GSI Machine Coordination Meeting 4th June 2024

Thomas Sieber
for the CCC Team

Cryogenic Current Comparators (CCC) for nA Beam Intensity Measurement at FAIR

Report from Engineering Runs 12/23 and 04/24

Outline

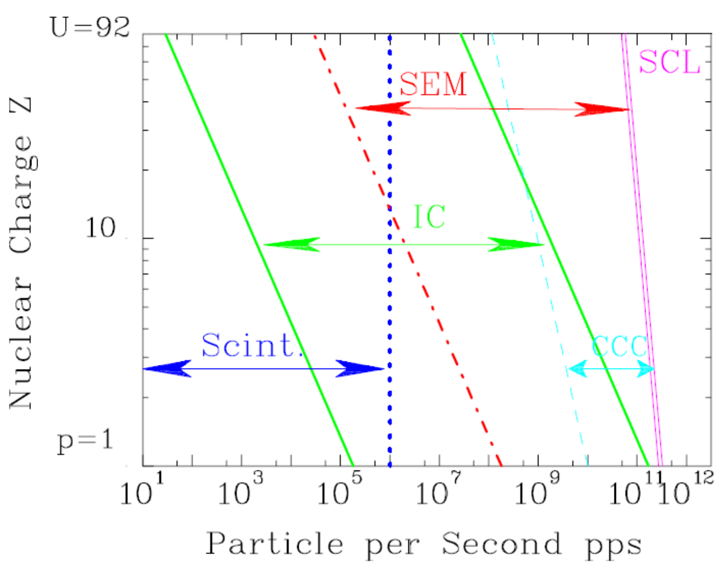
CCC-

- Principle + Layout
- Development steps
- Beam tests at HTA

Nondestructive measurement of low intensity (nA) beams at FAIR

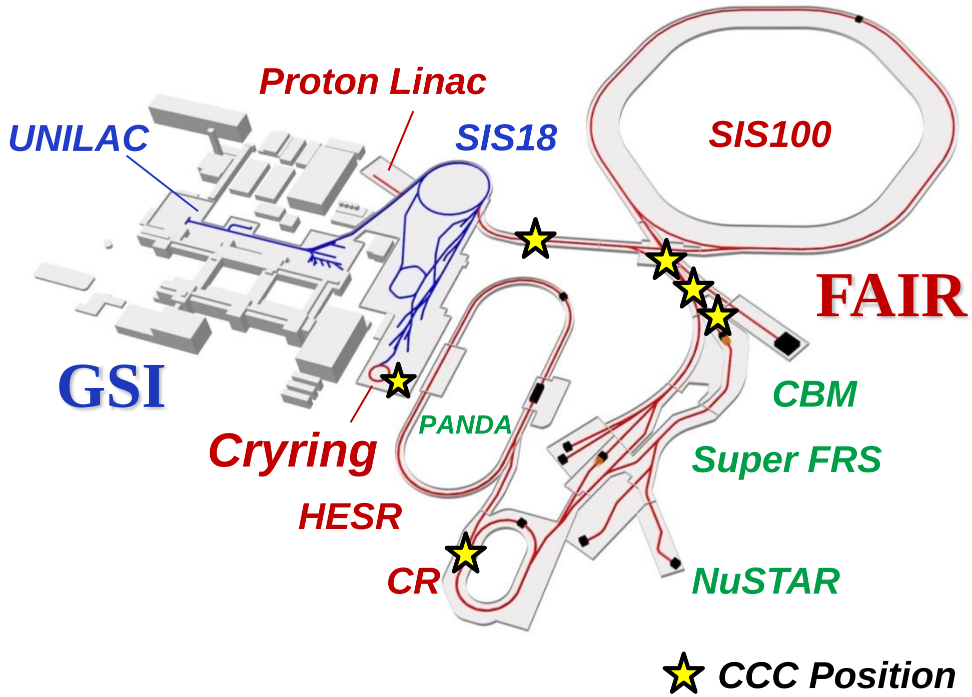
- Slow extracted beam from SIS18/SIS100 (RIB, CBM), spill optimization

- Circulating beams (CRYRING, CR → HESR)

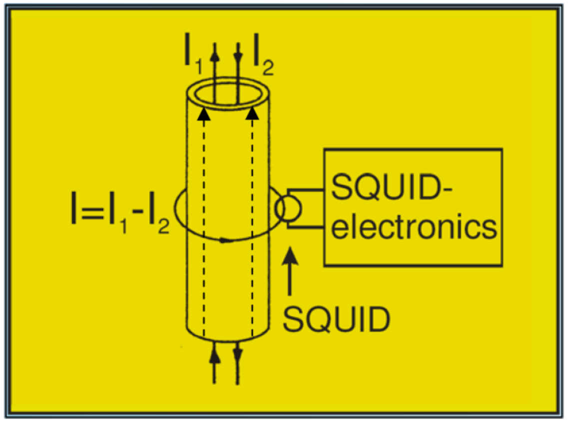


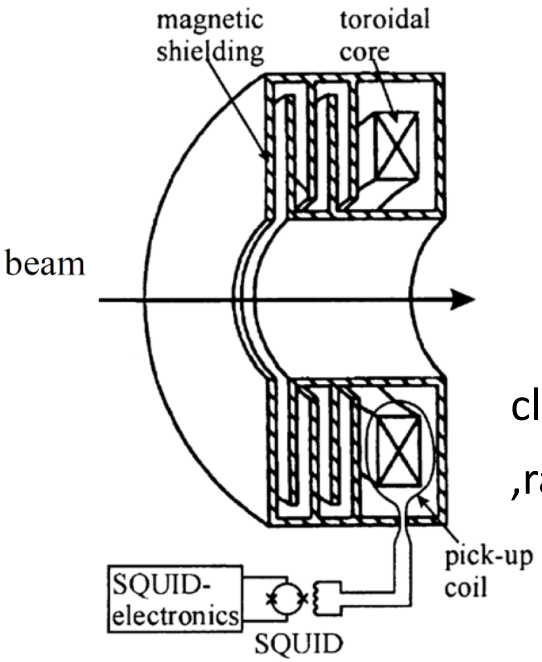
Detector systems used for slow extraction at SIS18 (P. Forck)

SCINT ...Scintillator
IC ...Ionization Chamber
SEM ...Secondary Electron Monitor



CCC:
Precise measurement of azimuthal magnetic field (fT-range) using DC-SQUIDS





classical or
‚radial' CCC

CCC (Harvey 1972):

- Uses Meissner-effect and SQUID for I_1/I_2 measurement
- If $I_1 \neq I_2$ magn. field produces compensation current
- Magnetic flux through SQUID → voltage change

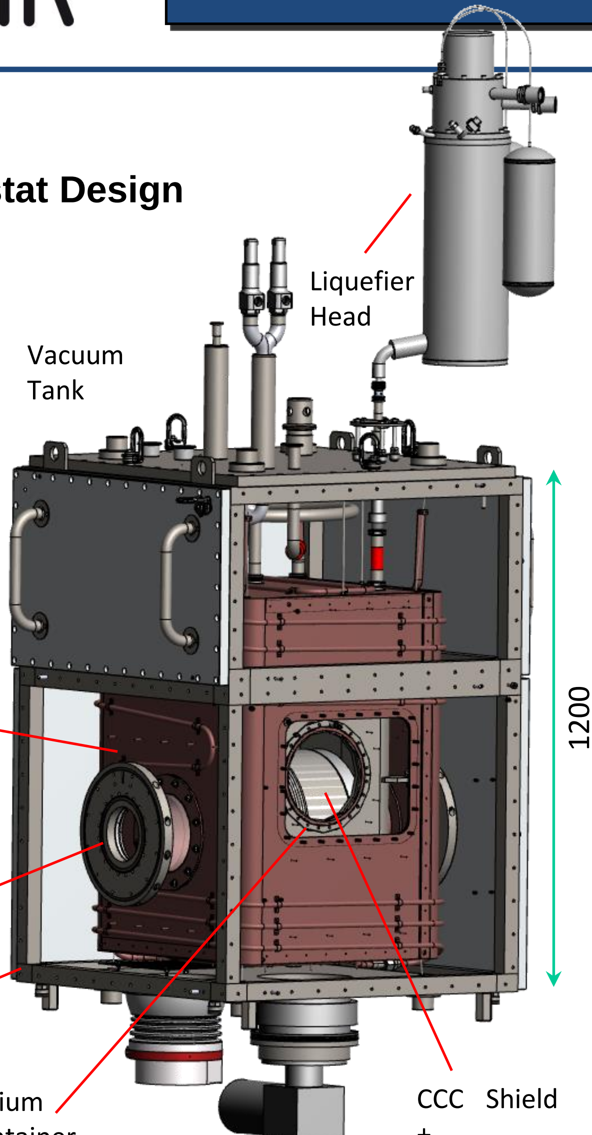
For charged particle beams:

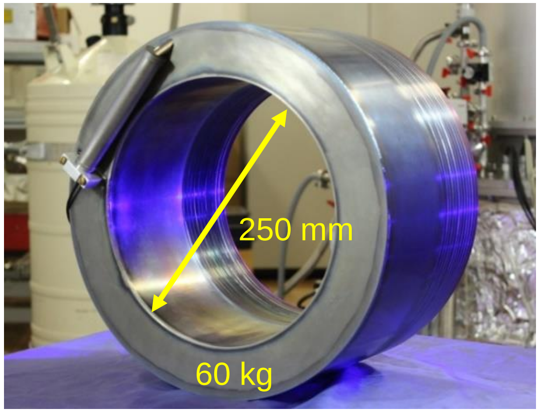
$I_{comp} = I_1 - I_2 = I_{beam} - 0$ (position independent)

Proof of Principle in Accelerators: A. Peters at. al. 1994

- SC shielding for non-azimuthal fields
- SC pickup coil with toroidal core ($\mu_r \approx 50000$)
- Low noise, high performance DC SQUID + control electronics (FSU Jena) → commercial products (MAGNICON, SUPRACON)
- FLL electronics: → $\mu\Phi_0$ Resolution

Cryostat Design





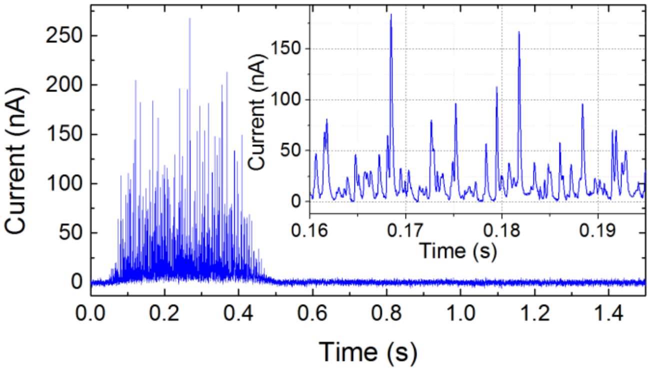
standing time ~ 10 days

System costs (2019)

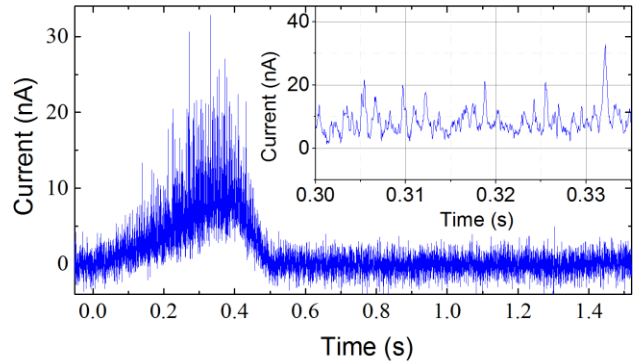
Nb CCC	150 k€
Cryostat	200 k€
Liquefier	80 k€
SQUID + electronics	10 k€
DAQ	10 k€
Support	5 k€
Total	**~ 450 k€**

Spill Measurements at GSI - History

Spill analysis unbunched beam



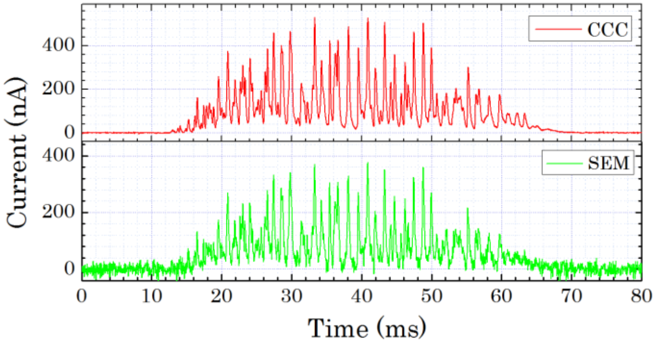
Bunched beam

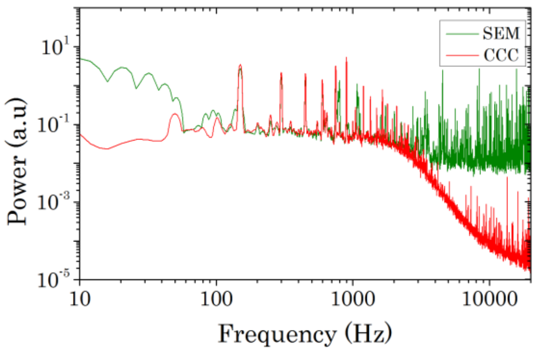


Forck et. al. 2004, Ne^{10+}, 300 MeV/u, t_{extr} 100 ms – 2 s; FSU Jena SQUID + electronics

Experimental setup
CCC prototype (A. Peters et al.)

