24th August, IBIC 2017, Grand Rapids

Thomas Sieber for the CCC Collaboration

Optimization of the Cryogenic Current Comparator (CCC) for Beam Intensity Measurement

Outline

- CCC: Motivation and working principle
- Beam measurements at GSI and CERN/AD
- Thermal drift and system noise
- Numerical calculations for shielding design
- The new CCC for FAIR and CRYRING
- Summary and Outlook

Non-destructive measurement for low intensity beams at FAIR

Examples:

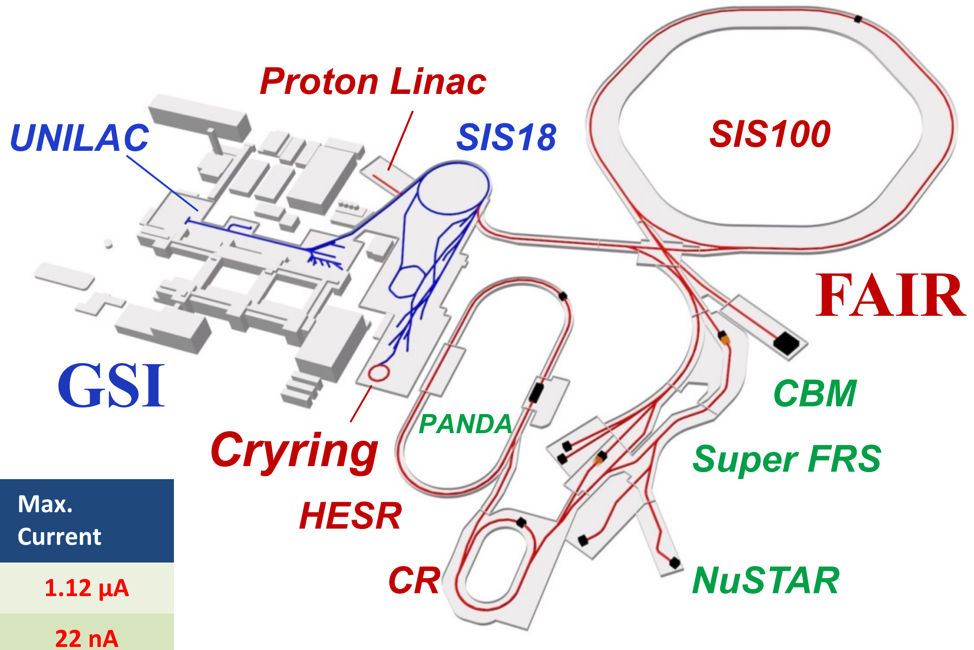
1) Slow extracted beam from SIS100

Extraction time up to 10 s

Cycle	Ion species	Energy	No. of particles	Extraction time	Max. Current
RIB	U^{28+}	2.7 GeV/u	5E11	2 s	**1.12 µA**
CBM	U^{92+}	10.6 GeV/u	1.5E10	10 s	**22 nA**

2) Circulating Beam in Collector Ring (CR)

Mode	Species	Energy	Intensity	Revolution Frequency	Max. Current
pBar	pBar	3 GeV	< 1E8	1.37 MHz	**22 µA**
RIB	U^{28+}	740 MeV/u	< 1E9	1.17 MHz	5 mA
Isochr.	U^{28+}	790 MeV/u	1E8	1.18 MHz	529 µA



CCC at FAIR

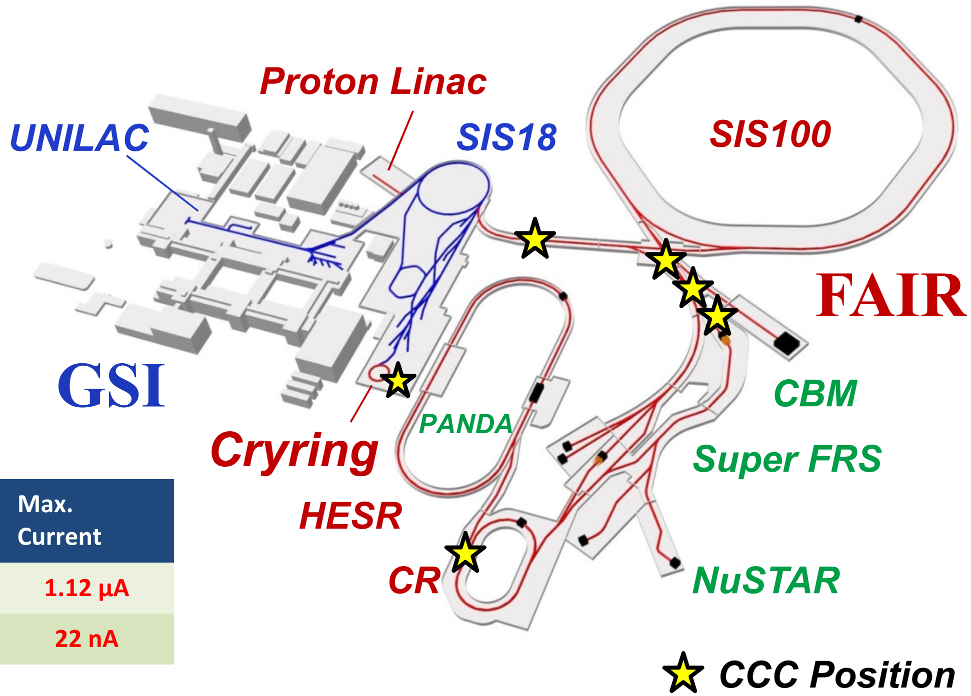
Non-destructive measurement for low intensity beams at FAIR

Examples:

1) Slow extracted beam from SIS100

Extraction time up to 10 s

Cycle	Ion species	Energy	No. of particles	Extraction time	Max. Current
RIB	U^{28+}	2.7 GeV/u	5E11	2 s	1.12 µA
CBM	U^{92+}	10.6 GeV/u	1.5E10	10 s	22 nA



2) Circulating Beam in Collector Ring (CR)

Mode	Species	Energy	Intensity	Revolution Frequency	Max. Current
pBar	pBar	3 GeV	< 1E8	1.37 MHz	22 µA
RIB	U^{28+}	740 MeV/u	< 1E9	1.17 MHz	5 mA
Isochr.	U^{28+}	790 MeV/u	1E8	1.18 MHz	529 µA

