Industry meets Academia: Beam Monitoring Instrumentation and Quality Assurance

Beam Diagnostics Makes FAIR Play

M. Schwickert, for the GSI Beam Diagnostics Department

- GSI and the FAIR Project
- Example Developments for FAIR Machines
  - **SIS100:**
    - Intensity: Novel DC Current Transformer
    - Beam Position Monitors
    - Transverse Profiles: Ionization Profile Monitor
  - **High Energy Beam Transport:**
    - Profile Grid Read-out using Charge-to-Frequency Conversion
    - Intensity: Cryogenic Current Comparator
    - Transverse Profiles: Beam Induced Fluorescence
- Summary

GSI and the FAIR Project

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

UNILAC:
Length: 120 m
Energy: 11 MeV/u

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)

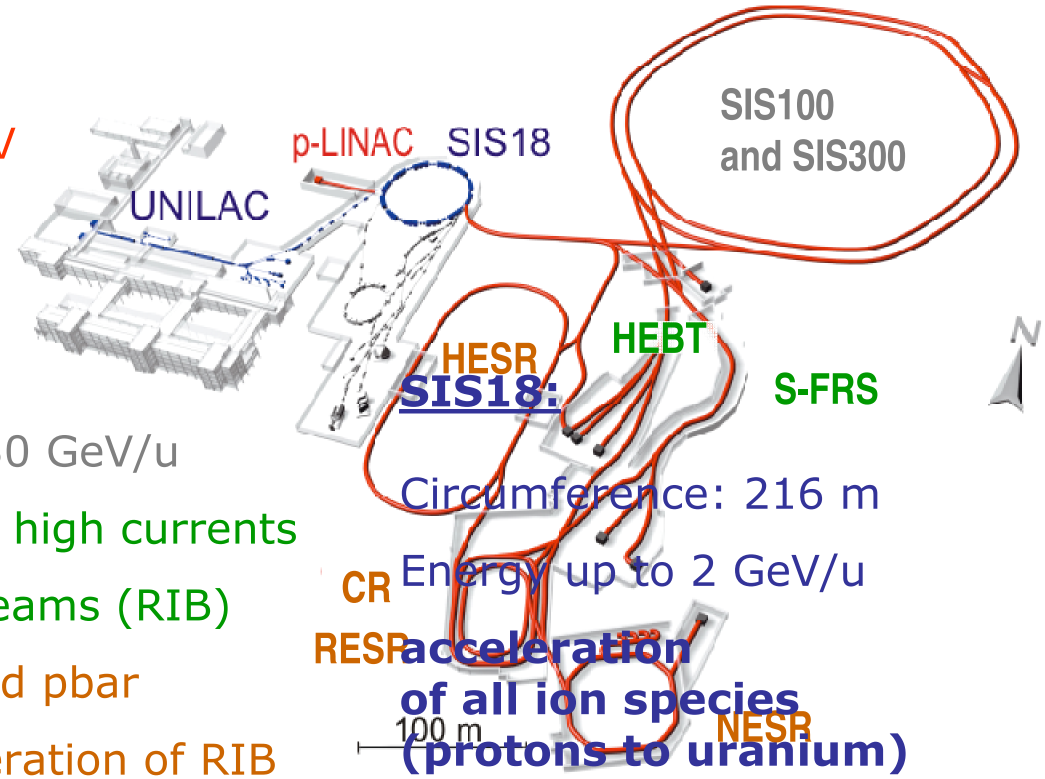
CR: stochastic **cooling** of RIB and pbar

