A Cryogenic Current Comparator for FAIR

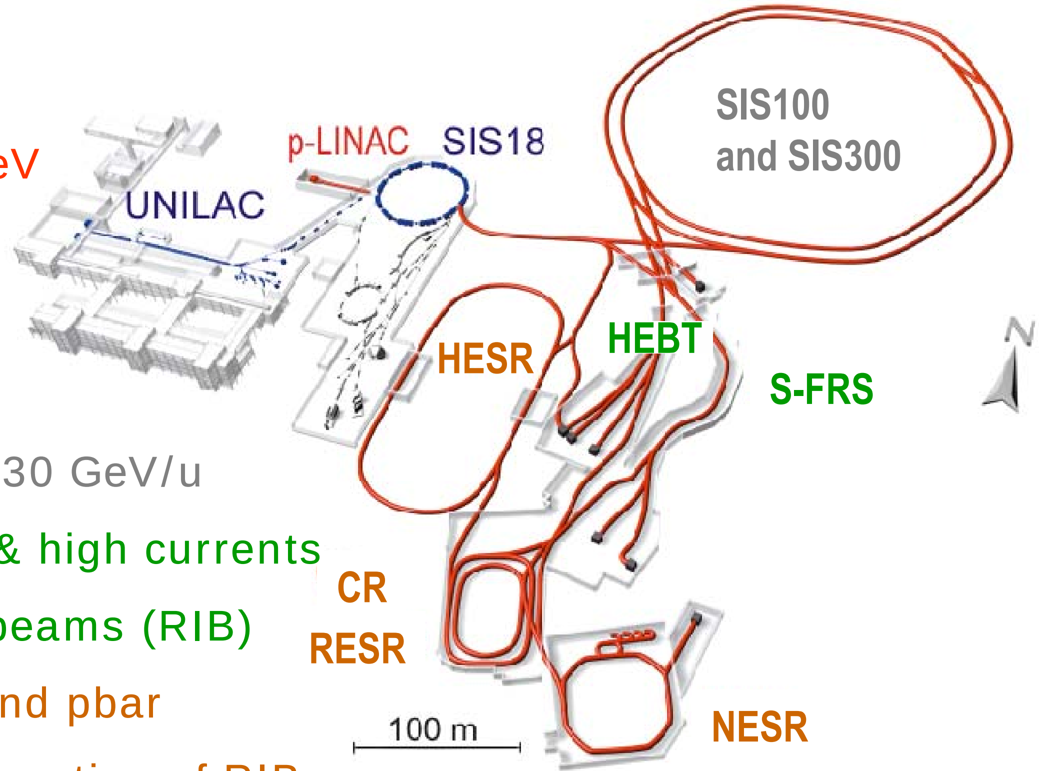
M. Schwickert, H. Reeg, GSI Beam Diagnostics Department
W. Vodel, R. Geithner, Friedrich-Schiller-Universität Jena
T. Sieber, R. v. Hahn, MPI-Kernphysik Heidelberg

- GSI and the FAIR Project
- Requirements for Low Beam Current Measurements
- Cryogenic Current Comparator (CCC)
- Present Developments
- CCC-Prototype at Cryogenic Storage Ring
- Summary

GSI and the FAIR Project

Existing GSI facility:
UNILAC & **SIS18** as injectors

FAIR: Facility for Antiproton and Ion Research



- **p-LINAC:** high current 70 mA, 70 MeV
- **SIS100:** Superconducting, 100 Tm, 1-29 GeV/u, **high current operation p to U**
  p: 2.5×10^{13}, U^{28+}: 5×10^{11} /pulse
- **SIS300:** 300 Tm, acceleration up to 30 GeV/u
- **HEBT:** fast & slow extraction, low & high currents
- **S-FRS:** production of rare-isotope beams (RIB)
- **CR:** stochastic **cooling** of RIB and pbar
- **RESR:** accumulation of pbar, deceleration of RIB
- **NESR:** versatile experimental ring for stable ions, RIB, pbar cooling, gas-target, e-A collider
- **HESR:** storage and acceleration of pbar to 15 GeV/u