CCC at FAIR

Non-destructive measurement for low intensity beams at FAIR

Examples:

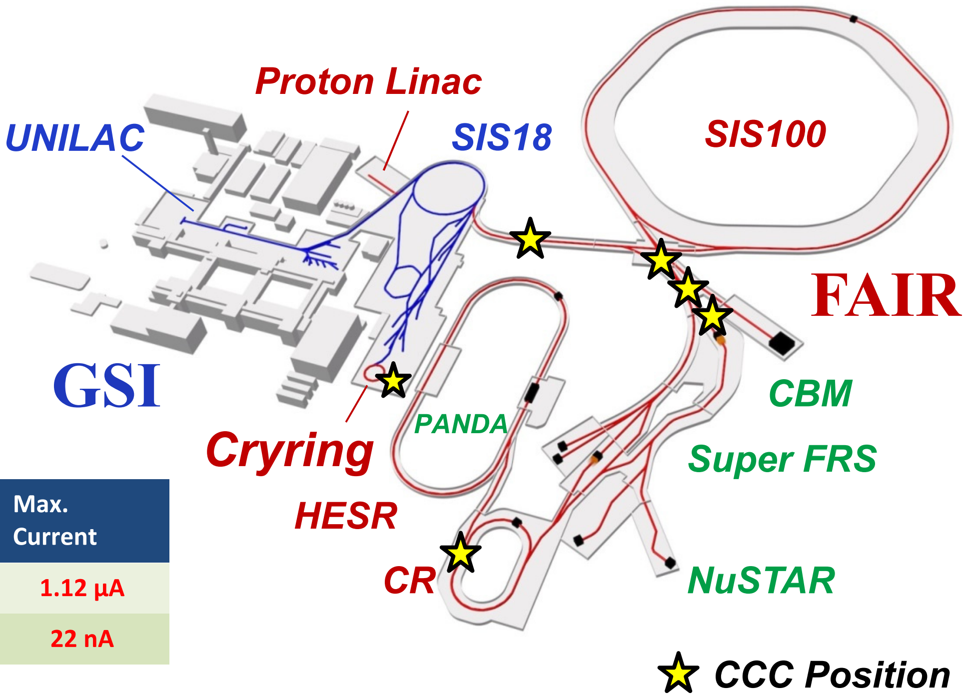
1) Slow extracted beam from SIS100

Extraction time up to 10 s

Cycle	Ion species	Energy	No. of particles	Extraction time	Max. Current
RIB	U^{28+}	2.7 GeV/u	5E11	2 s	**1.12 µA**
CBM	U^{92+}	10.6 GeV/u	1.5E10	10 s	**22 nA**

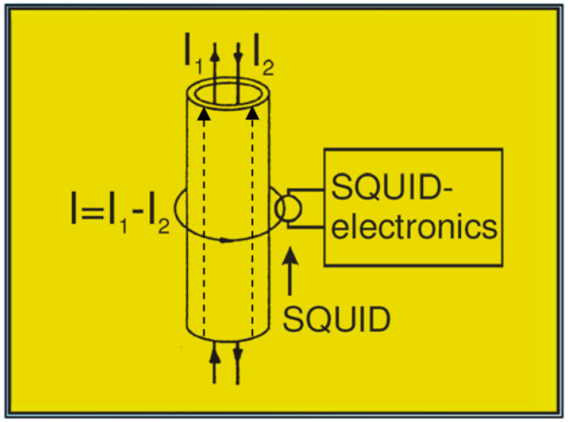
2) Circulating Beam in Collector Ring (CR)

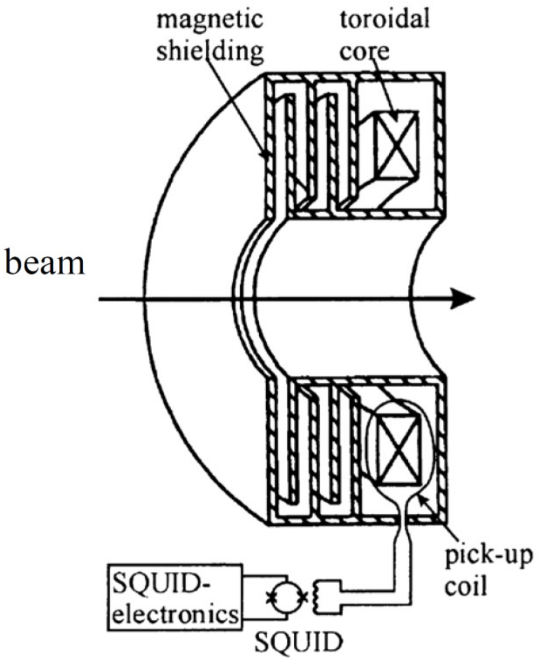
Mode	Species	Energy	Intensity	Revolution Frequency	Max. Current
pBar	pBar	3 GeV	< 1E8	1.37 MHz	**22 µA**
RIB	U^{28+}	740 MeV/u	< 1E9	1.17 MHz	5 mA
Isochr.	U^{28+}	790 MeV/u	1E8	1.18 MHz	529 µA



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

CCC working principle I





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 $\rightarrow$ voltage change

For charged particle beams:

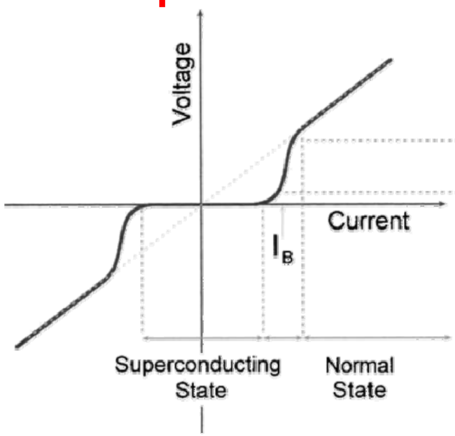
$I_{comp} = I_1 - I_2 = I_{beam} - 0$ (position independent)

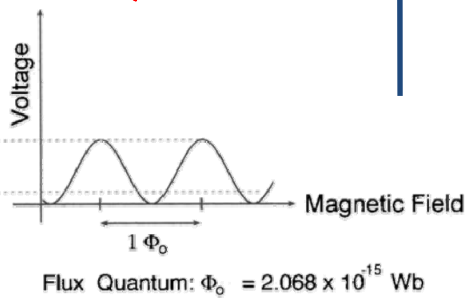
- SC shielding for non-azimuthal fields
- SC pickup coil with toroidal core ($\mu_r \approx 50000$)
- Low noise, high performance DC SQUID + control electronics (FSU Jena) → commercial products (MAGNICON, SUPRACON)
- FLL electronics: → $\mu\Phi_0$ **Res.**

