at GSI

- Refinement of cryogenic system (extended cryogenic operation)
- Increase signal quality
  - Background suppression (e.g. signal filters)
  - Optimize SQUID stability (mechanical & electrical interference, slew rate)
- Advanced detector design
  - SQUID-cascade
  - Multi ring core (Dual-CCC)

V. Tympel, M. Stapelfeld





Cryogenic Current Comparator (CCC) at CRYRING

→ *Preparation for FAIR series production*

The

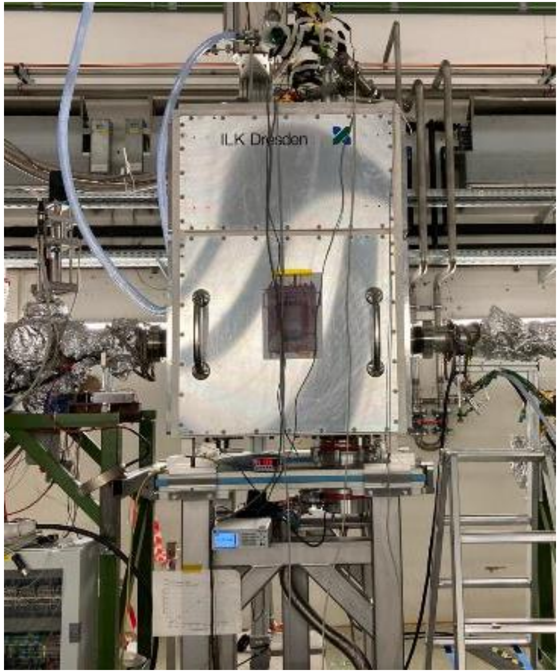
Cryogenic Current Comparator

at CRYRING@ESR

David Haider

Beam Diagnostics Group, GSI

On behalf of the CCC collaboration



CCC@CRYRING