Modularized FAIR Version

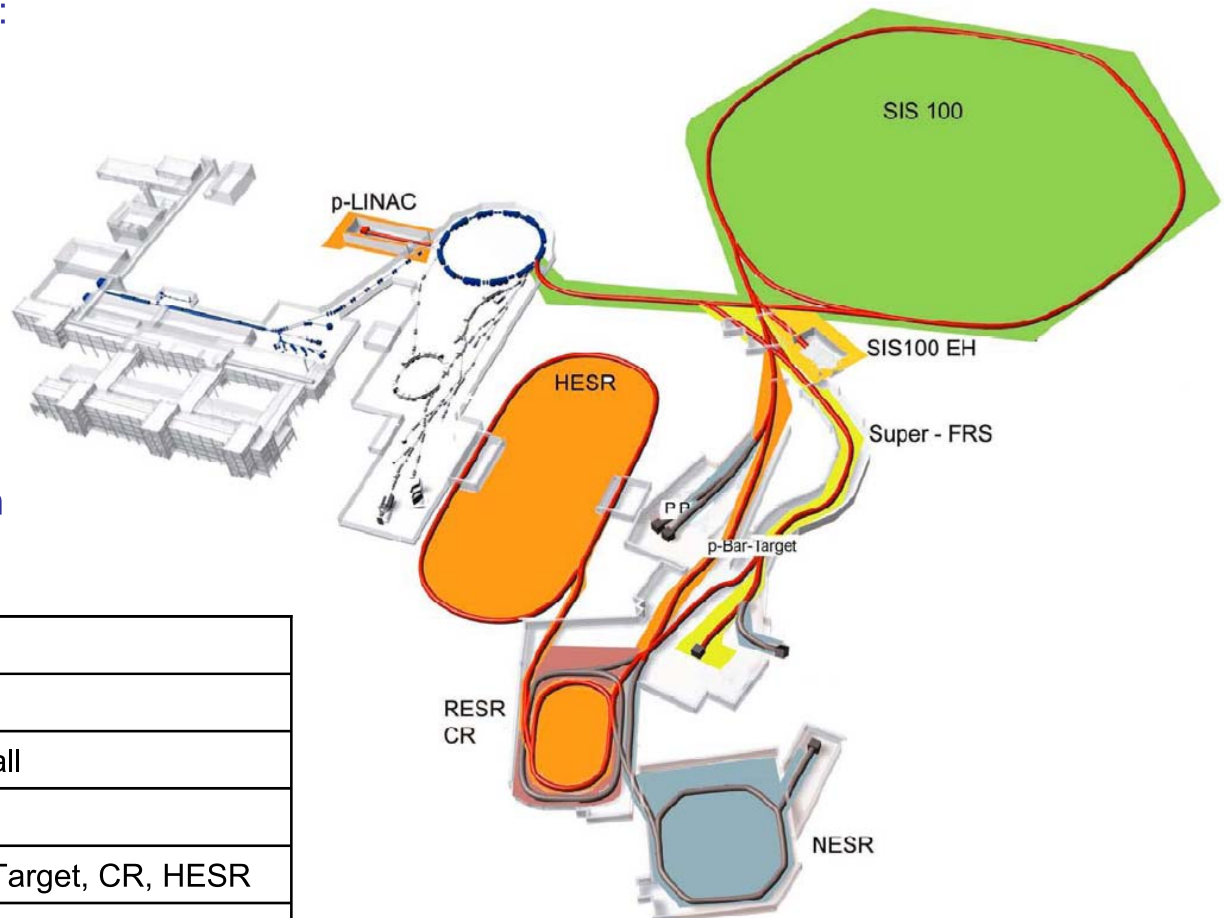
International Steering Committee:

For soon start of the FAIR construction

FAIR Joint Core Team and Scientific and Technical Issues Working Group

were mandated to prepare a proposal for

a start version accounting for recent cost estimates and firm funding commitments



Module	Color	Machine
0	green	SIS100
1	ochre	Experimental hall
2	yellow	Super-FRS
3	orange	p-Linac, p-Bar-Target, CR, HESR
4	blue-gray	NESR, experiment stations
5	red-brown	RESR

SIS100 Synchrotron

SIS100 is the primary accelerator in the FAIR project

- magnetic rigidity of $B\rho$ =100 Tm
- acceleration of high intensity and high energy proton and ion beams
- $3\cdot10^{11}$ U^{28+}/s or $5\cdot10^{11}$ ions per pulse to E= 400 - 2700 MeV/u

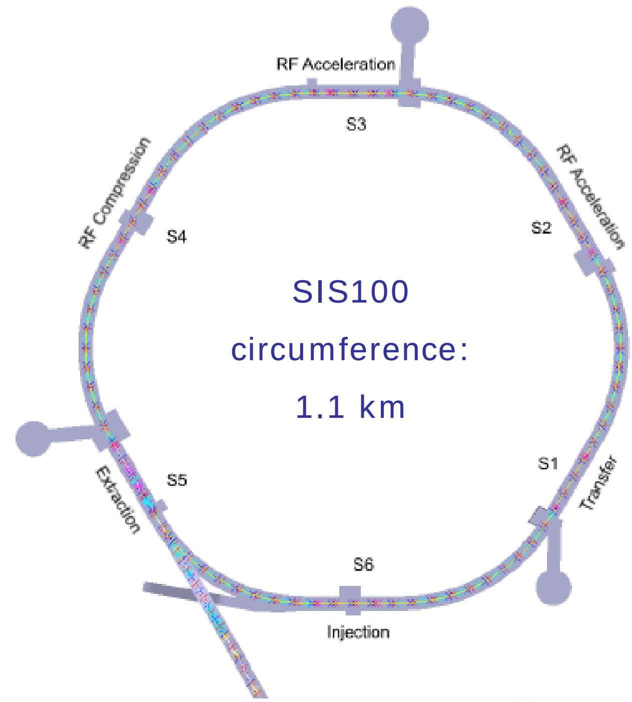
Key parameters from experiments:

for **radioactive ion beams**:
long duty cycle or single bunch of 50-100 ns

for **antiproton production**:
acceleration of $2.5\cdot10^{13}$ protons per pulse to 29 GeV within 5s-machine cycle

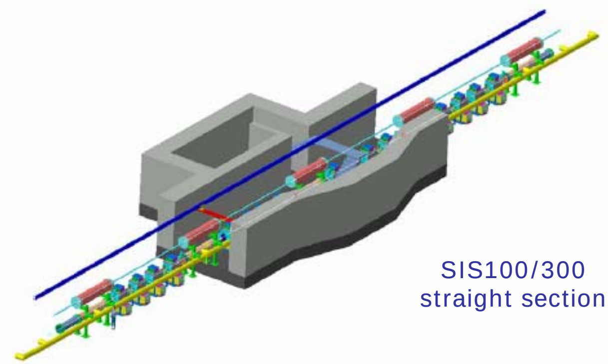
for **plasma physics research**:
$5\cdot10^{11}$ U^{28+}- ions in single bunch of 50-100 ns to 400 - 2700 MeV/u

for the research program with **high energy heavy ion beams**:
$2\cdot10^{10}$ U^{92+}-ions per cycle.