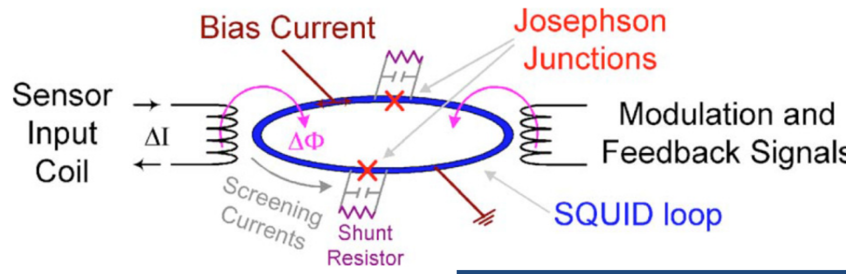
CCC working principle II

SQUID principle uses two quantum effects:

Josephson Effect **Flux Quantisation**

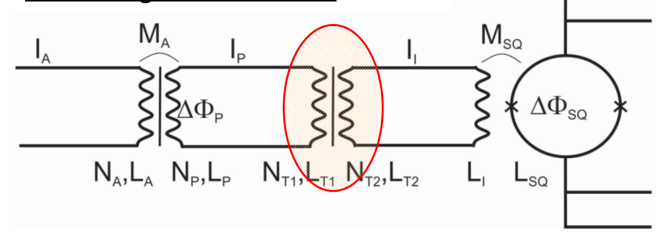




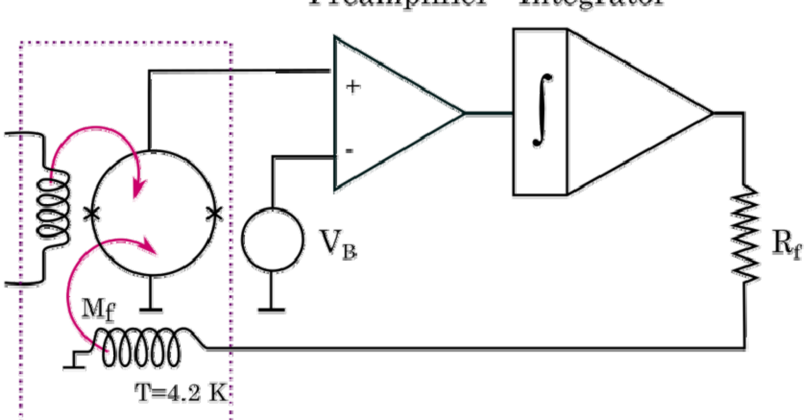


Courtesy R. L. Fagaly, Tristan Techn.

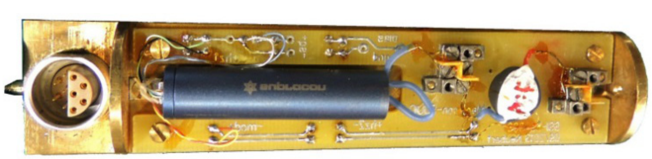
Matching Transformer



Schematic of the FLL /SQUID electronics



SQUID Cartridge



Beam measurements at GSI

Experimental setup

- GSI CCC prototype system refurbished, new vacuum/ cryogenics comp., electrical connections, calibration loop, T-sensors...

- Supracon SQUID installed in combination with Magnicon electronics + readout (VITROVAC toroid)

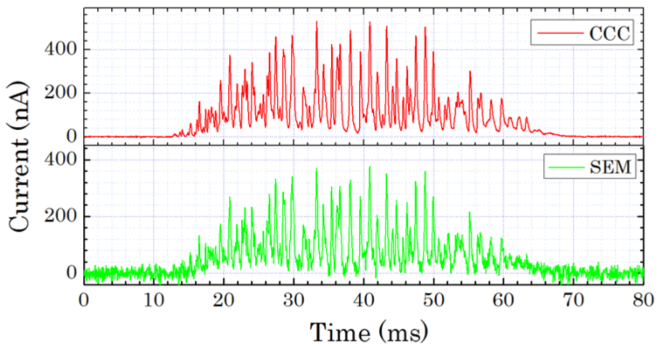
- Manual He filling 30l / 10h

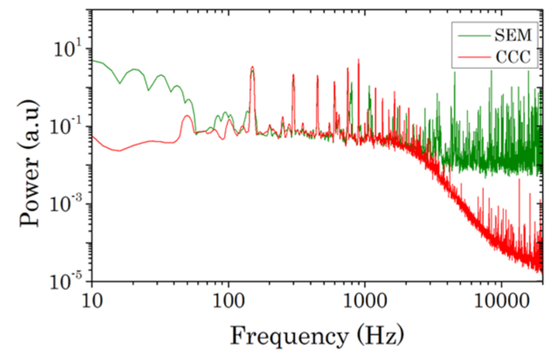
- Installation at BD testbench in SIS18 extraction line
- DAQ = oscilloscope + Laptop for sensors and SQUID

- Beam parameters: 600 MeV/u Ni^{26+}, extr. times 64 ms – 5 s

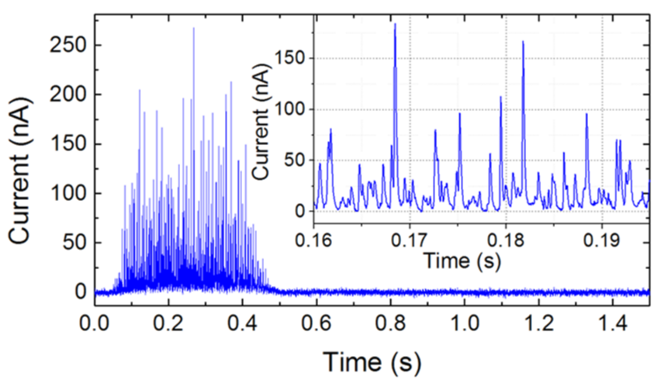
Current resolution (100 Hz):
120 pA/√Hz (old setup 250 pA/√Hz)