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

FAIR: Facility for Antiproton and Ion Research



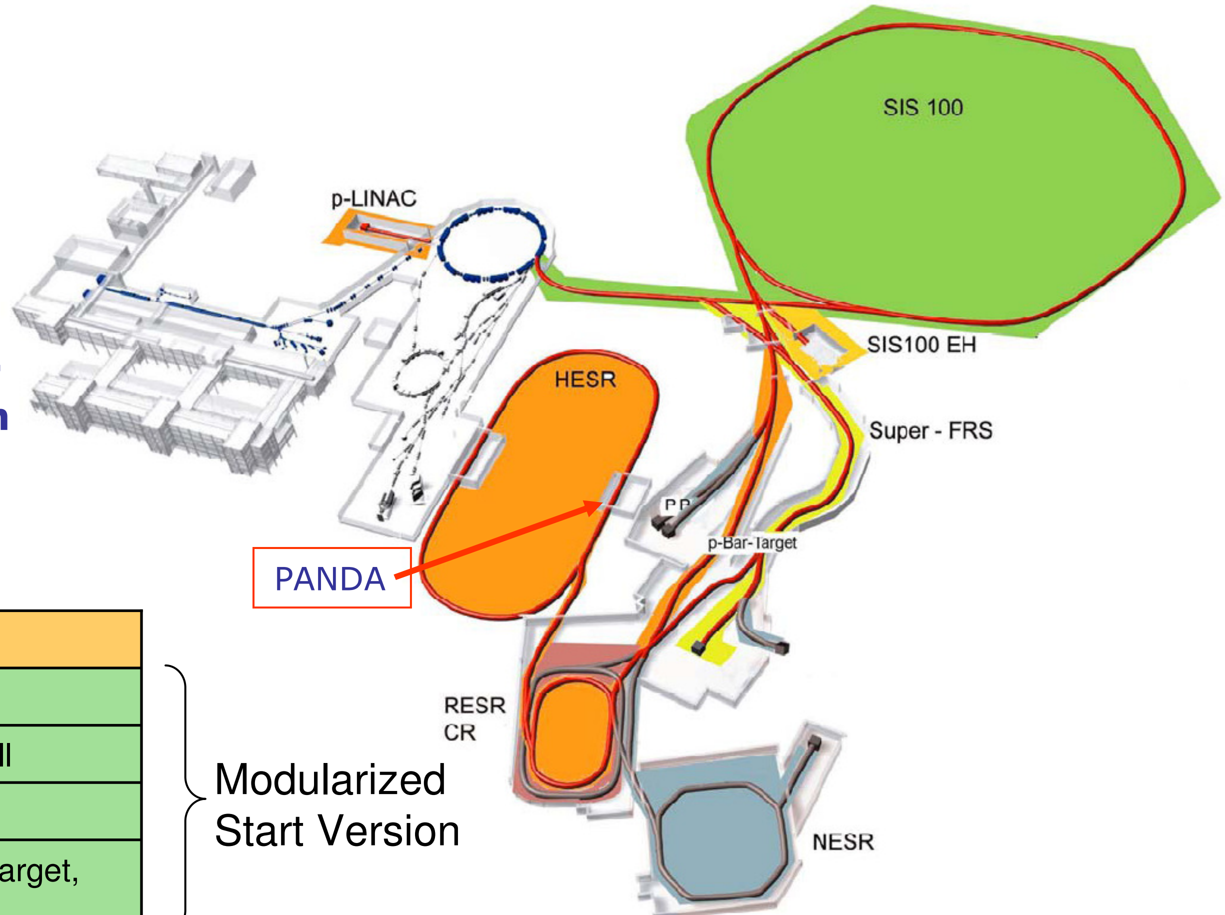
SIS18:
Circumference: 216 m
Energy up to 2 GeV/u
acceleration of all ion species (protons to uranium)

Modularized FAIR Version

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

Modularized Start Version (modules 0–3)

Final Stage (modules 4–5)