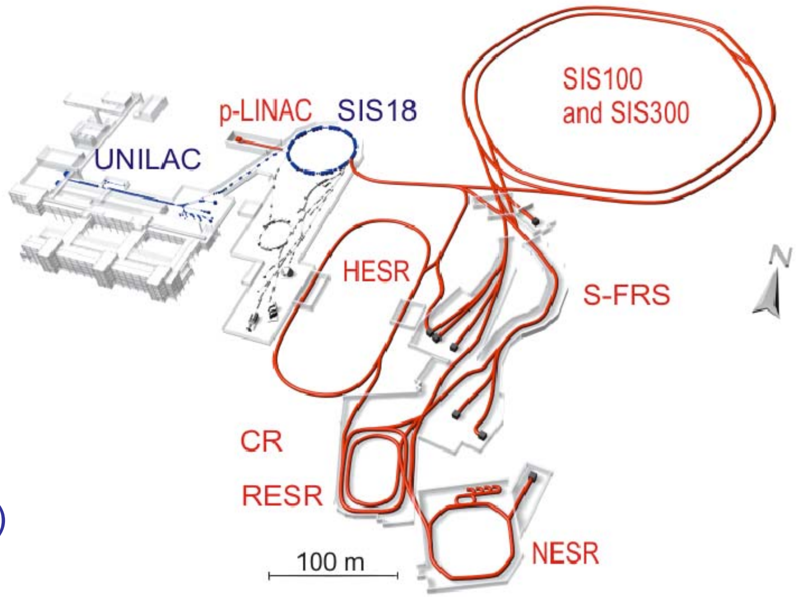
Technical challenges:

- Very **low base pressure** p= $5\cdot10^{-12}$ mbar (XHV range)
- Careful control of beam loss (e.g. charge exchange 28+→29+) by well designed **collimator system**,
- **Superconducting** synchrotron magnet operation (**ramp rate of up to 4 T/s**)
- **RF compression** system for generation of a single high-intensity bunch
- Layout of **double synchrotron** (SIS100, SIS300) in common tunnel.



SIS100/300
straight section

Current Measurement for FAIR



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

BUT:

At several locations **a device required for online monitoring of very low currents** of slow extracted ion beams is required

- in extraction chanel of synchrotrons (SIS18, SIS100, SIS300)
- in front of beam dumps (verify complete beam extinction)
- at experiments using slow extracted beams (Super-Fragment Separator, S-FRS)

⇨ Devices located in High Energy Beam Transport (HEBT) Section of FAIR

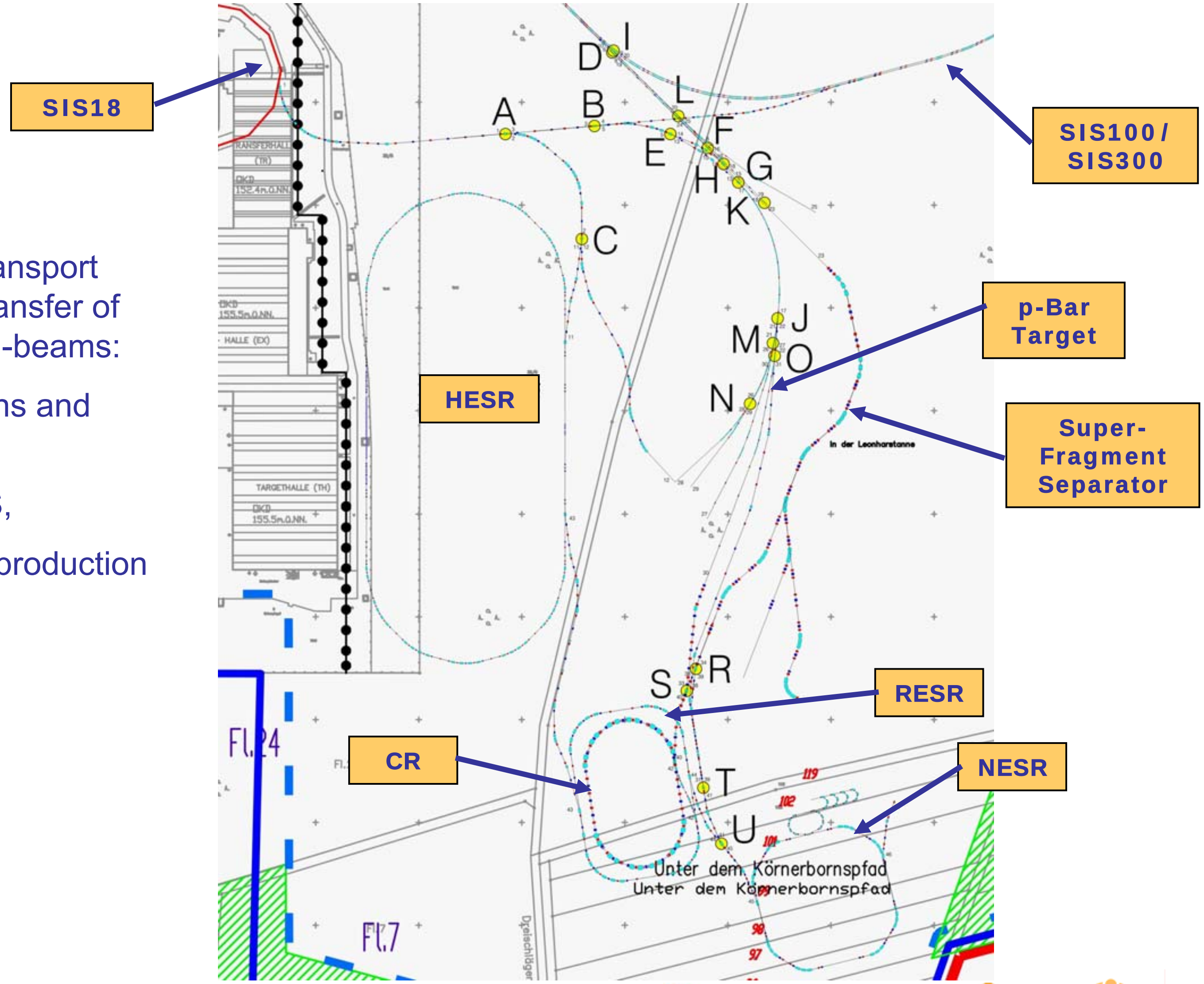
PROBLEM:

Typical currents of slow extracted beams (~nA) are well below the detection threshold of regular DC current transformers (~ several μA)

High Energy Beam Transport (HEBT) Section

The High Energy Beam Transport (HEBT) system provides transfer of ion-, proton- and antiproton-beams:

- to and from the synchrotrons and storage rings,
- to and from the Super-FRS,
- to and from the antiproton production target and separator,
- to the experimental areas.



CCC Installations in HEBT

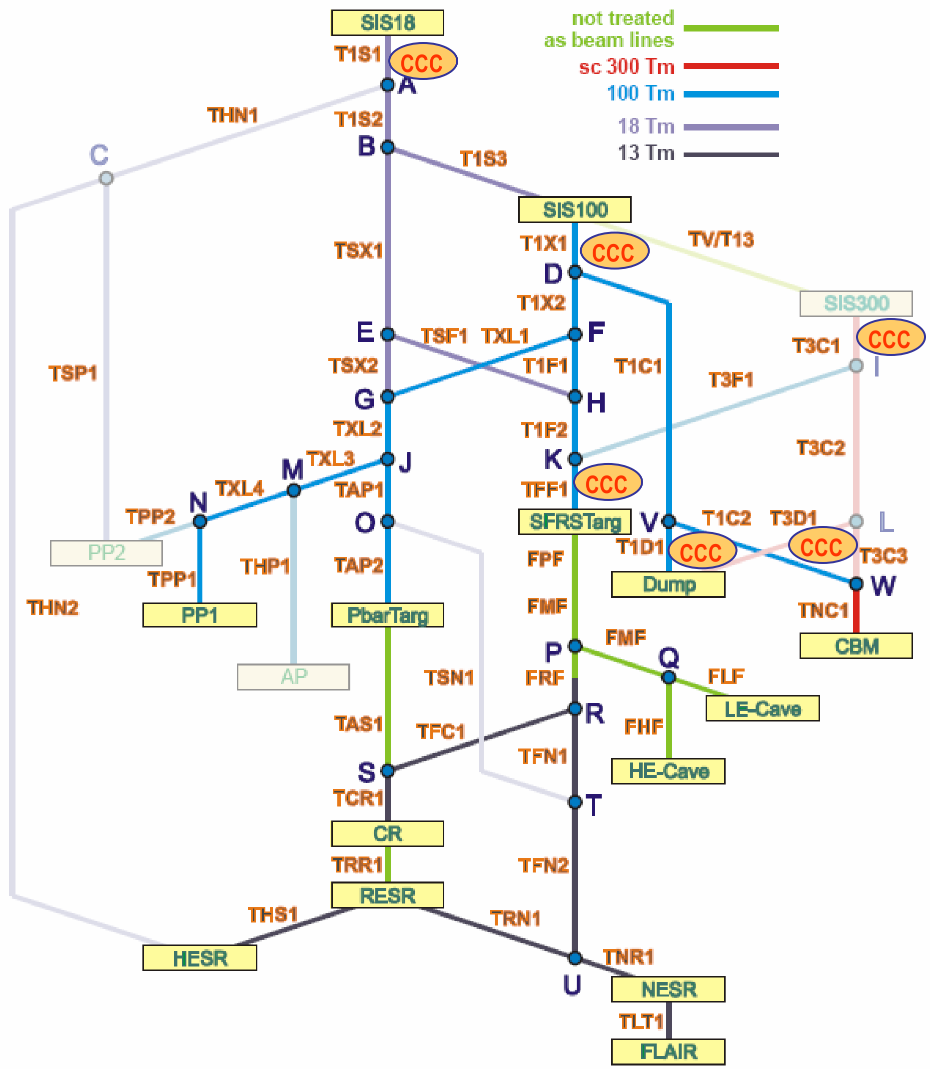
Beamline	Location	Extraction type	Particle species	Stage
T1S1	SIS18-SIS100	slow, fast	ions, protons	FAIR Startversion (Modules 0-3)
T1X1	SIS100 extraction	slow, fast	ions,protons	
T1D1	SIS100 ->dump	slow	ions, protons	
TFF1	SFRS-Target	slow	ions	
T3C1	SIS300 extraction	slow	ions, protons	Phase B
T3D1	SIS300 ->dump	slow	ions, protons	