Spill measurement with CCC and SEM → FFT spectrum

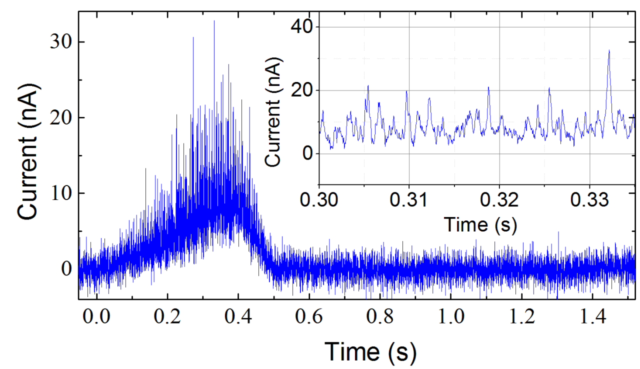




Spill analysis unbunched beam



Bunched beam



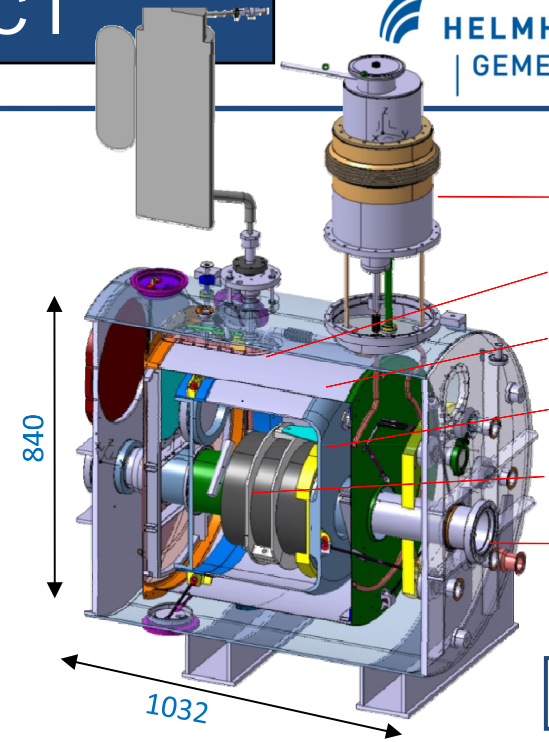
Results from AD CCC I

<u>Collaboration between FSU/HIJ, IPHT Jena, CERN, TU DA and GSI since 2014</u>

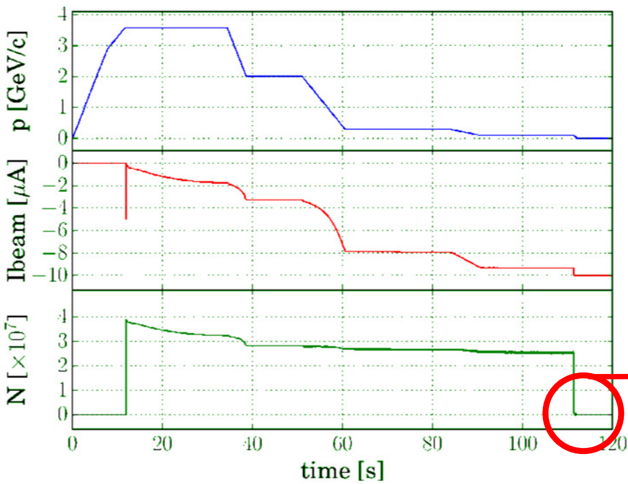
<u>Requirements in AD:</u>
- Intensity measurement alternative to Schottky
- Current resolution: 10 nA
- Bandwidth DC - 1 kHz, slew rate damping
- Stand alone system, integrated in AD control system

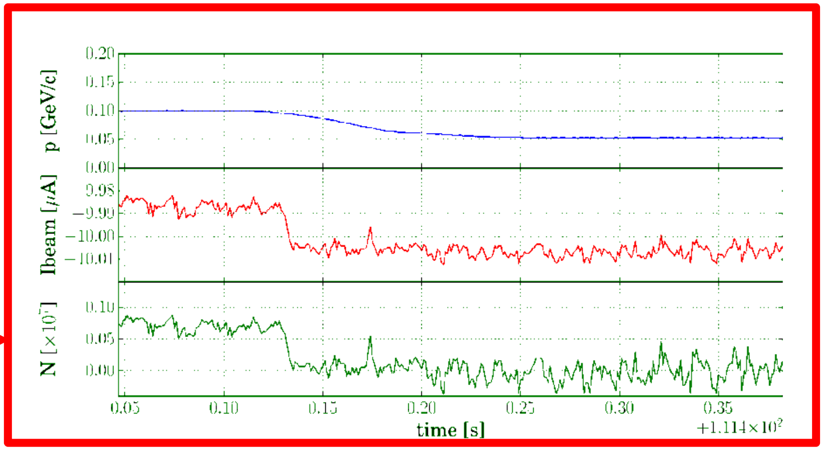
→ Nb shield, 100 mm beamtube (UHV), Magnicon SQUID
→ New cryostat design with improved vibrational damping + reliquefier

<u>Status:</u> ‚Routine' operation in AD, requirements fullfilled
tbd: optimization work on signal processing (AD ramp + pulsed tube cooler), cryostat and electronics



Courtesy A. Lees (CERN)





Courtesy M. Fernandes (CERN)

Temperature / pressure offset drift

Offset temperature/pressure dependence

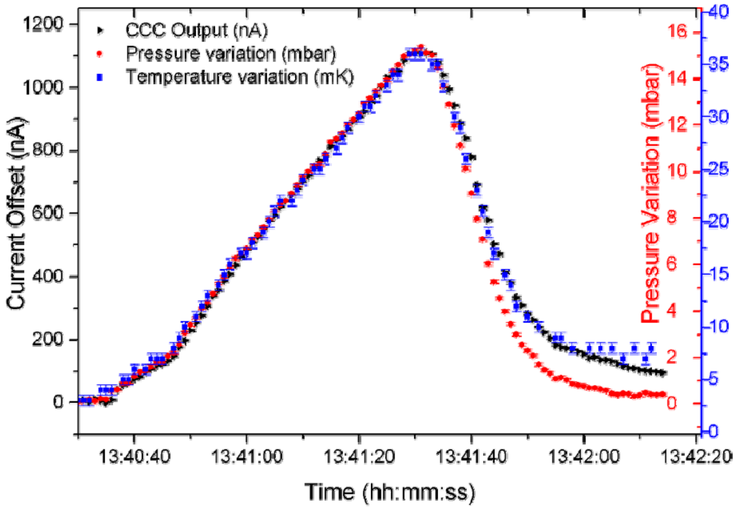
- Baseline drift of ~1nA/s observed during beam tests, curve flattens when thermal equilibrum is reached