Spill measurement with CCC and SEM → FFT





Kurian et. al. 2015, Ni^{26+}, 600 MeV/u, t_{extr} 60 ms – 2 s; Magnicon SQUID + electronics

Change requests for FAIR:

Beamline and isolation vacuum coupled ~5*10-6 mbar → no UHV operation

Shield not completely enthalpy cooled → additional cold head required

Material appropriate for FAIR beamline dimensions – Nb instead of Pb

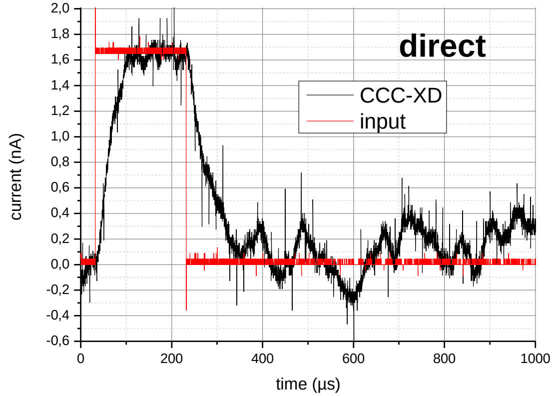
Manual filling → (no standalone operation, thermal drift unavoidable)

SQUID, electronics + controls from 80‘s

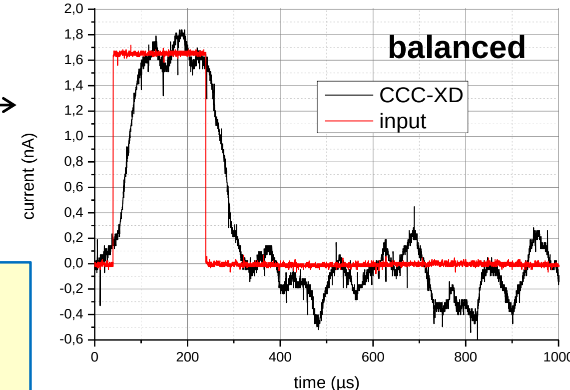
In general: improve magn. shielding, system noise, current resolution …..

Pulsed Current Measurement from Calibration Loop

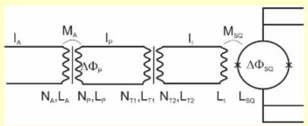
Direct = without Matching Transformer / Balanced = Matching Transformer adjusted

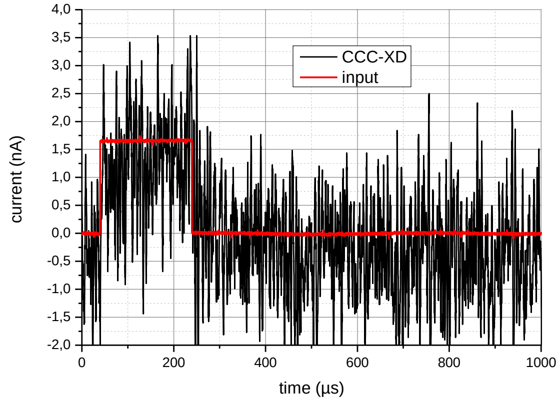


10 kHz Filter ON



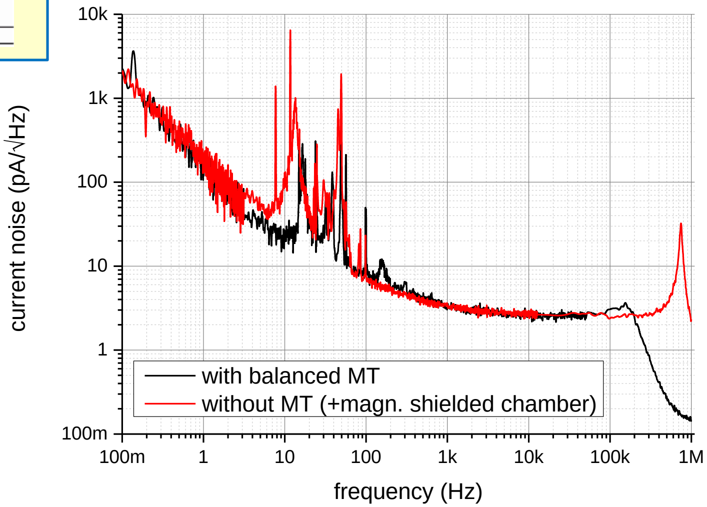
Matching Transformer





balanced
10 kHz Filter OFF

noise spectrum



Low beam currents

- Resolution limited by external perturbations (liquefier, dipole ramp)

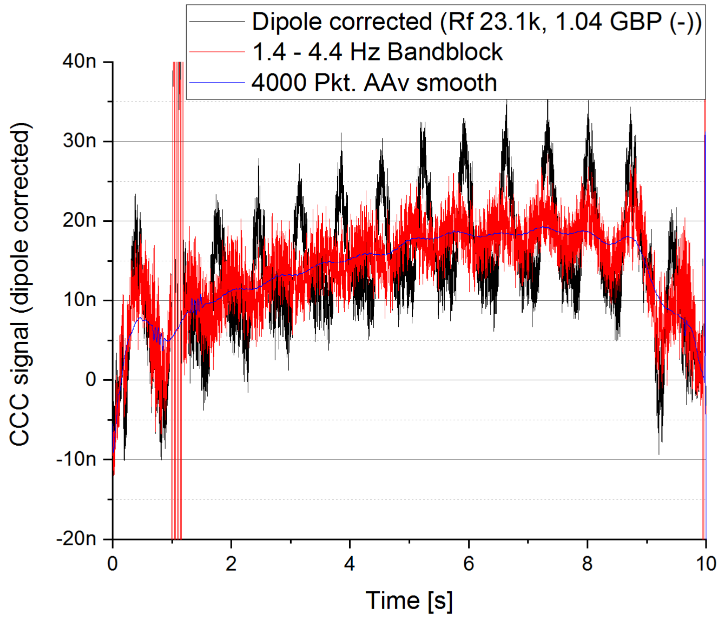
→ improve software filtering

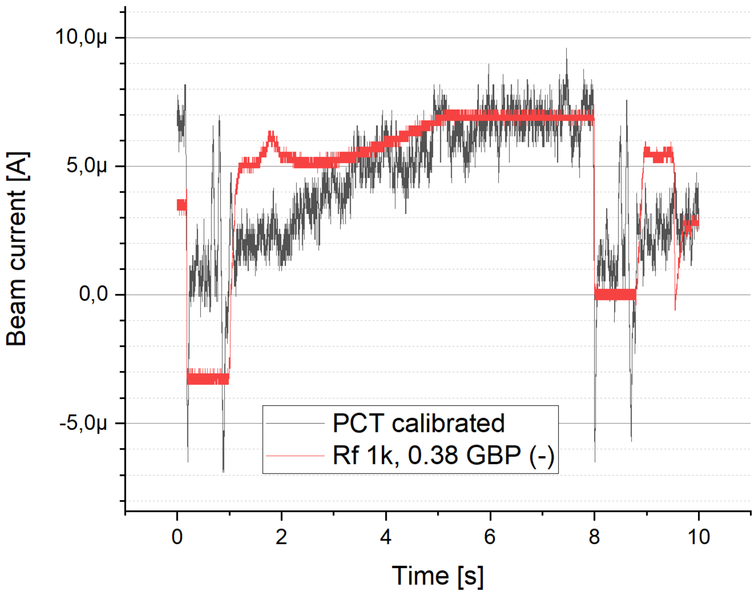
→ hardware optimization

High beam currents

- High slew rates → loss of signal lock
- Threshold around 500 nA of D^+

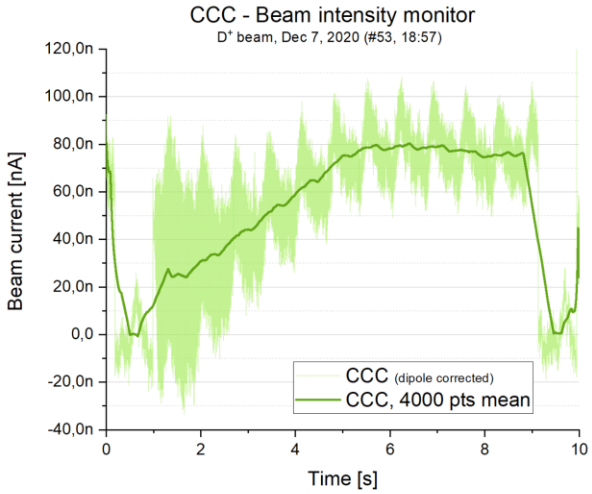
→ add low pass to reduce slew rate (10 kHz instead of 100 kHz cut off)

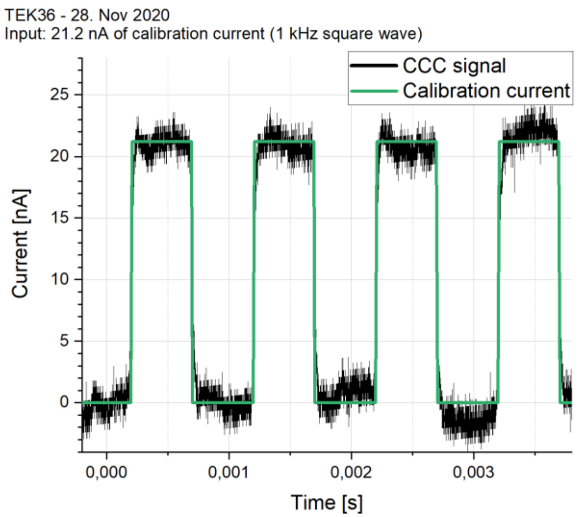




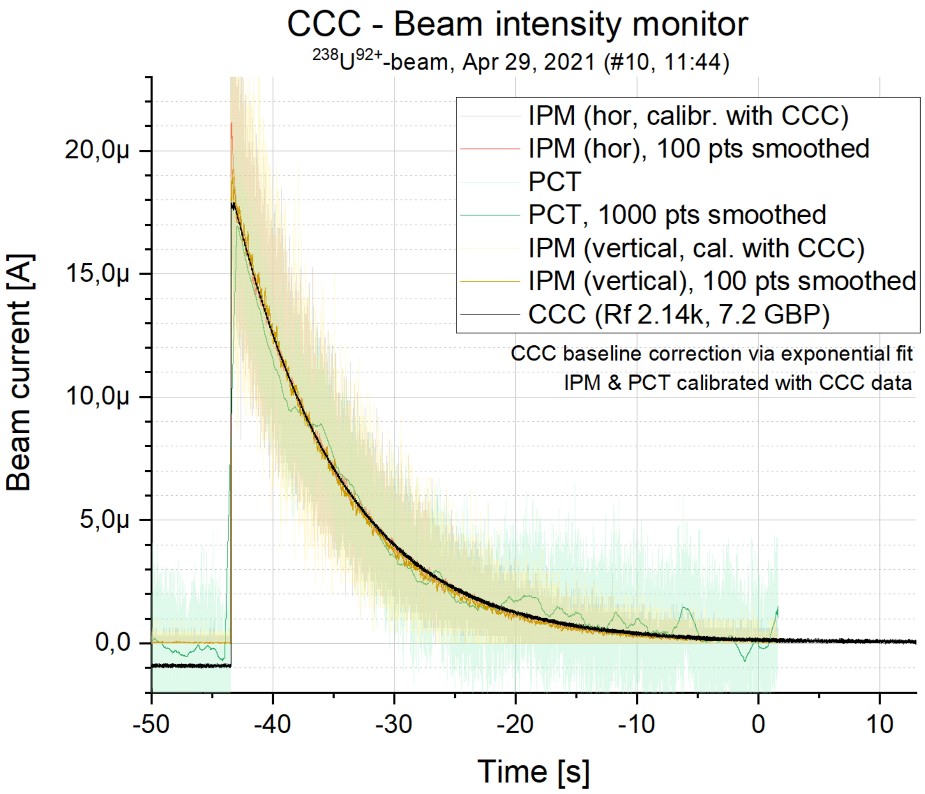
transition laboratory → accelerator reduces current resolution by factor 10