For all 6 beam lines above:

minimal Intensity: 10^4 pps

maximal intensity: 10^{12} pps

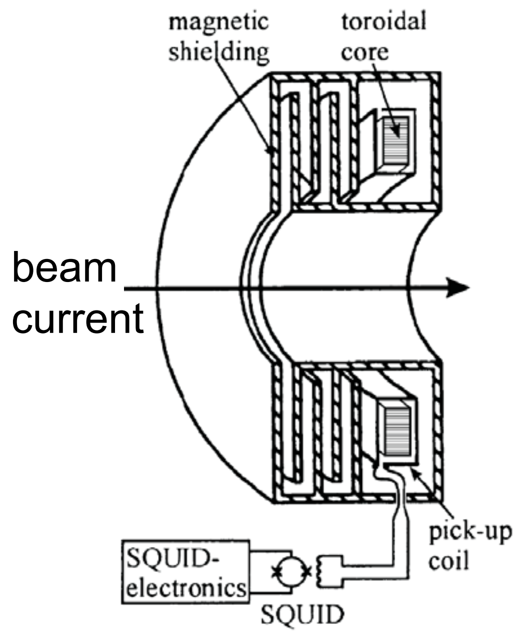
Ion	maximum beam current
p	160 nA
U^{28+}	4.5 μA

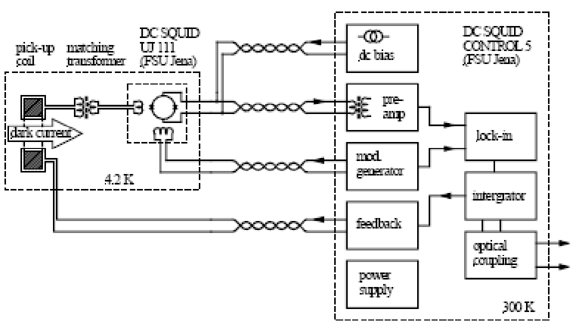


HELMHOLTZ GEMEINSCHAFT GSI FAIR

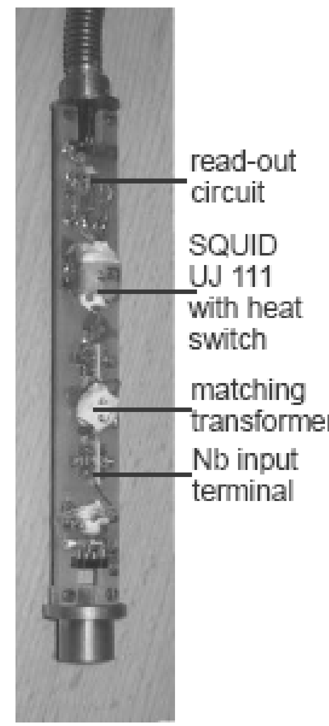
CCC-Principle

Measurement Principle





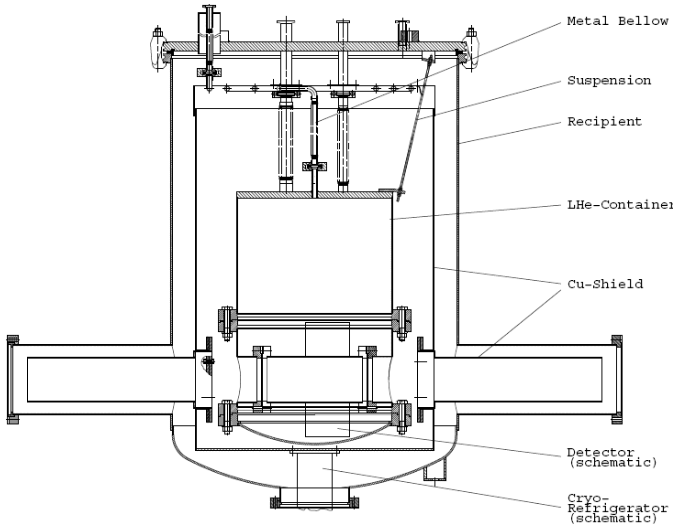
- Idea: high-resolution detection of the **beam's azimuthal magnetic field**
- Ion beam induces screening currents in **superconducting pick-up coil** with ferromagnetic core
- Coil signals fed to sc transformer for **impedance matching**
- **Readout via DC SQUID** for sensitive detection of coil magnetic field (SQUID: UJ 111, Nb-NbO_x-Pb/In/Au window-type Josephson tunnel junctions with dimensions of 3 µm x 3 µm
- Important: extensive **shielding against magnetic noise**
  → meander-shaped niobium structure to suppress non-azimuthal field components,
  e.g. 14 ring cavities allow for 200 dB shielding factor