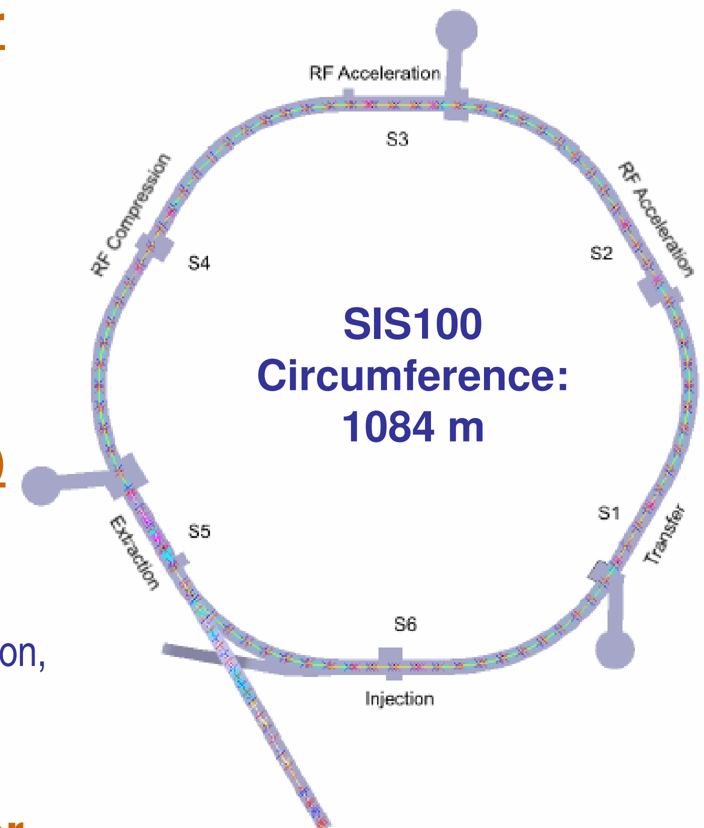
SIS100 – Machine Requirements

(1) Beam Current – Novel DC Current Transformer

- bunch length: 25 ns - 8 μs
- beam current: 5×10^{11} U^{28+}/pulse, 2.5×10^{13} p/pulse

} up to 10 A bunch current

- bunch frequency: 0.5 - 2.7 MHz → critical for standard DC Current Transformer



(2) Beam Position – BPMs (Baseband Digitization)

- bunch length: 25 ns - 8 μs → high dynamics, amplification / attenuation
- RF 'gymnastics' (barrier bucket, bunch compression system) → sophisticated data acquisition, as feedback source

(3) Online Beam Profile – Ionization Profile Monitor

- bunch frequency: 0.5 - 2.7 MHz
- acceptance = $3 \times$ beam width σ

} turn-by-turn profile detection on μs timescale

- space charge effects → online emittance control, injection matching

SIS100: Current Measurement

Goals

- **Precise current determination** of stored and accelerated beam
- **Beam lifetime** determination and coarse **beam loss** measurement

Requirements

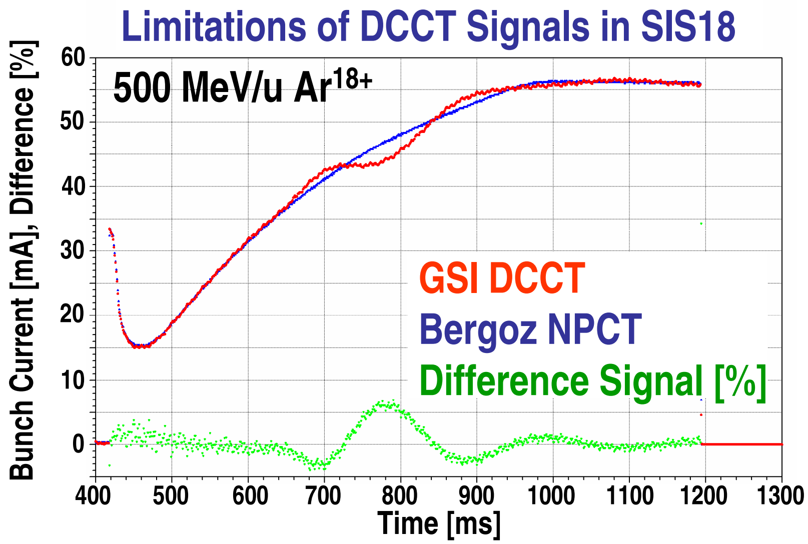
- dynamic range of 10 μA – 20 A for typical beam parameters
- bandwidth of 10 kHz to measure beam lifetime
- beam loss: acquisition on ms timescale

