A SQUID-BASED BEAM CURRENT MONITOR FOR FAIR / CRYRING
OUTLINE

- Future Installations at FAIR
- Challenges
- Cryogenic Current Comparator (CCC) principle
- Experimental results for improved sensitivity
- Conclusions and Outlook
Facility of Antiproton and Ion Research (FAIR)

- Beam current measurement in
  - High-Energy Beam Transport (HEBT)-section,
  - Collector Ring (CR)
  - CryRing
### Beamline Location Extraction

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Location</th>
<th>Extraction type</th>
<th>Particle species</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1S1</td>
<td>SIS18-SIS100</td>
<td>slow, fast</td>
<td>ions, protons</td>
<td>FAIR Startversion (Modules 0-3)</td>
</tr>
<tr>
<td>T1X1</td>
<td>SIS100 extraction</td>
<td>slow, fast</td>
<td>ions, protons</td>
<td></td>
</tr>
<tr>
<td>T1D1</td>
<td>SIS100 dump</td>
<td>slow</td>
<td>ions, protons</td>
<td></td>
</tr>
<tr>
<td>TFF1</td>
<td>SFRS-Target</td>
<td>slow</td>
<td>ions</td>
<td></td>
</tr>
<tr>
<td>T3C1</td>
<td>SIS300 extraction</td>
<td>slow</td>
<td>ions, protons</td>
<td></td>
</tr>
<tr>
<td>T3D1</td>
<td>SIS300 dump</td>
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</tbody>
</table>

For all 6 beam lines above:
- minimal Intensity: $10^4$ pps
- maximal intensity: $10^{12}$ pps

### Ion Maximum Beam Current

<table>
<thead>
<tr>
<th>Ion</th>
<th>Maximum Beam Current [slow extraction, 1 s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>160 nA</td>
</tr>
<tr>
<td>$^{28+}$U</td>
<td>4.5 µA</td>
</tr>
</tbody>
</table>
### Challenge

<table>
<thead>
<tr>
<th>Beam current measurement</th>
<th>Detector requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport section, Storage rings</td>
<td>On-line, non-destructive, absolute measurements easy, linear calibration</td>
</tr>
<tr>
<td>Maximum beam current: 160 nA for (anti-)protons 4.5 µA for uranium ions U$^{28+}$</td>
<td>goal: Current resolution &lt; 1nA</td>
</tr>
<tr>
<td>Current pulses with DC-part</td>
<td>High bandwidth incl.DC High slew rate</td>
</tr>
</tbody>
</table>
- Detection of the beam’s azimuthal magnetic field
- Superconducting Pick-up coils
  - DC-magnetic field measurements due to flux conservation in closed sc loops
  - Lower noise, because of no hysteresis losses
- DC-Superconducting QUantum Interference Device, (DC-SQUID) acting as current sensor
  - Highly sensitive, low intrinsic noise contribution
- Superconducting Shielding
  - Attenuation of all non-azimuthal magnetic field components
CCC-principle

T ≤ 5 K

charged particles

Meander-shaped shielding

SQUID-electronics
300K

SQUID-cartridge

Pick-up coil incl. core
Photography of the CCC assembled in the beam line and some technical details.
Beam measurement

$^{28}\text{Ni}^{26+}$ at 600 MeV/u

- Replacement of
  - SQUID-sensor
  - SQUID-electronics
- Secondary Electron Emission Monitor (SEM) for comparison
- Perfect agreement between two independent spill monitors (CCC vs. SEM)

$^{26+}$ at 600 MeV/u extracted from SIS18
Improvements using new core materials and concepts
Improved pick-up coil

\[ \langle I^2 \rangle = 4k_B T \int \frac{R_S(\nu)}{(2\pi \nu L_S(\nu))^2 + (R_S(\nu))^2} d\nu \]

Requirements to core materials:

- frequency independent high real part of the permeability \((L_S)\).
- low imaginary part over a wide frequency range which corresponds to a low losses in the material \((R_S)\).
Improved pick-up coil

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- frequency independent high real part of the permeability \( L_S \).
- low imaginary part over a wide frequency range which corresponds to a low losses in the material \( R_S \).

red: Vitrovac 6025F  
blue: Nanoperm M764
Setup FAIR-CCC

- Nanocrystalline Nanoperm M764 as core material
- Electron beam welded niobium parts
- Commercial SQUID-sensor Supracon CP2 blue.
- Commercial SQUID electronics Magnicon XXF-1
Setup FAIR-CCC

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- White noise 3.5 pA/Hz$^{1/2}$
- 3 nA total noise
- SQUID system bandwidth $f_{3dB}$ adjusted by electronics settings
- Decrease at 200 kHz estimated as CCC bandwidth
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- 3 nA total noise
- SQUID system bandwidth $f_{3dB}$ adjusted by electronics settings
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Step function response

Tests with battery powered current source
(a) 2 µA, (b) 1 µA, (c) 200 nA, (d) 100 nA, (e) 20 nA, (f) 10 nA
Current sensitivity
Linearity

Current sensitivity = 42.0 ± 0.3 nA/Φ₀
Slew rate limitation

(black) 14 nA test signal with low signal slew rate
(red) CCC response
Slew rate limitation

CCC response on a 8 nA (black) and 86 nA (red) test signal with high signal slew rate
Future Investigations

- Investigations on microphonic effects
- Development of cryostat with local liquid helium supply
  - Reducing microphonic effects by damping of mechanical vibrations, pressure and temperature stabilization

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Advantages of a SQUID based CCC

- Non-destructive measurement method
- Measurement of the absolute values of the current
- Exact absolute calibration using an additional wire loop
- Independency of charged particle trajectories and particle energies
- Demonstration of the suitability at GSI and HoBiCat
- High resolution (< 100 pA/√Hz), 3.5 pA/√Hz white noise
- High bandwidth of 200 kHz estimated
- High linearity
Acknowledgement

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THANK YOU FOR YOUR ATTENTION!