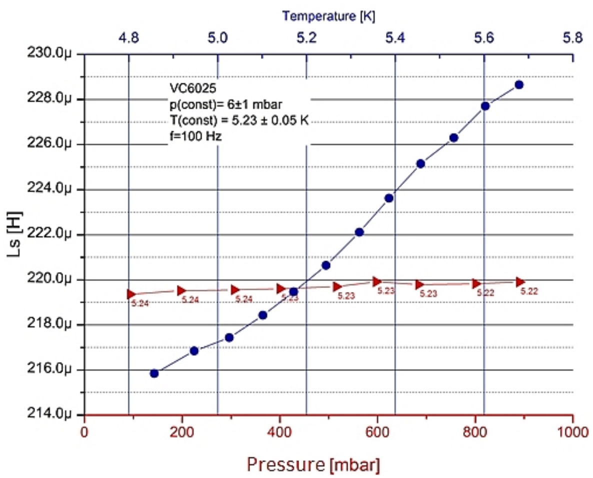
- If T/P effect, high relevance due to backpressure + fluctuations from recovery lines
→ offline tests with closed exhaust line

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

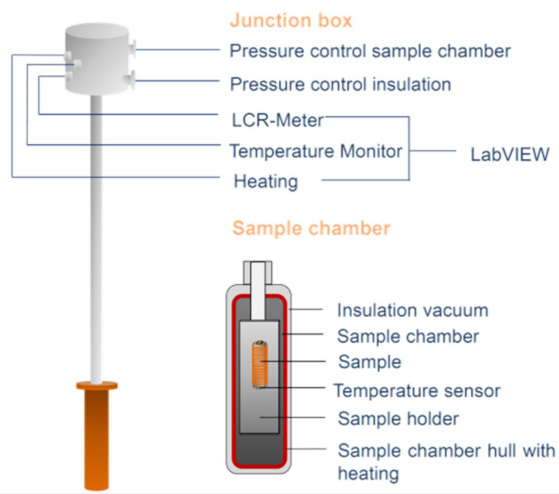
Reason identified as T-dependent inductance variation

→ can this be avoided ? → coreless CCC ?





Experimental setup: anticryostat



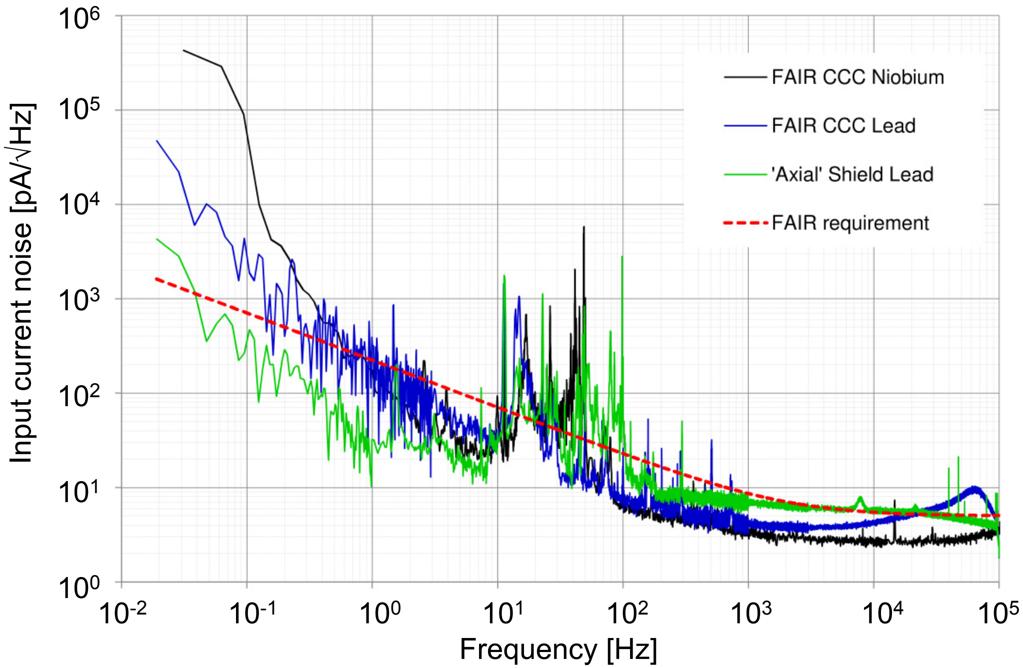
System noise / alternative shielding

Contributions to CCC noise

Setup for intrinsic noise from FAIR CCC and twin system made of Pb ← MSR + additional shielding

Constitutents of noise:

< 0.5 Hz: He boil off, building vibrations, Barkhausen noise
1 Hz - 100 kHz: Ext. influences: Building, **toroid microphony, toroid current noise, vibrations of shielding**
100 Hz - 1 kHZ: System noise without ext. influence



System noise / alternative shielding

Contributions to CCC noise

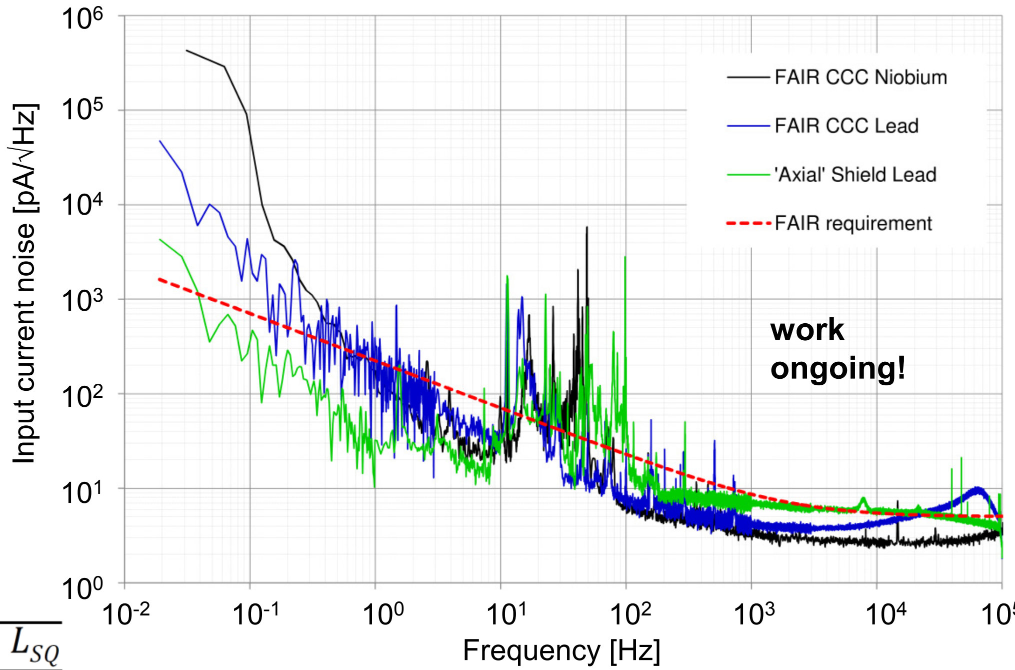
Setup for intrinsic noise from FAIR CCC and twin system made of Pb ← MSR + additional shielding