The GSI Precursor - Setup

GSI prototype in 1997

Purpose-built bath cryostat



SQUID and readout electronics

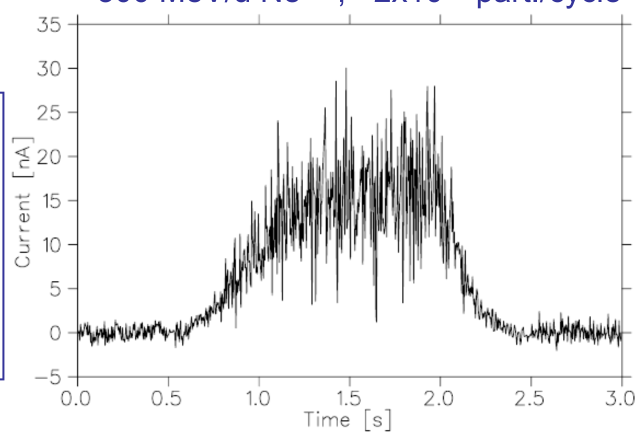
GSI prototype resolution:

250 pA/√Hz

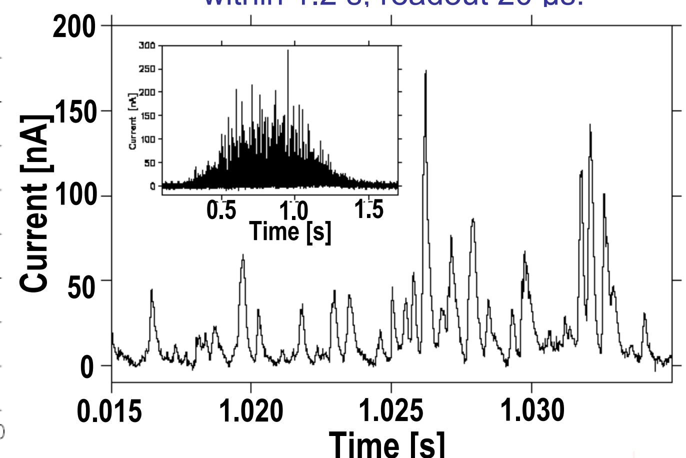
→ **8 nA (1 kHz readout)**

→ **2×10^9 U^{28+} / s**

300 MeV/u Ne^{10+}, ~2×10^{10} part./cycle



7×10^9 Ar^{11+} at 300 MeV/u within 1.2 s, readout 20 μs:



Special Requirements / Challenges

Possible Optimizations to Improve CCC Sensitivity / Reduce System Noise

1. DC-SQUID (approaching quantum limit, mature device)

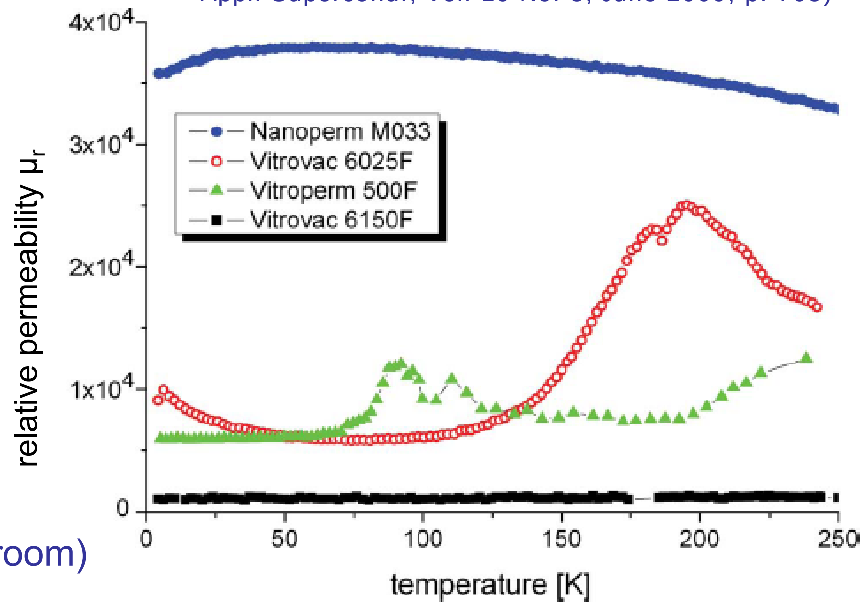
2. magnetic shielding
   goals: - use Nb instead of Pb (GSI prototype),
   - higher number of meander rings

3. ferromagnetic core material

$$\frac{I_S}{I_N} \propto \sqrt{\mu_r}$$

→ search for core material **with highest relative permeability**

(Steppke, Geithner, Vodel et al., IEEE Transactions on Appl. Supercond., Vol. 19 No. 3, June 2009, p. 768)



Engineering Challenges:

- Production of **Nb-shield**
  (delicate Nb structure, electron-beam welded in clean room)
- Manufacturing of **toroids** with great diameter
  (Custom-made devices, low quantities)
- **local cryogenics** (standalone liquid He supply/cold head, problem e.g. in radiation safety areas)
- microphonic effects (reduction of vibrations, decoupling)

Present CCC Developments

Friedrich-Schiller-University Jena:

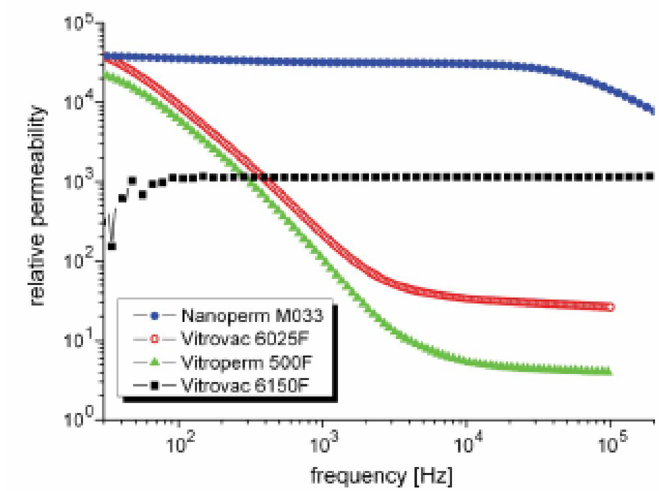
SQUID-Electronics:
Increase in modulation frequency to 350 kHz (higher bandwidth)