Low Intensity





High Intensity



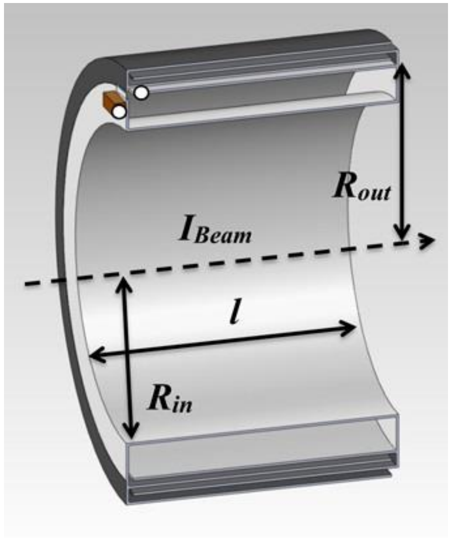
Lessons learned from CRYRING

- CCC-XD (Niobium) successfully operated in storage ring, nA measurement could be demonstrated, support for Cryring experiments provided.
- strong influence of rf-background on V/Φ Curve when moving from lab to machine. Bias Current reduced, operation less stable than in laboratory
- unavoidable jump at injection, slew rate problems partly solved by damping the system
- magnetic ramp up to 30 nA → better shielding required
- CCC used for calibration of standard diagnostics in the ring (IPM, PCT)
- filtering of periodic disturbances (liquefier, 30 nA) required, to be implemented in FESA class

Todos:

- improve slew rate limitations (→ damping + modified eigenmodes by matching trafo)
- improve magnetic shielding (→ shield from axial CCC)
- longer standing time (→ new thermal shield, bigger liquefier)
- less expensive (→ lead shielding)
- better noise behavior, current resolution etc. (→ matching transformer design, Dual Core CCC)

Alternative CCC Types



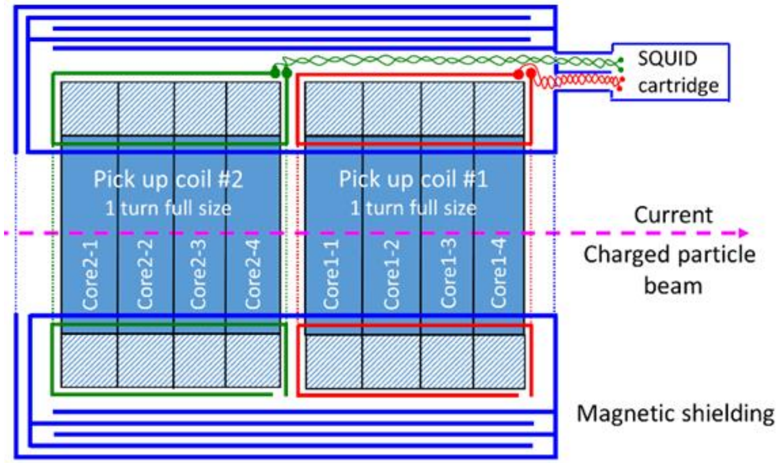
Axial/Coreless-CCC

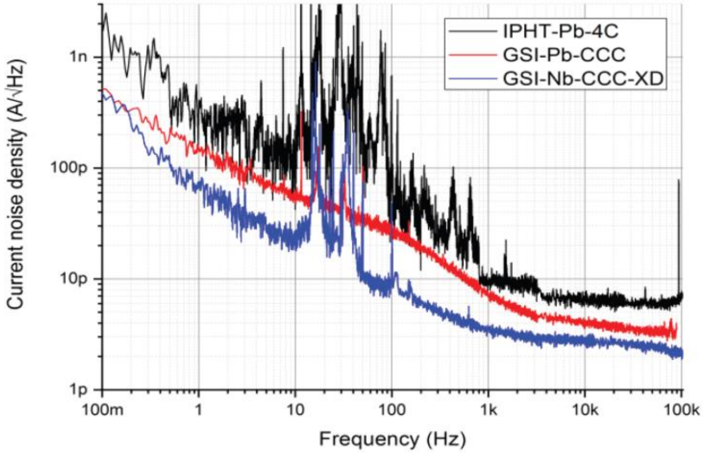
Pros

- magn. shielding (-150 dB instead of -75 dB)
- lead / costs
- easy manufacturing
- [two stage SQUID]

Cons

- weak coupling (beam)
- excessive noise



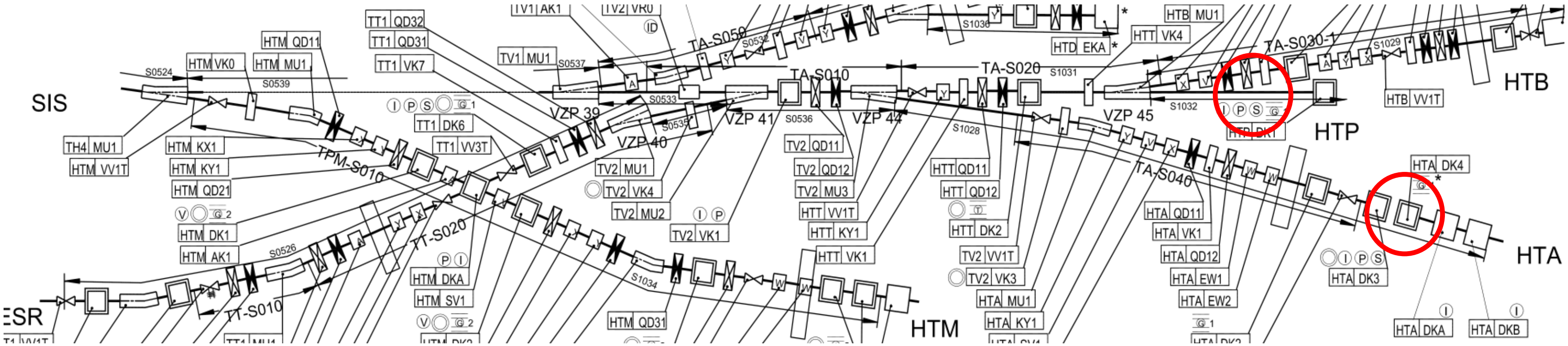


Noise figures for classical and axial CCC

Dual-CCC

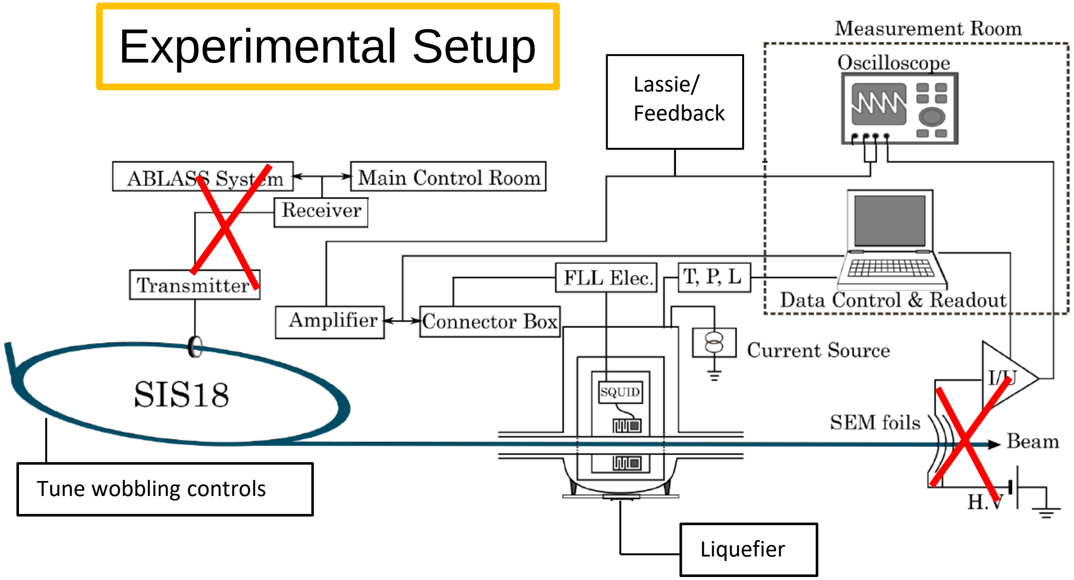
Pros

- magn. shielding (150 dB instead of 75 dB)
- lead / costs
- easy manufacturing
- [two stage SQUID]
- strong coupling
- low noise background
- redundancy

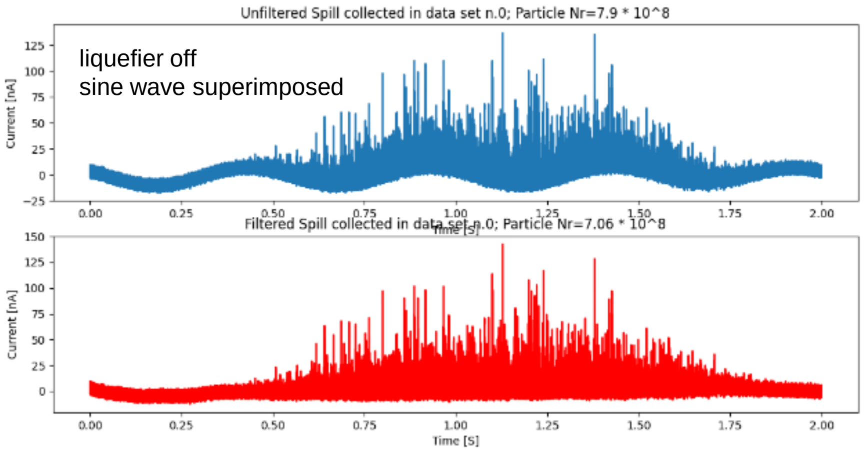


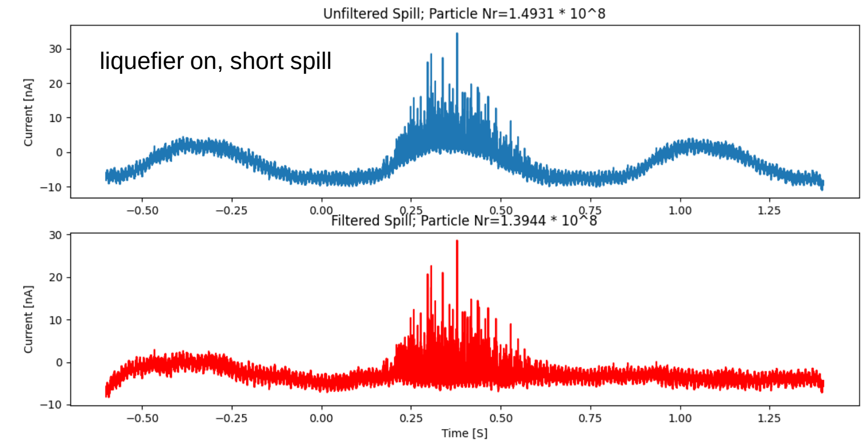
Crescimbeni et. al. 2023, Beam: U^{73+}, 2*10^9,200 MeV/u, t_{extr} 50 ms – 1 s; Magnicon SQUID + electronics

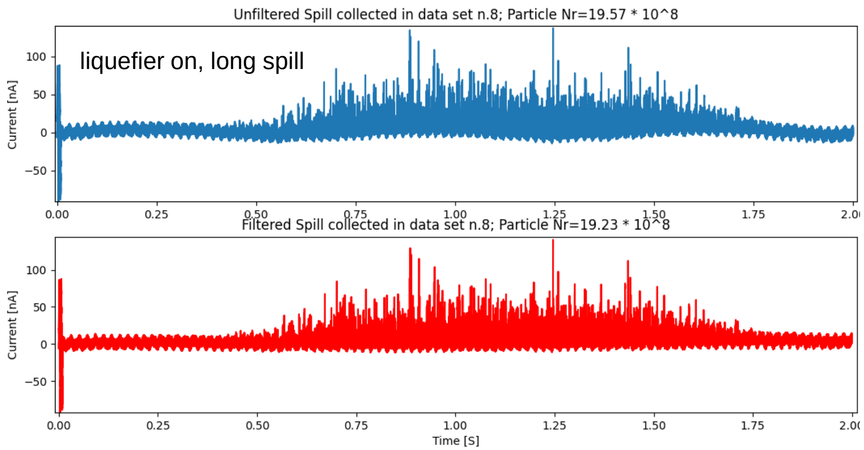
Experimental Setup

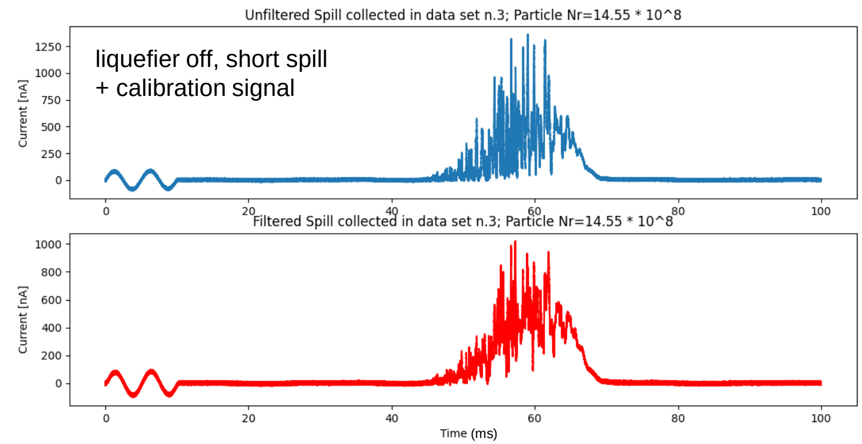


Eliminating Pertubations, investigation of filtering effects (spill shape, particle numbers) …