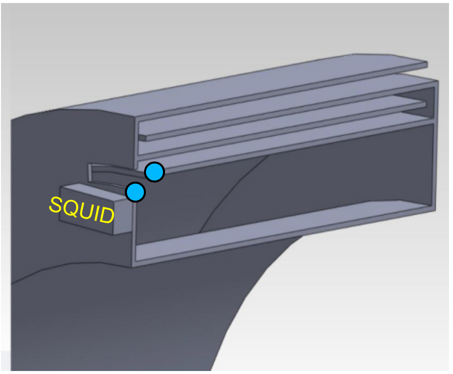
Constitutents of noise:

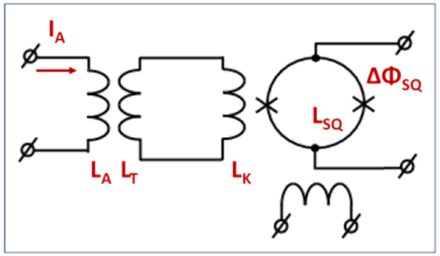
< 0.5 Hz: He boil off, building vibrations, Barkhausen noise
1 Hz - 100 kHz: Ext. influences: Building, **toroid microphony, toroid current noise, vibrations of shielding**
100 Hz - 1 kHZ: System noise without ext. influence

Can the CCC work without a toroid ?

Current to flux transfer: $$\frac{\Delta\Phi_{SQ}}{I_A} = \frac{\sqrt{L_A \cdot L_T \cdot L_K \cdot L_{SQ}}}{L_T + L_{par} + L_K}$$







L_T: 100 µH → 10 nH
Compensated by noise reduction ?

Properties of axial shielding:

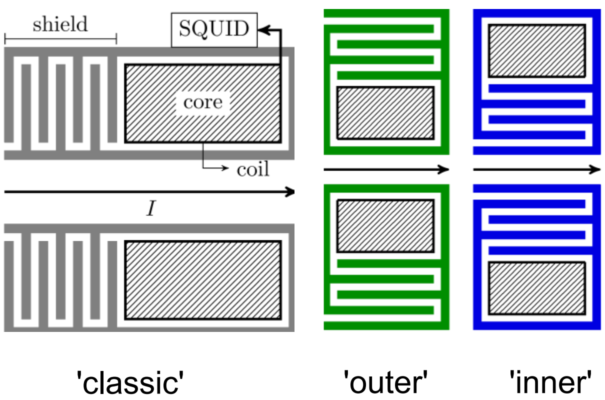
no / reduced thermal drift	reduced sensitivity (?)
no matching transformer (noise)	vibration sensitivity
simplified construction	position dependence (?)
smaller Nb / Pb volume	
lower weight (Nb + toroid)	

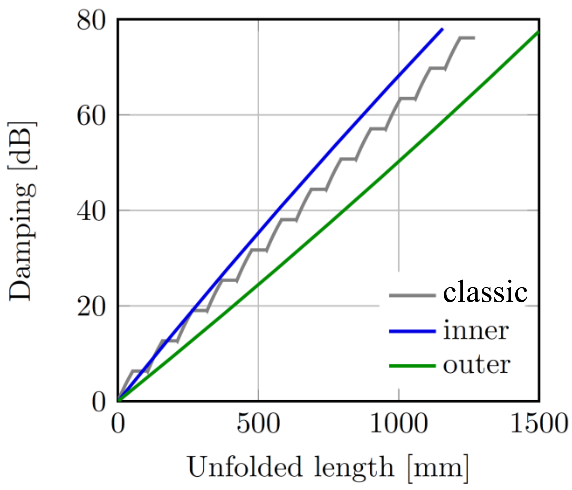
Simulations for shielding design

Simulations performed with MWS to check shielding properties

Assumptions:

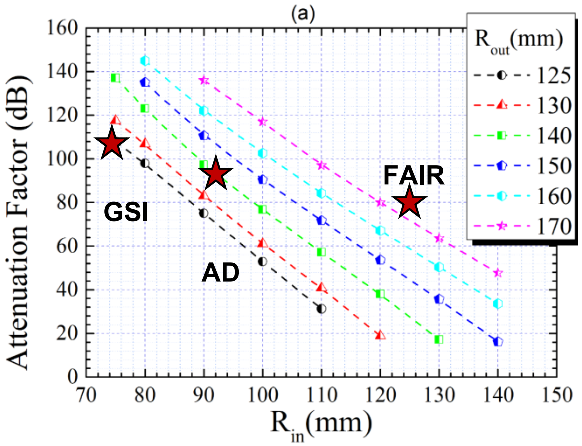
- Material = perfect diamagnet
- Shield currents + toroid not included
- Homogeneous dipole field used
- Real meander geometry used





Shielding design for the FAIR and AD CCC

- 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



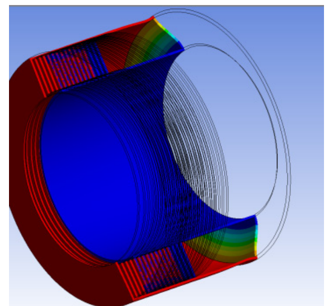
- Number of meanders increases attenuation
- CCC-Prototype: R_{in}=75 mm, R_{out}=125 mm → Att. 108 dB
- FAIR-CCC: R_{in}= 125 mm, R_{out}=175 mm → Att. ~ 80 dB