Pickup coil:
Optimization of the magnetic shielding (~200 dB, depending on gap width and number of meanders)
Studies on toroidal core material with high μ_r with test cryostat

Present result: use NANOPERM instead of VITROVAC, because of high permeability over a large frequency range ($\mu_r \approx 50000$, $f \approx 1$ Hz - 70 kHz)

Currently achieved resolution: 40 pA/√Hz (under laboratory conditions), thus current measurements in the sub nA range might become possible.

(Steppke, Geithner, Vodel et al., IEEE Transactions on Appl. Supercond., Vol. 19 No. 3, June 2009, p. 768)



GSI Darmstadt:

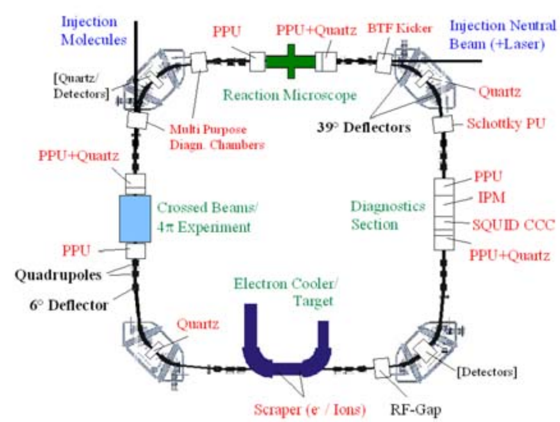
Specification and layout for FAIR 'standard' CCCs

Future: Production of CCC prototype

MPI-K Heidelberg:

Mechanical and cryogenic design of a CCC for new Cryogenic Storage Ring

Future: manufacturing and assembly of CCC as prototype for FAIR

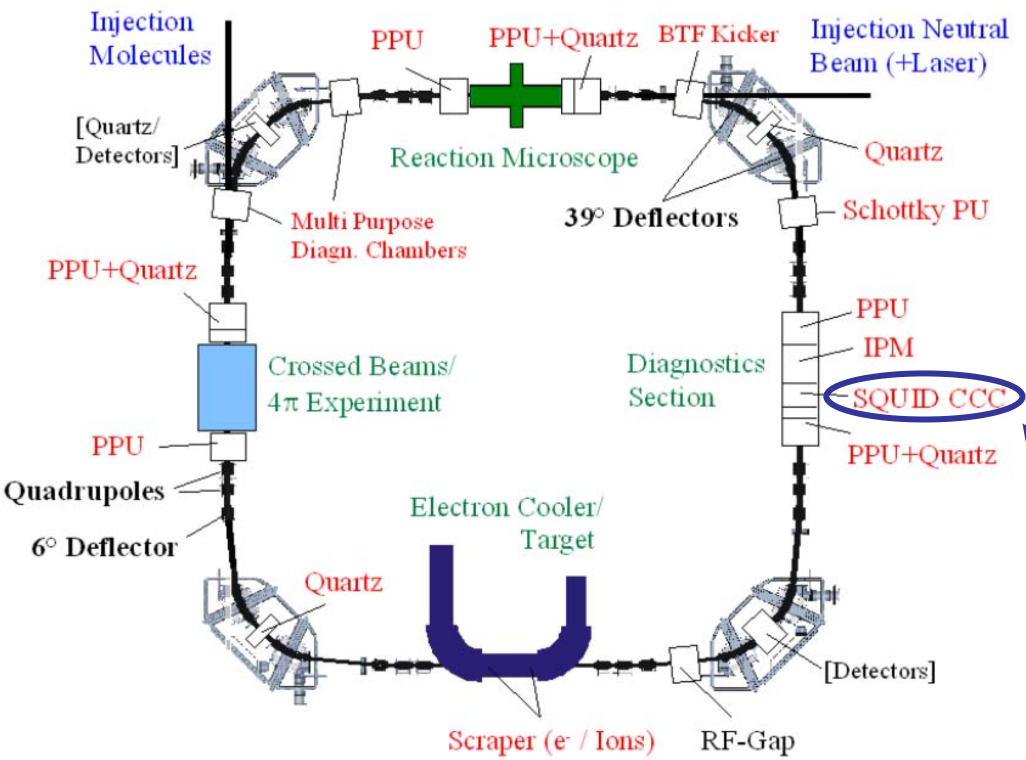


(Figure courtesy T. Sieber, MPI-K Heidelberg)

CCC-Application: Cryogenic Storage Ring of MPI-K

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

(-> presentations of R. v. Hahn, M. Grieser, F. Laux)