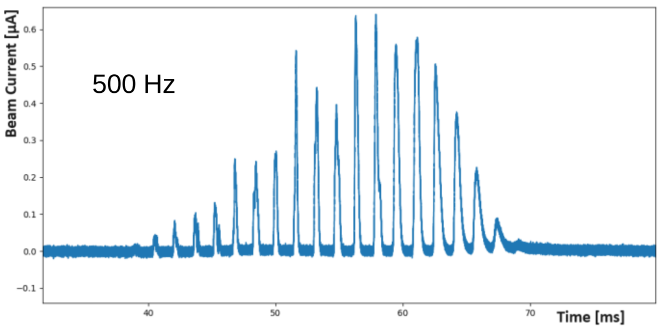


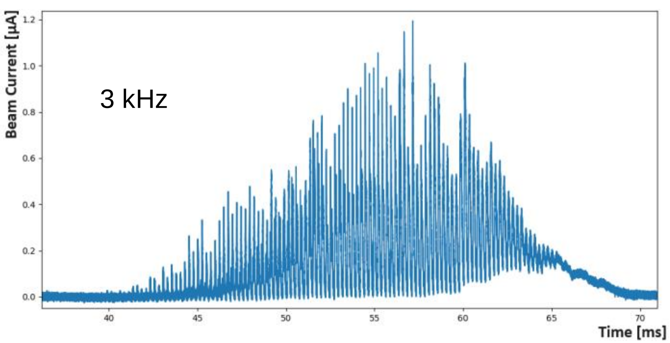


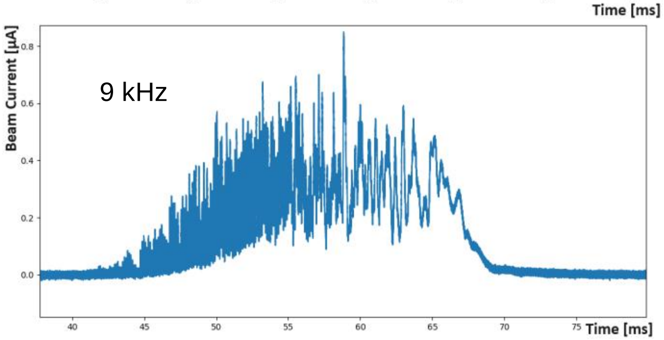




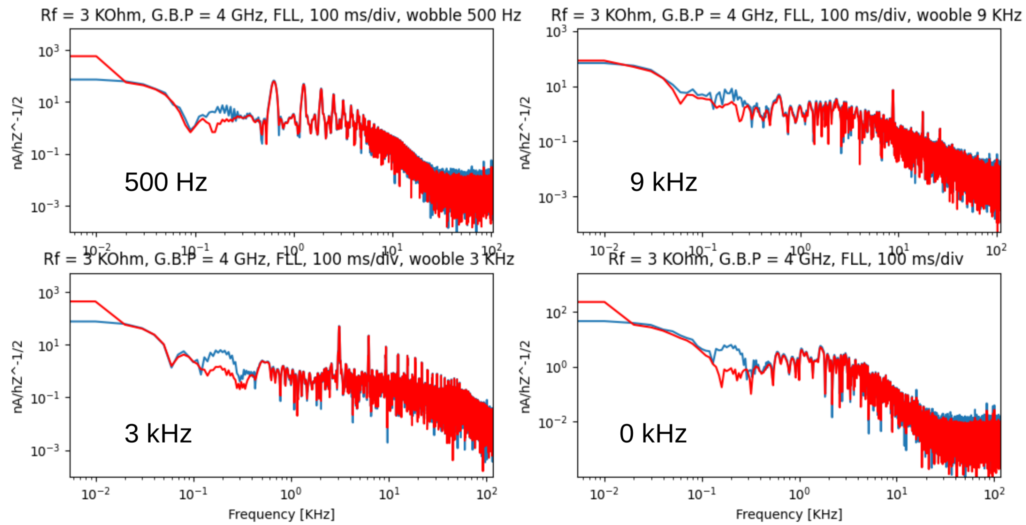
Analysis of spill optimization, tune wobbling …



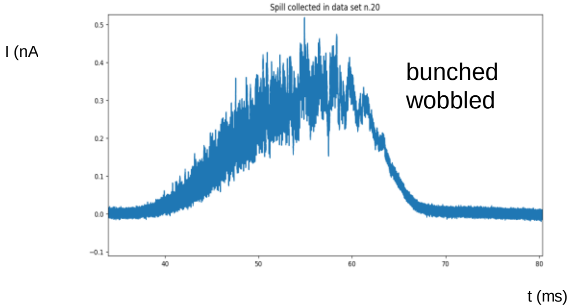


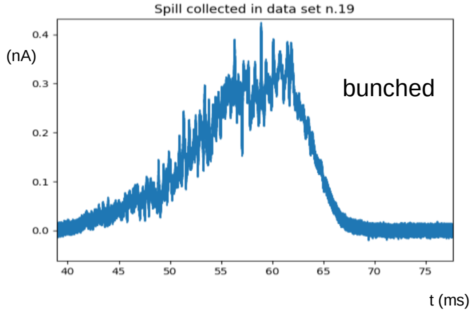


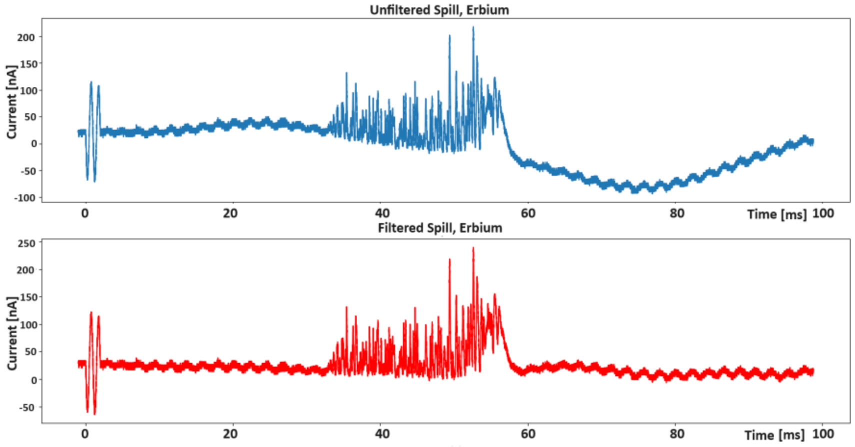
FFT spectra for different wobbling frequencies



… and bunching

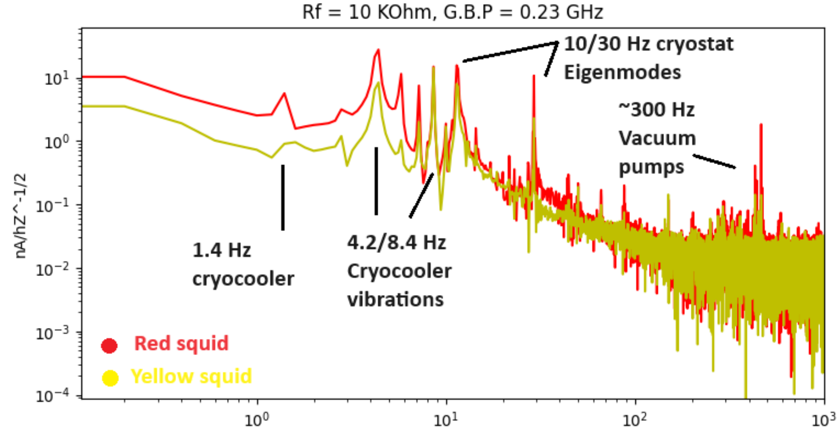






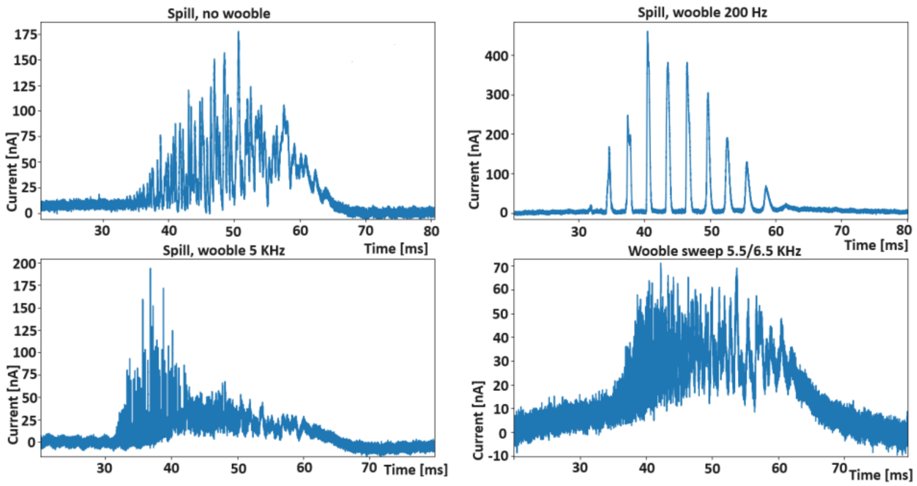
Beam: Er^{57+}, ~$5*10^8$pps, 400 MeV/u, t_{extr} 20 ms – 1 s