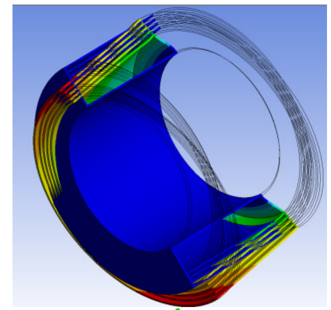
→ 4 more meanders required for comparable attenuation

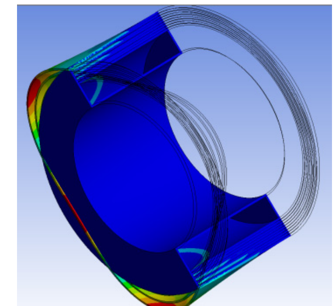
Shielding vibration analysis

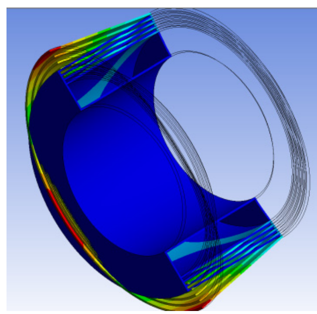
SC shielding mechanical eigenmode analysis

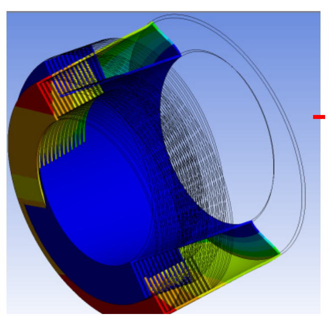
- ANSYS© calculations to identify mechanical modes ≤ 150 Hz
- Geometry:
  Radial: R_i = 120 mm;
  R_{out}=170 mm; Length 204 mm)
  Axial: R_i = 120 mm,
  R_{out}=184 mm; Length 186 mm)
- inner cylinder considered as stable (→ PEEK fittings)
- modes in x and y-direction
  → appear doubled
- tbd: detailed analysis of mode strength and displacement

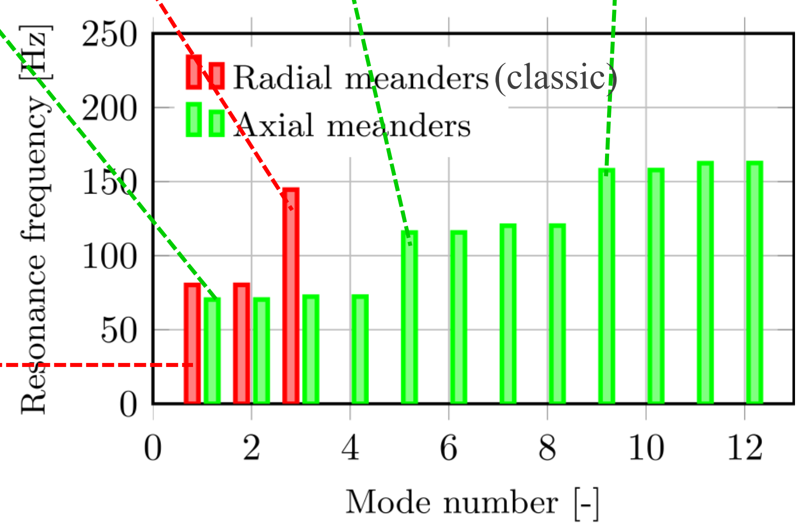








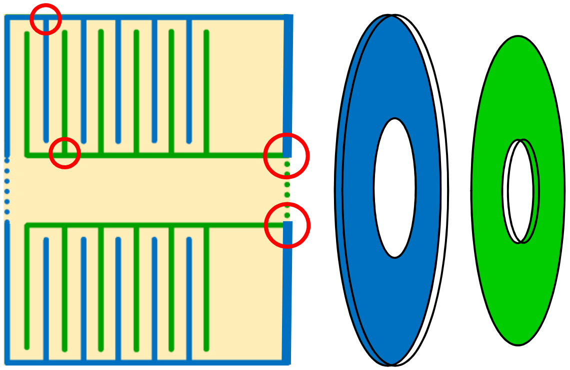




How to suppress shield eigenmodes ?

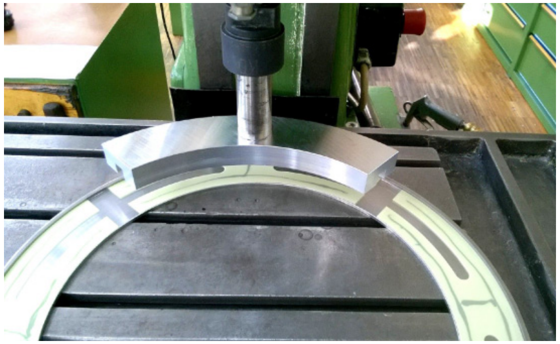
- production process:
  welding inner to inner and
  outer to outer segments

- GFK layer as distance holder



→ **modify GFK layer to avoid radial motion**
→ **change material ?**
→ **cylindrical symmetry required ?**