(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

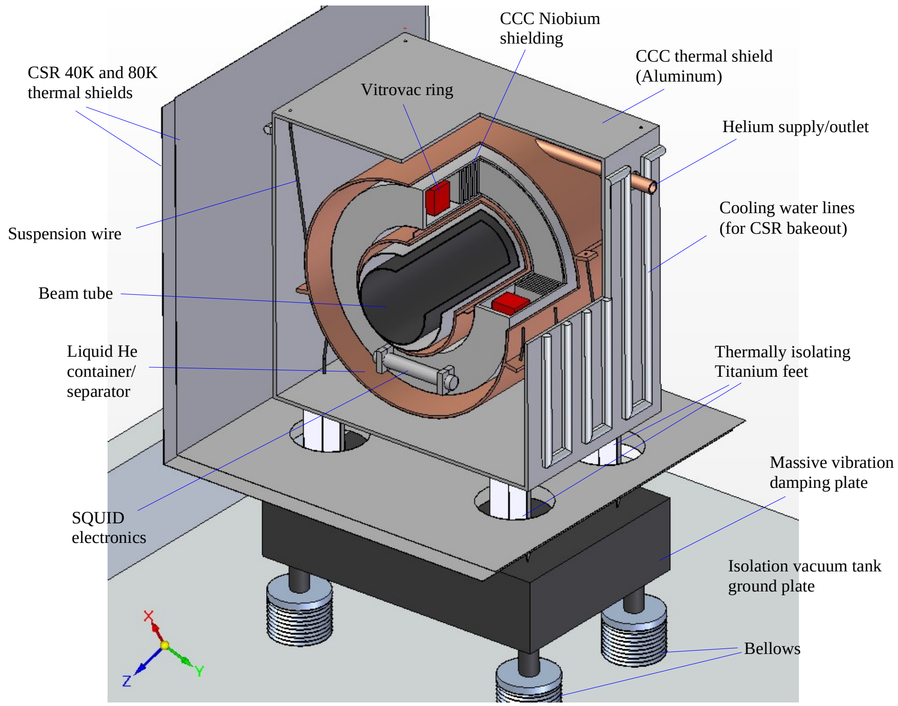
⇩

Common development MPI-K / FSU Jena / GSI:

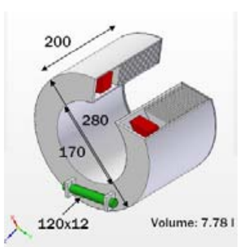
A CCC for the Cryogenic Storage Ring as **prototype for FAIR CCC**

CCC Prototype for CSR

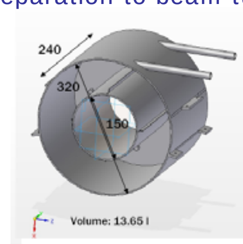
Development of a mechanical and cryogenics design for a Cryogenic Current Comparator (CCC) with SQUID sensor



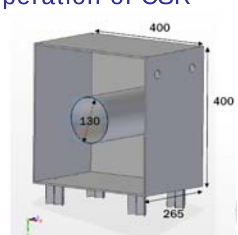
Toroid with Magnetic Shield



lHe-Container (Separation to beam tube)



Thermal Shielding for RT operation of CSR



Common Requirements CSR & FAIR:

- mechanical and cryogenic design: all components have to be cooled down to liquid Helium temperature
- temperature stability 50 mK to minimize noise and zero drift
- Suppression of mechanical vibrations: thermally isolating feet on massive, mechanically decoupled ground plate

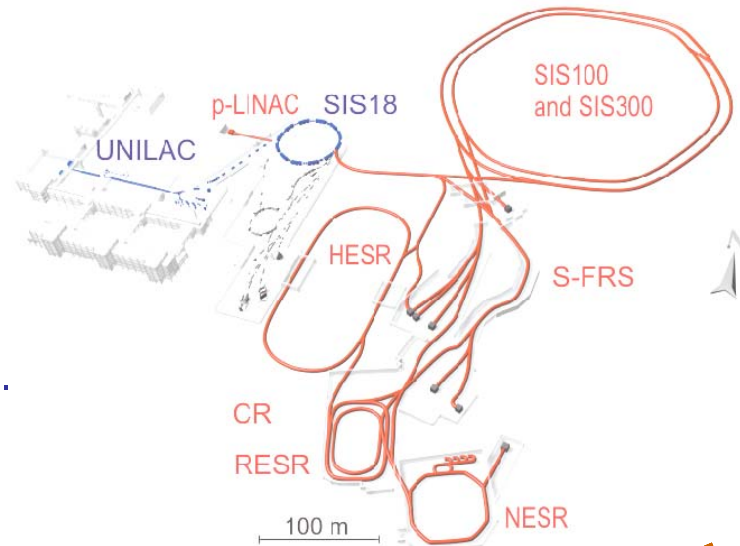
CSR specific:

- CSR has operation mode at room temperature
  → separate thermal shielding
- upper temperature limit for toroidal core and SQUID: 80° C
  → water-cooling needed for CSR bakeout

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

Summary

- **GSI and FAIR**
  - versatile accelerator facility for high intensity, high brightness ion beams
  - modularized start version
  - 6 CCC to be installed in FAIR HEBT for online current measurement of slow extracted beams



- **Cryogenic Current Comparator**
  - detection principle
  - GSI CCC-precursor (resolution 250 pA/√Hz)
  - detailed component studies in Jena include μ_r as a function of temperature, frequency etc.
  - present CCC resolution: 40 pA/√Hz
- **CCC for Cryogenic Storage Ring CSR**
  - definition of mechanical requirements
  - design study on mechanical/cryogenic layout
- **Many thanks to our Collaboration Partners:**

W. Vodel, R. Geithner, Friedrich-Schiller-University Jena
R. v. Hahn, T. Sieber, MPI-Kernphysik, Heidelberg
A. Peters, HIT, Heidelberg

Thank you for your attention!