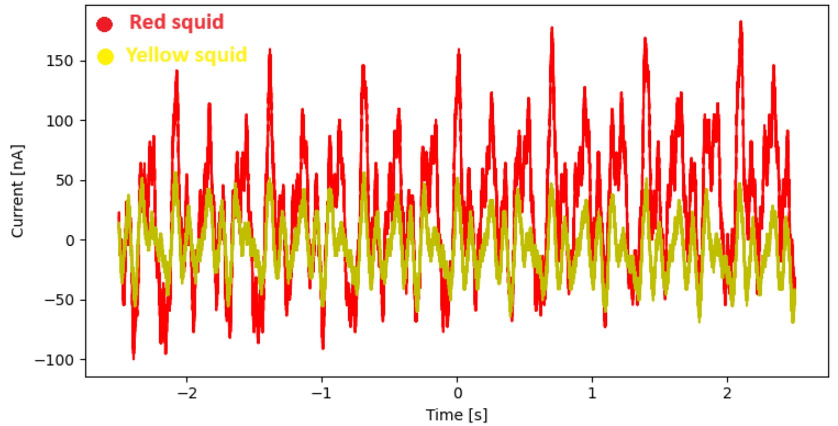
FFT from Er beam

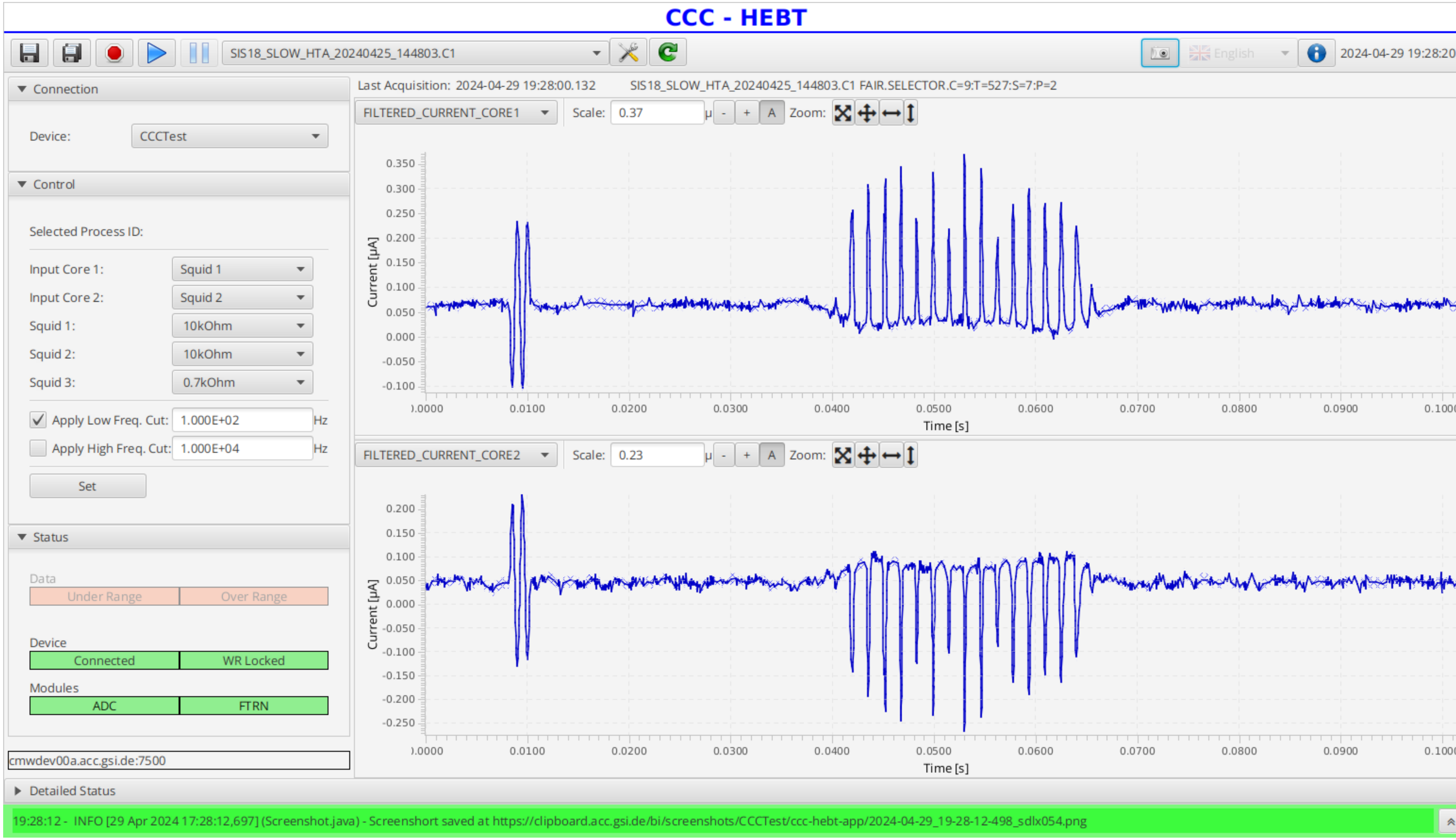


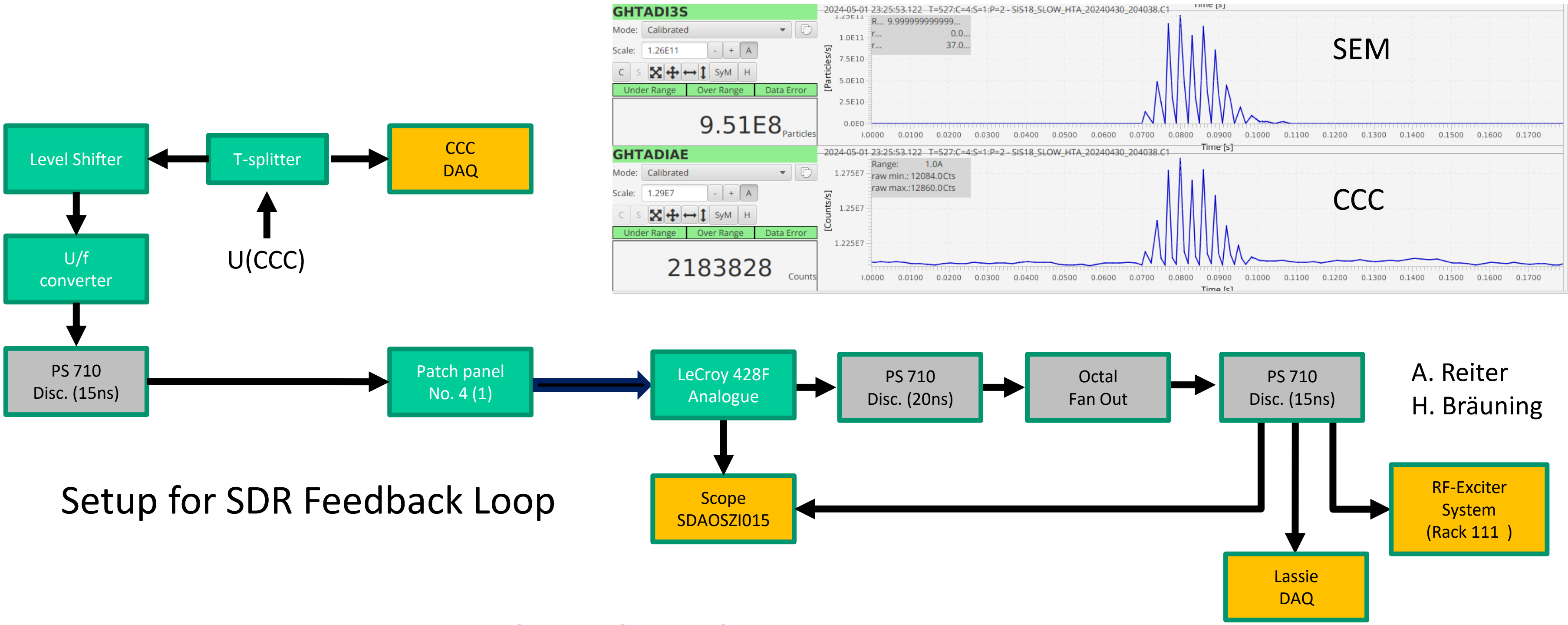
Test of tune „wobbling“ with Ar beam

Beam: Ar^{18+}, ~$3*10^9$pps, 400 MeV/u, t_{extr} 50 ms – 2 s



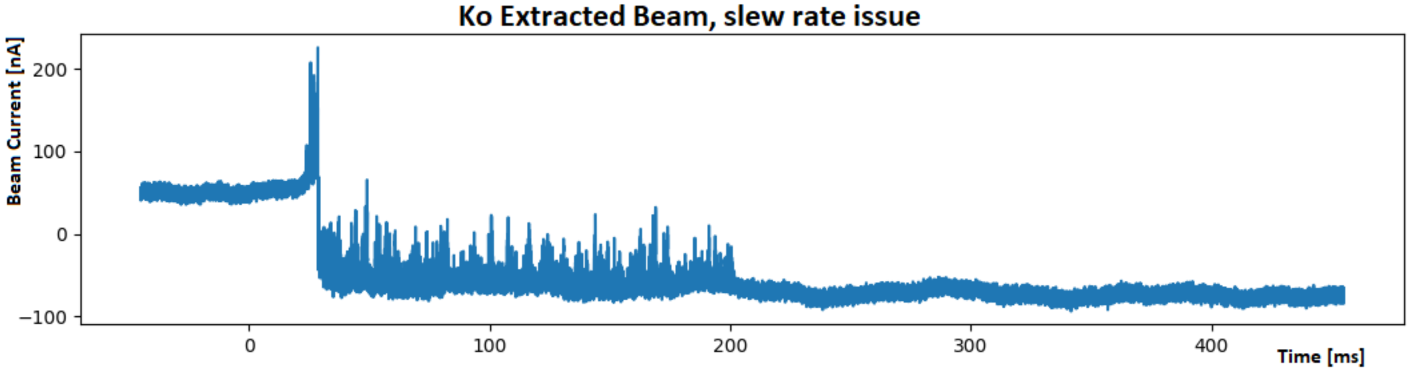



CCC - HEBT
SIS18_SLOW_HTA_20240425_144803.C1
English
2024-04-29 19:28:20
Connection
Device: CCCTest
Control
Selected Process ID:
Input Core 1: Squid 1
Input Core 2: Squid 2
Squid 1: 10kOhm
Squid 2: 10kOhm
Squid 3: 0.7kOhm
Apply Low Freq. Cut: 1.000E+02 Hz
Apply High Freq. Cut: 1.000E+04 Hz
Set
Status
Data
Under Range
Over Range
Device
Connected
WR Locked
Modules
ADC
FTRN
cmwdev00a.acc.gsi.de:7500
Last Acquisition: 2024-04-29 19:28:00.132 SIS18_SLOW_HTA_20240425_144803.C1 FAIR.SELECTOR.C=9:T=527:S=7:P=2
FILTERED_CURRENT_CORE1
Scale: 0.37 μ
Zoom:
Current [μA]
Time [s]
FILTERED_CURRENT_CORE2
Scale: 0.23 μ
Detailed Status
19:28:12 - INFO [29 Apr 2024 17:28:12,697] (Screenshot.java) - Screenshort saved at https://clipboard.acc.gsi.de/bi/screenshots/CCCTest/ccc-hebt-app/2024-04-29_19-28-12-498_sdlx054.png



A. Reiter
H. Bräuning

Setup for SDR Feedback Loop



- Flux Jump occurred at both SQUIDS
- Due to spill properties at Ar beam or general problem?
- Once CCC works filtering in FESA will provide good signal

Lessons learned from HTA Beamtime

- Dual Core CCC successfully operated in Testinghalle and with beam in Cave A
no significant performance reduction from lab to beamline

- direct comparison with CCC XD shows comparable behavior/resolution
or better

- idea of dual-core noise subtraction works (partially)
→ symmetry of the system must be improved

- spill measurements performed for different extraction times → filtering
spill optimization (tune wobbling) could be analyzed in detail

- feedback for spill optimization of KO extracted beam did not work out

- HEBT CCC FESA was available during beamtime, to be completed

Todos:

- improve symmetry of the DCCC, introduce matching transformer for adjustment
- longer standing time → new thermal shield, new liquefier
- improved signal processing and filtering required

Summary and Outlook

- CCC focus at FAIR changed from storage rings to transport sections → FAIR Early Science … FS, FS+ scenarios
- CCC-XD successfully operated in storage rings and transport lines, nA and spill measurement could be demonstrated, system fulfils FAIR requirements (almost)
- Beamtime in Dec. 2023 showed capability for online spill analysis
- Axial CCC type provides excellent magnetic shielding, but is extremely noise sensitive
- Dual core CCC combines advantages of both systems and will be the choice for FAIR
- DCCC successfully tested with beam, operation as detector for feedback system did not work out (so far)

Current activities:

- New thermal shield test (June 2024)
- Liquefier test (June 2024) → collaboration with TransMIT Gießen?
- FESA class development ongoing, including filtering, online data processing and SQUID controls (and input for spill optimization)
- finalization of DCCC design
- collaboration with FH Jena for advanced signal processing
- purchasing of cryostat for 2nd CCC end of 2024

….. slow controls (Simatic) for cryostat, optimization of commercial electronics → whenever ressources available

- **HI Jena**: Laboratory tests, shielding and SQUID circuit design, SPICE models → signal processing
- **FSU Jena**: Laboratories (cold lab, EMV shielded), administration (BMBF appl.)
- **IPHT Jena**: SQUID development and production, SQUID electronics, magn. shield
- **TEMF**: Simulations, shielding factors, electrical and mechanical eigenmodes and stability
- **CERN**: Cryostat development, FESA, beamline tests (ring)
- **GSI**: Cryostat, beam test (HEBT/ring), detector development (2 PhD thesis), FESA, electronics optimization

… AND

- **Magnicon**: SQUID electronics, expertise, radiation test; **FH Jena:** Signal processing

Thank you for your attention !