Outer segment

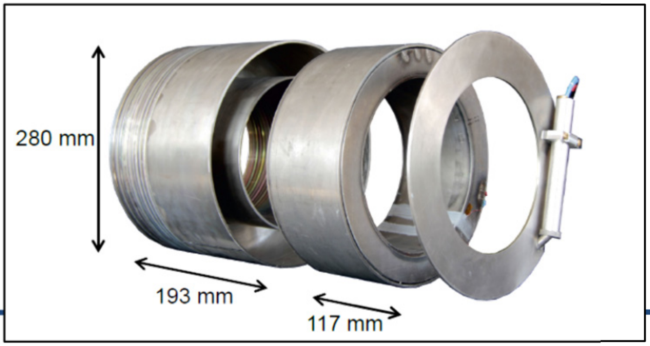


Fixation of GFK spacers

Segment with spacers

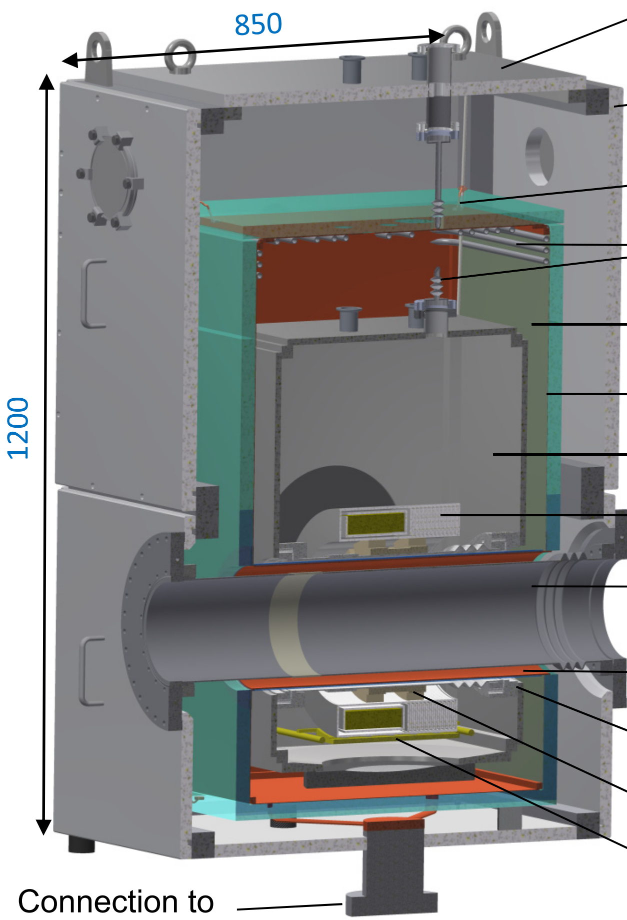
Inner and outer segments welded

Shielding completed (AD size)



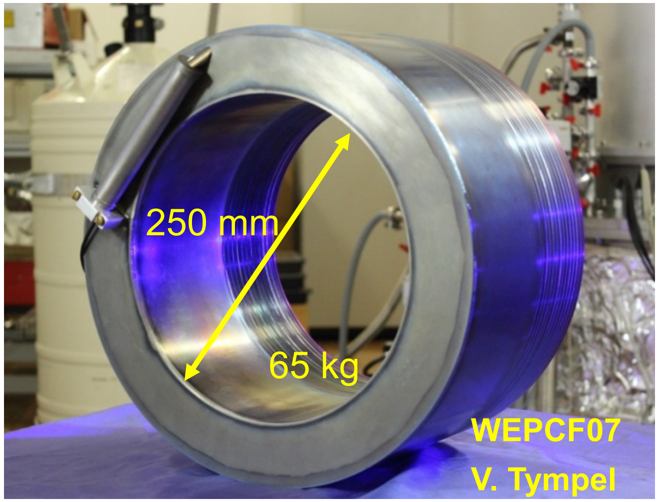
Design of the CCC for FAIR

FAIR/CRYRING cryostat



→ ANSYS© model for vibration analysis

FAIR CCC (FAT in April 2017)



System costs

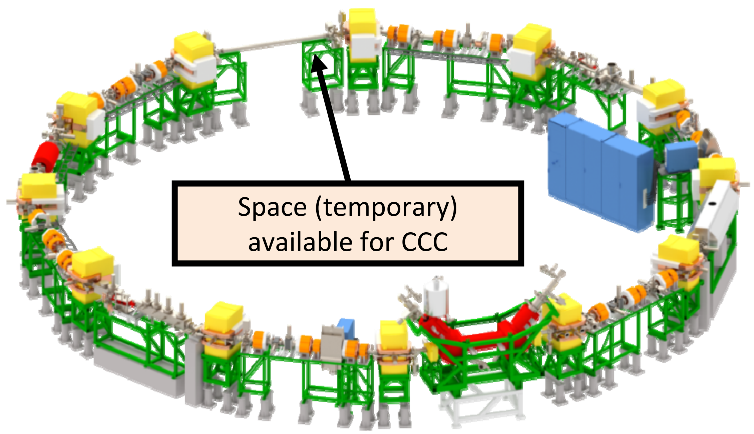
Nb CCC	180 k€
Cryostat	200 k€
Liquefier	80 k€
SQUID + electronics	15 k€
DAQ	20 k€
Support	5 k€
Total	**~ 500 k€**

CCC installation in Cryring

CCC Test/Operation in Cryring@ESR

- Cryring = Swedish inkind contribution to FAIR
- Beam from ESR for Atomic Physics experiments
- Currently under commissioning (vacuum, ecool)
- **Remains operational during FAIR shutdown !!!**

CCC: → tool for commissioning
→ support for experimental program
→ test bench for further development



CCC test program

- Radiation hardness test at SIS18 in 2018 beamtime

After CRYRING installation in 2018

- check new cryostat design + reliquefier scheme
- verification of FAIR CCC lab results
- Lead / Niobium comparison
- alternative shielding geometries
→ CCC without toroid / new SQUID types
- FESA class for CCC
- improve MAGNICON electronics
- bakeable CCC version ?

And in the following

- CCC with reference SQUID
- CCC cascades for enhanced dynamic range
- resonant operation for single particle detection
+ many other new ideas ☺

Summary and Outlook

- Successfull operation of refurbished GSI prototype in 2014 (2 nA, 10 kHz)
- CCC standard diagnostics in AD now, some minor problems to be solved
- Detailed simulations for shield efficiency and mechanical resonances
- Thermal drift caused by toroid inductance change
- Excessive noise contributions from toroid and shield vibrations
- Tests of coreless (lead) pickup and new shield geometry (IPHT design) ongoing

  → new SQUID types with low intrinsic noise and high inductance
- **XD-CCC for FAIR finished and tested successfully in Jena** [WEPCF07]
- **Design for FAIR cryostat finished, funding approved, tendering starts after IBIC**

- CRYRING operational during FAIR shutdown → extensive CCC test program from 2018 on
- Follow-up application at BMBF planned

Thanks to...

- HI Jena: T. Stöhlker, V. Tympel
- FSU Jena: R. Neubert, P. Seidel, T. Köhler, J. Golm, F. Schmidl
- IPHT: R. Stolz, M. Schmelz, V. Zakosarenko
- TEMF: H. De Gersem, N. Marsic, W. Müller
- CERN: M. Fernandes, R. Jones, J. Tan, L. Soby, T. Koettig, A. Lees, M. Wendt
- GSI: F. Kurian, M. Schwickert, H. Reeg, P. Kowina
- HIT Heidelberg: A. Peters
- University of Liverpool: C. Welsch

Thank you for your attention !