Appendix

Key Development Steps and Achievements 2015 -

- CCC in CERN AD standard diagnostics, commercial electronics, standalone system, ring FESA class incl. SQUID controils

- cryostat for FAIR CCC developed and built up

- CCC-XD for FAIR beamline dimensions designed, produced and tested, cryostat commissioning, commercial electronics optimized (PhD thesis D. Haider)

- in parallel design of axial CCC and DCCC, both built from lead

- systematic investigation of noise behavior, magnetic cores – all CCC types

- test of axial CCC prototypes in Jena (thesis D. Haider and L. Crescimbeni)

- development of DCCC (PhD thesis M. Stapelfeld, Jena))

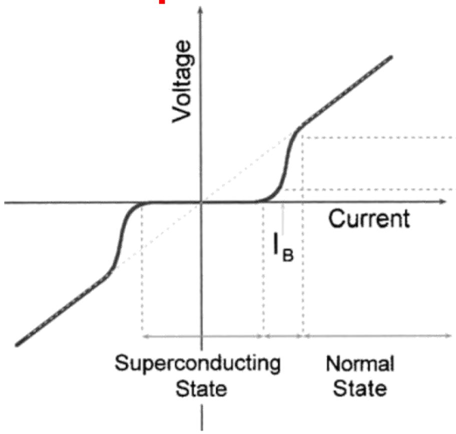
- laboratory- and beamtest of DCCC, HEBT FESA class started (PhD thesis L. Cresciembeni)

Next steps: ES FAIR CCCs and CCC for ELENA and SPS extraction Lines

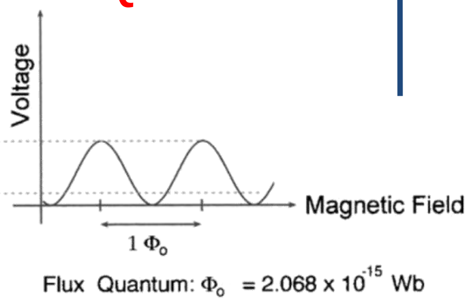
CCC Working Principle II

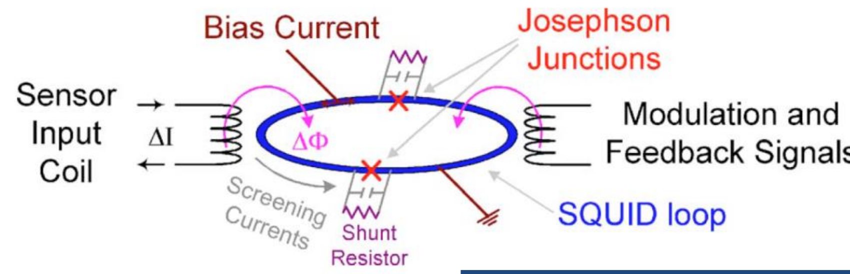
SQUID principle uses two quantum effects:

Josephson Effect



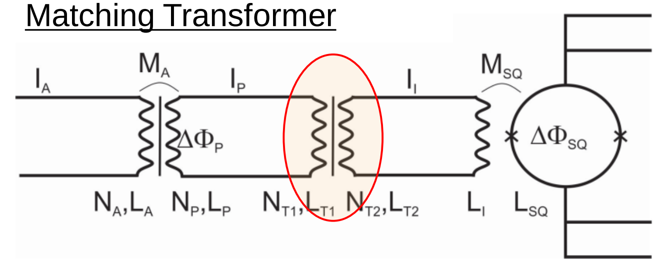
Flux Quantisation



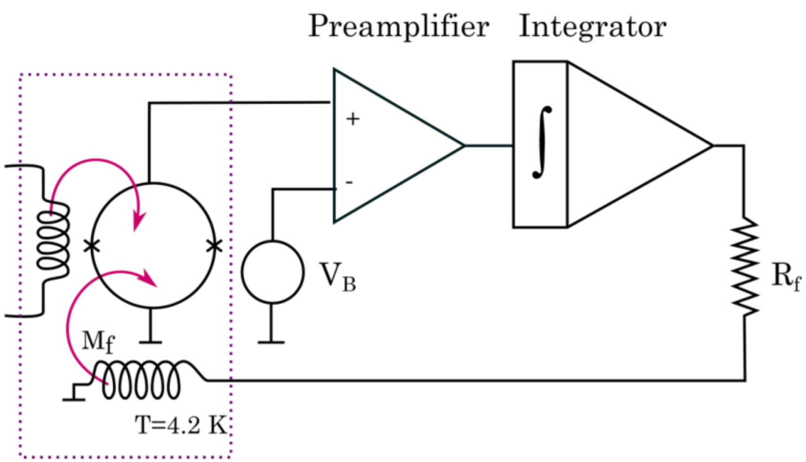


Courtesy R. L. Fagaly, Tristan Techn.

Matching Transformer



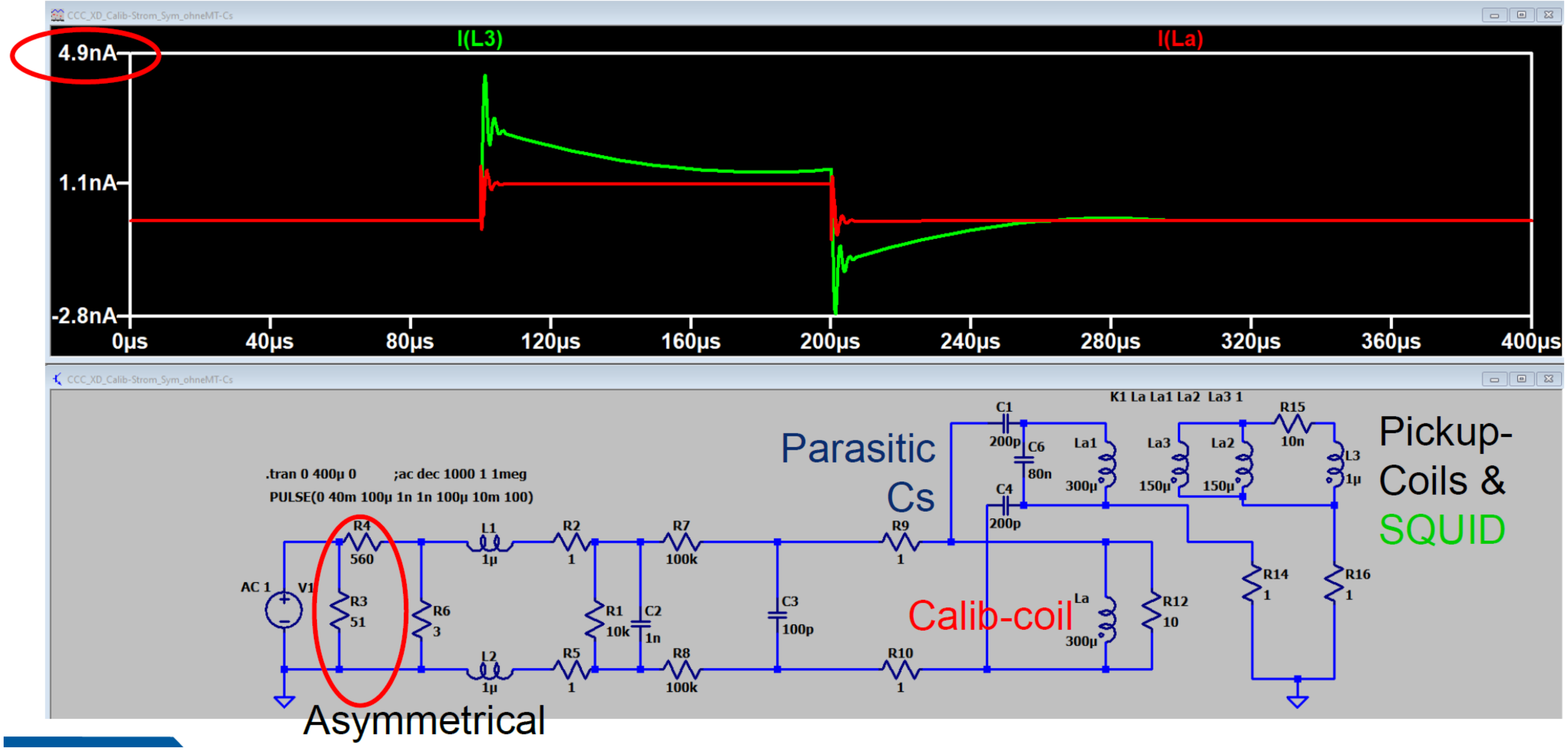
Schematic of the FLL /SQUID electronics



SQUID Cartridge

CHALLENGE: LOW TEST CURRENT

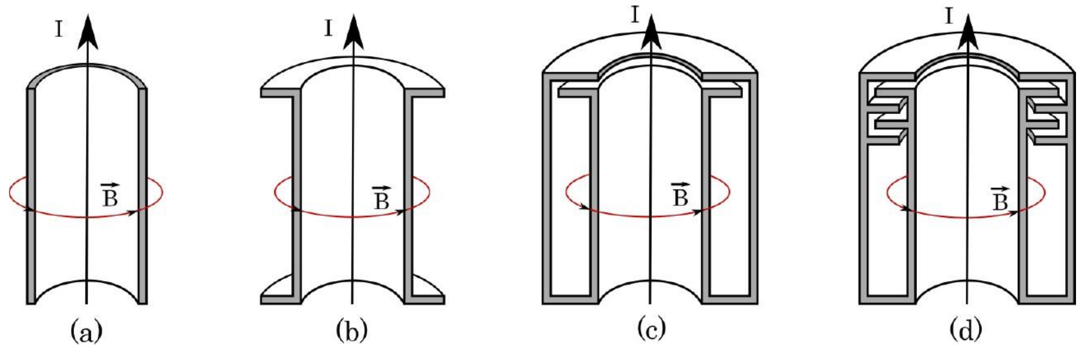
Pb-DCC-Sm-300

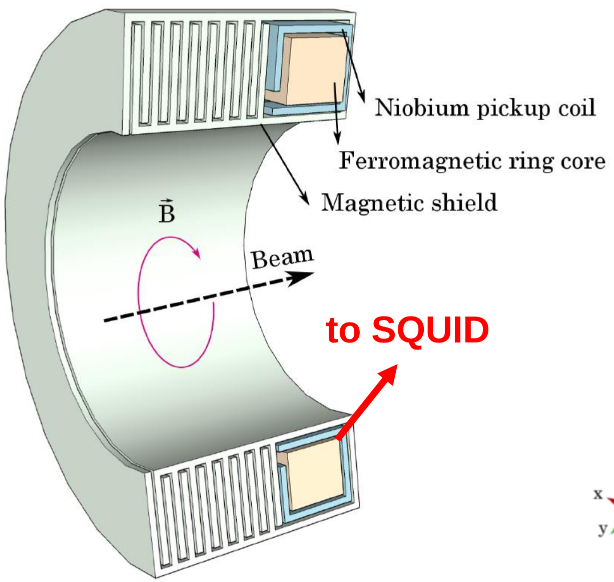


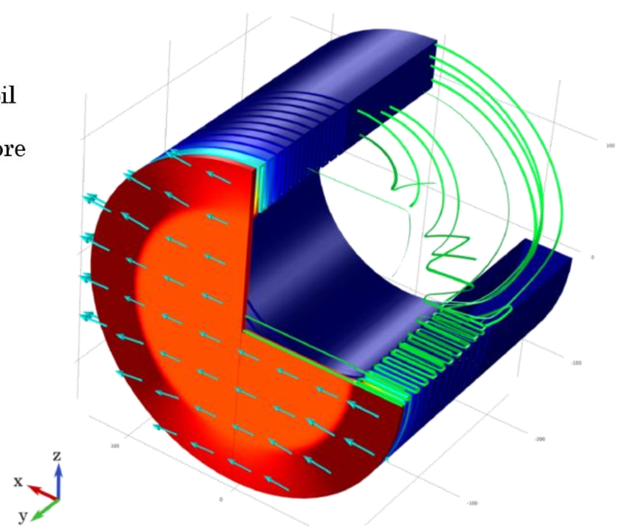
Evolution from cylindrical over coaxial tp meandrical shielding

<u>Analytical approach by PTB:</u>

→ Damping is function of radius ratio (R_{out}/R_{in}) and number of meanders







COMSOL + Microwave-Studio calculations for field penetration into the shielding

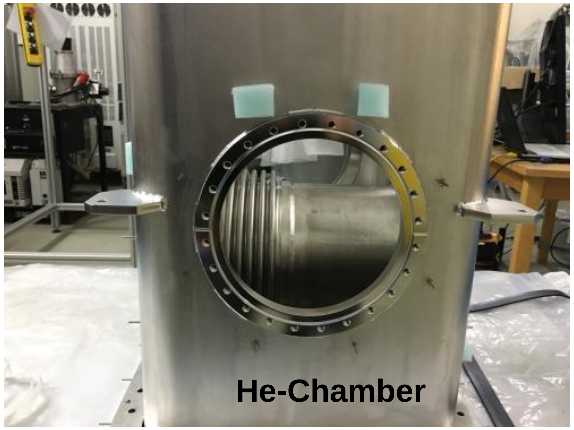
<u>Example Dipole field:</u>

Attenuation achieved:
~75 dB

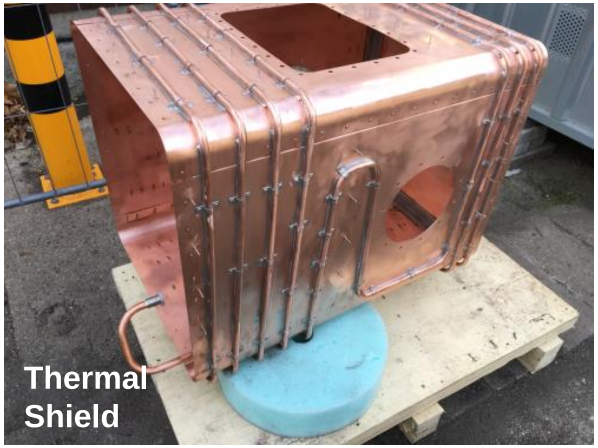
BUT:
Beam field (10nA): 50 fT
Earth magn. field: 50 µT

Production of the CRYRING Cryostat

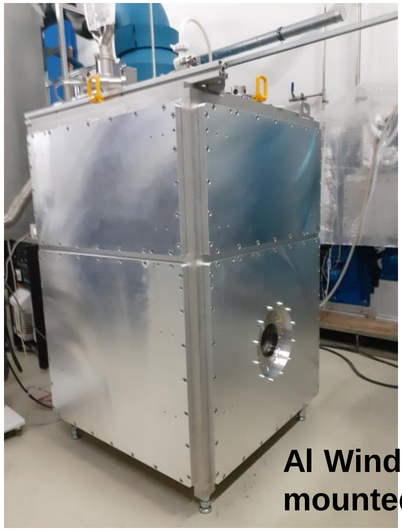
Frame



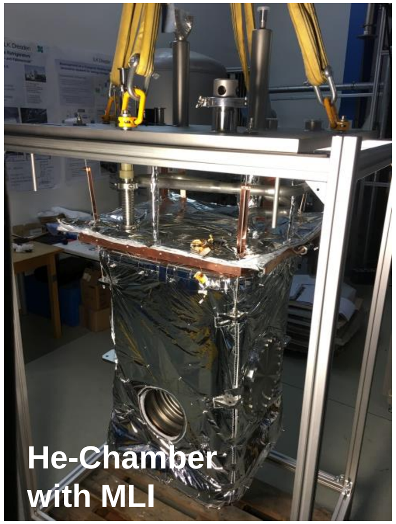
He-Chamber



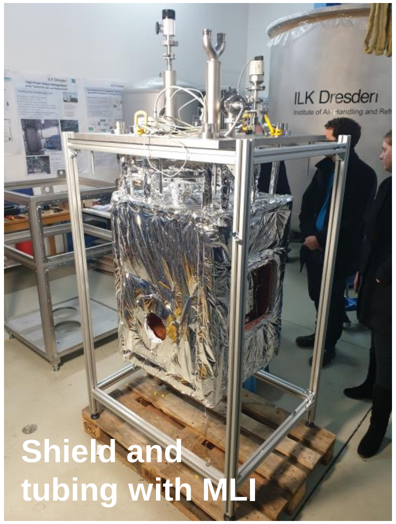
Thermal
Shield



Al Windows
mounted

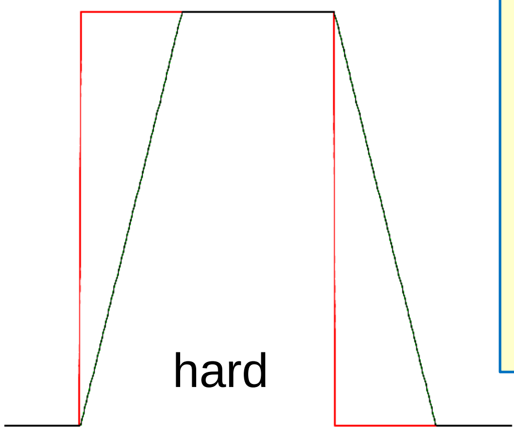


He-Chamber
with MLI

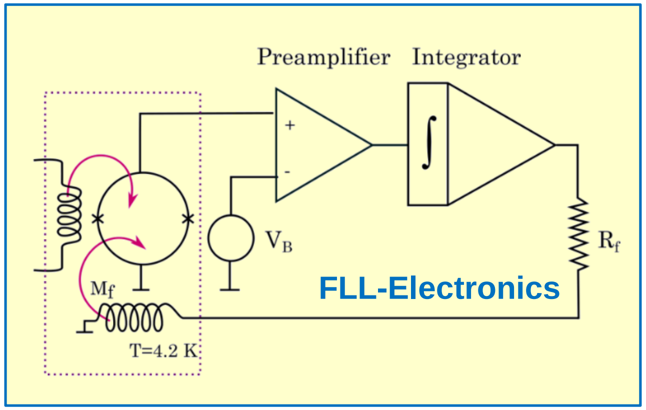


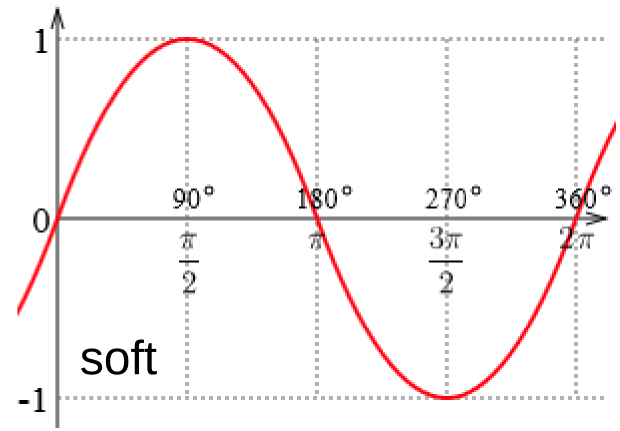
Shield and
tubing with MLI

Tolerable rise time of pulses in flux locked mode → Slew Rate



$$SR = \max\left(\left|\frac{dI_{out}(t)}{dt}\right|\right)$$





$$I(t) = I_{max} \cdot \sin(2\pi \cdot f \cdot t)$$

$$\max(|\dot{I}|) = \dot{I}(t=0) = |2\pi \cdot f \cdot I_{max} \cdot \cos(2\pi \cdot f \cdot t)|_{t=0}$$

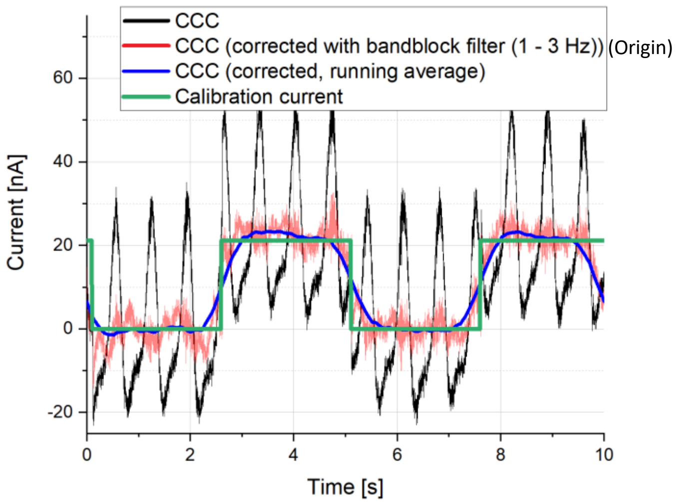
$$SR = 2\pi \cdot f \cdot I_{max}$$

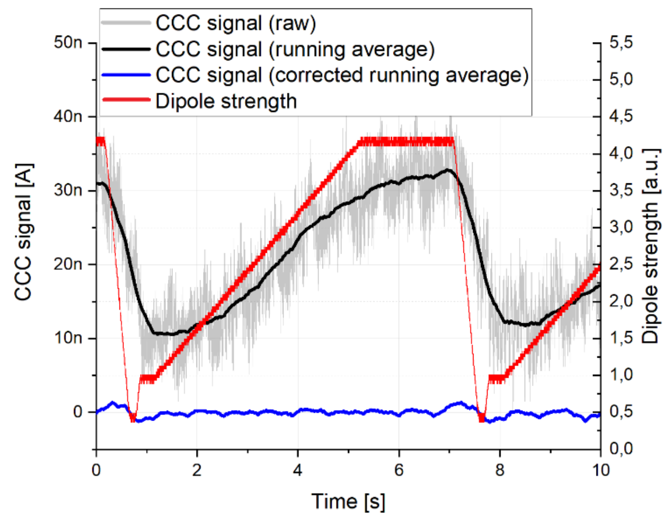
direct: 260 nA @ 200 kHz
=> 0.33 µA/µs

balanced: 130 nA @ 200 kHz
=> 0.16 µA/µs

Beam Operation: Pertubations and Filters

Main disturbances: liquefier pulse + dipole ramp





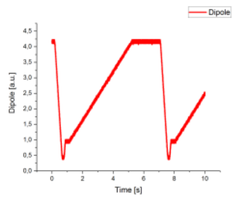
Dipole ramp

deterministic:
subtracted using
transfer function

Signal from helium refrigerator (1.4 Hz)

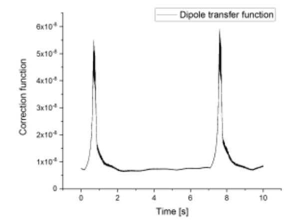
(no mechanical coupling!)

dipole field



x

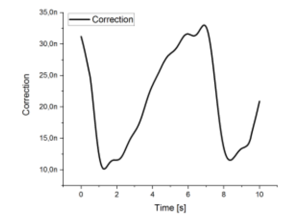
transfer function



calculated from
background measurements

=

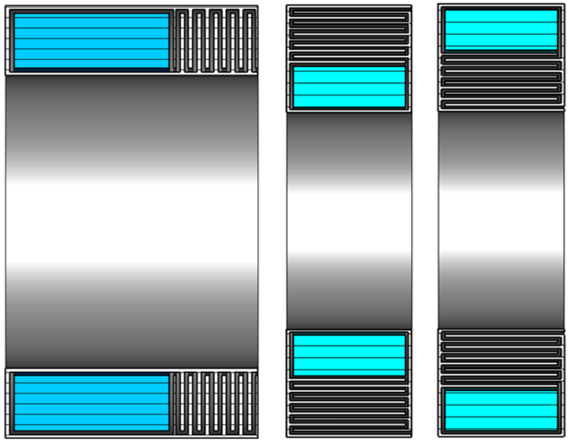
correction

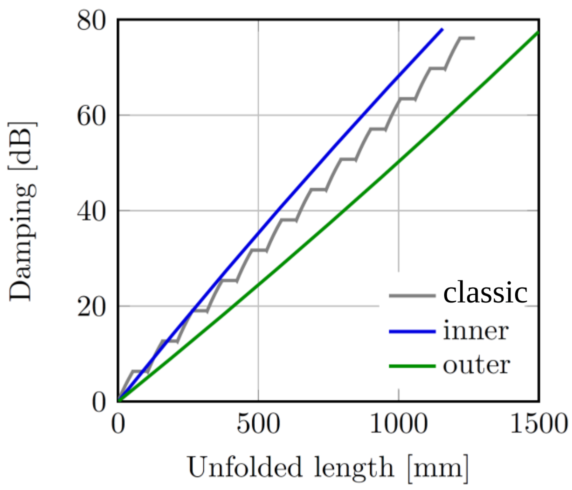


<u>Simulations performed with MWS to check shielding properties</u>

<u>Assumptions:</u>

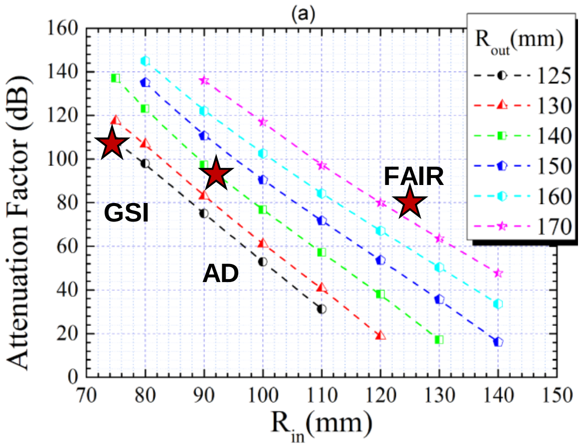
- Material = perfect diamagnet
- Shield currents + toroid not included
- Homogeneous dipole field used
- Real meander geometry used





<u>Shielding design for the FAIR and AD CCC</u>

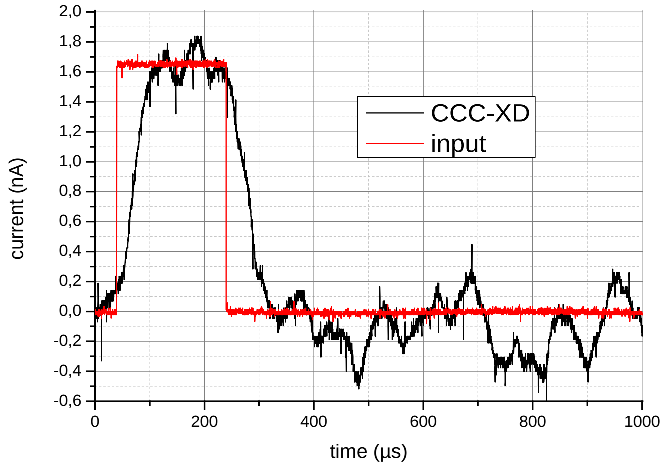
- Attenuation decreases for larger R_{in}
- For given R_{in}: Attenuation increases for larger R_{out}
- R_{out} related to total shield mass and cryostat dimensions

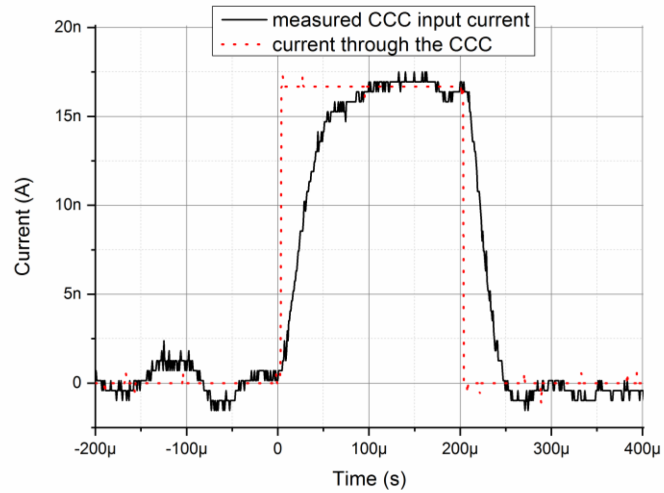


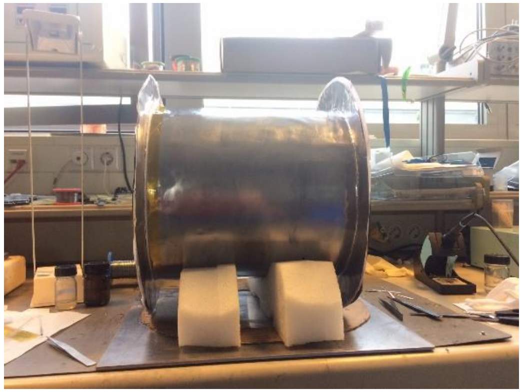
- Number of meanders increases attenuation
- CCC-Prototype: R_{in}=75 mm, R_{out}=125 mm → Att. 108 dB
- FAIR-CCC: R_{in}= 125 mm, R_{out}=175 mm → Att. ~ 80 dB

→ 4 more meanders required for comparable attenuation

Laboratory Tests: Comparison of CCC Types







Temperature / Pressure Offset Drift

Offset temperature/pressure dependence

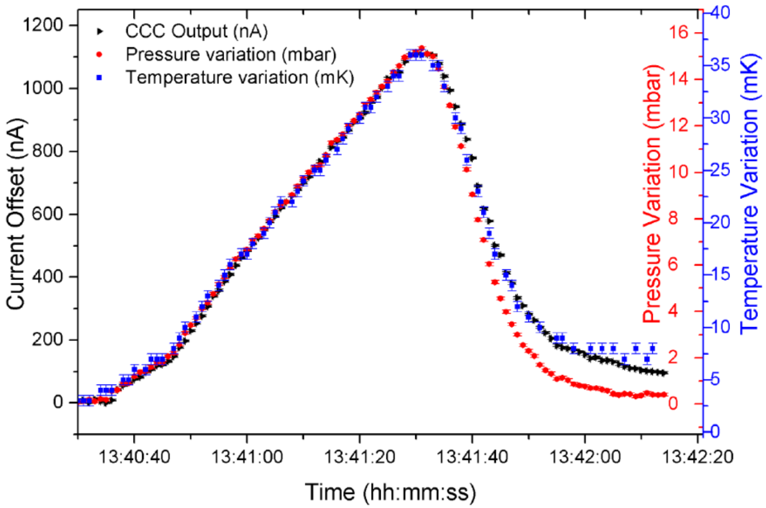
- Baseline drift of ~1nA/s observed during beam tests, curve flattens when thermal equilibrum is reached

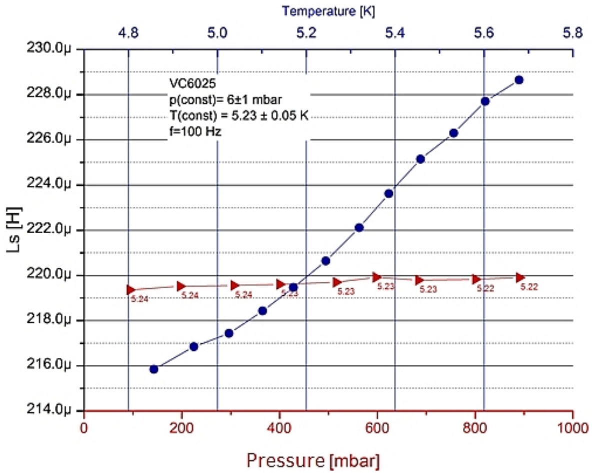
- If T/P effect, high relevance due to backpressure + fluctuations from recovery lines
→ offline tests with closed exhaust line

- Effect investigated at Jena with 'anticryostat' setup, decoupling T and P

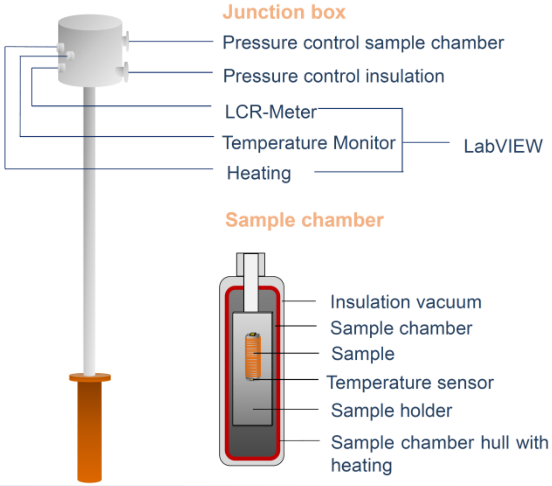
Reason identified as T-dependent inductance variation

→ can this be avoided ? → coreless CCC ?

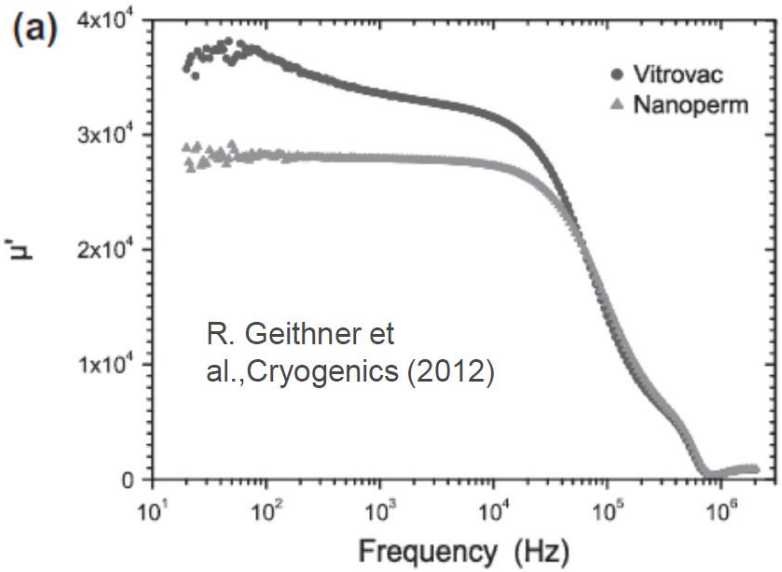


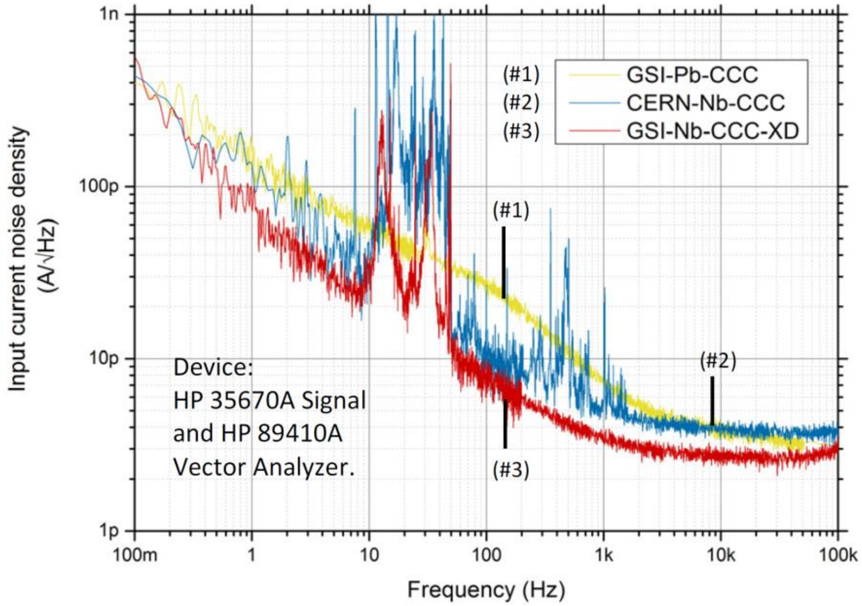


Experimental setup: anticryostat



Laboratory Tests: Core Materials





(# 1) amorphous Co-based Vitrovac 6025 → higher relative permeability

(# 2) nanocrystalline Fe-based Nanoperm M764

(# 3) nanocrystalline Fe-based Nanoperm 328 plus

} lower current noise contribution and frequency dependence of the permeability

J. Golm, V. Tympel, FSU / HIJ

IPHT cross type JJ technology

sub µm thickness
low junction capacitance

→ high voltage swings without hysteresis,
→ low noise
→ high tolerable background fields
→ inductance

SQUID	Standard CSBlue	Sub-µm CE1K
L_{SQ} [nH]	0.30	0.18
L_K [µH]	0.32	2.7
$\Delta\Phi_{SQ}/I_A$ [$\mu A/\Phi_0$]	0.21	0.10
Φ_n [$\mu\Phi_0/\sqrt{Hz}$]	≈ 5	≈ 2
Noise performance [$pA/\sqrt{Hz}$]	1.0	0.2

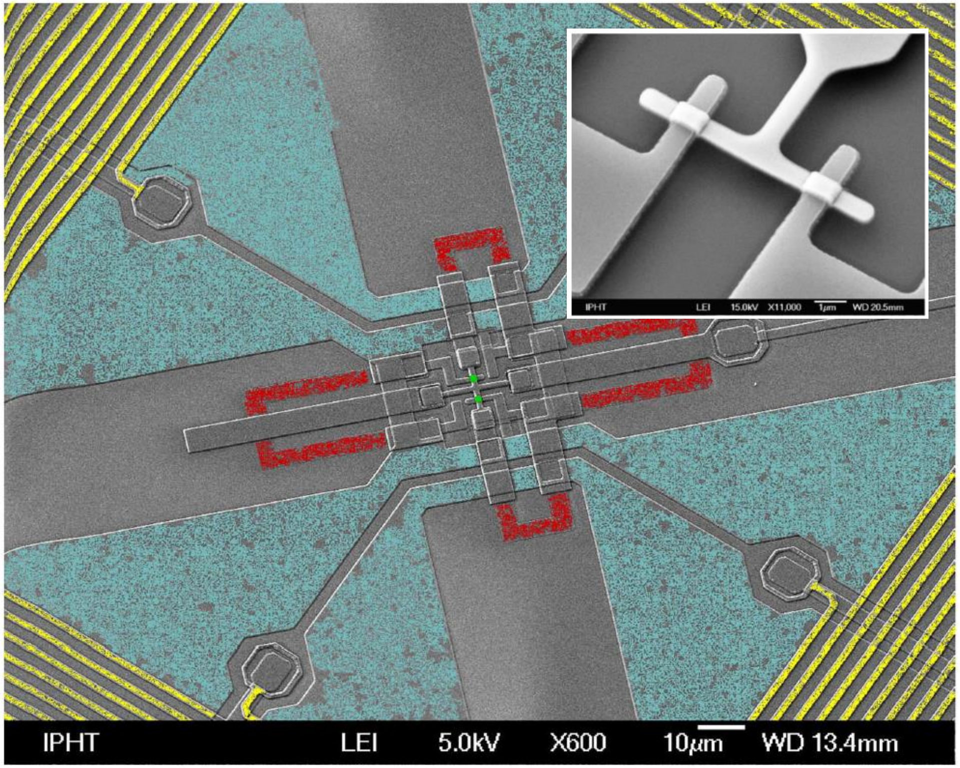


Figure 1. False-colored scanning electron microscope image showing the central part of a SQUID current sensor CE1K34 with the four washers (in light blue) starting in the corners and parts of the input coils (yellow) on top of them. The shunt resistors and washer shunts are shown in red, the Josephson junctions in green, respectively.