Feasible with GSI standard DCCT

Critical

- SIS100: High current bunched beams with MHz repetition rate

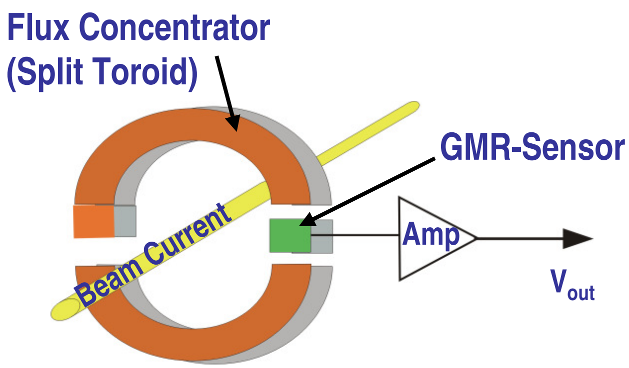
signal of standard DCCT disturbed due to internal resonance



- BUT: accuracy of few percent needed for beam current measurement

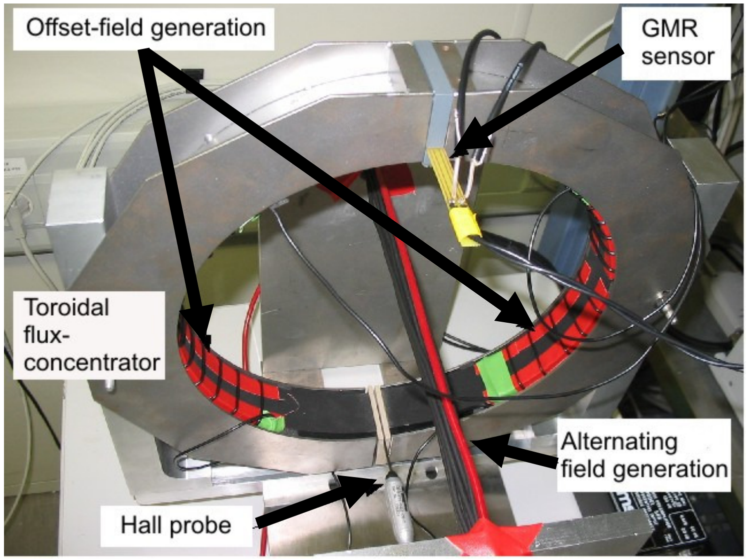
SIS100: Beam Current Measurement – Novel DCCT

Measurement Principle

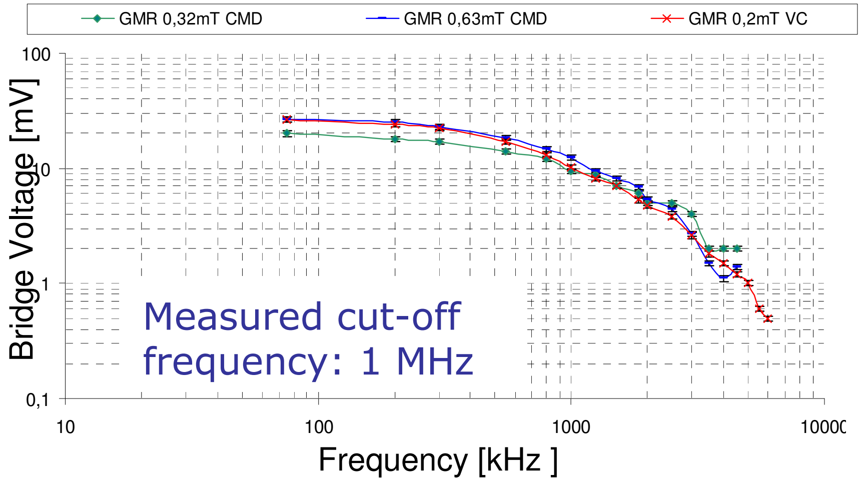


- idea: **clip-on Amperemeter** design
- **split toroid** to allow **dismounting** before bake-out
- soft-magnetic **flux concentrator** (amorph. VITROVAC®)
- **gap** with induction of 80 μT @ 1 A beam current
- **sensitive GMR** (Giant Magneto Resistance) magnetic field sensor (resolution: 10^{-9} T/√Hz) → used for harddisks

Test Setup



Frequency Response (GMR+Pre-amp)

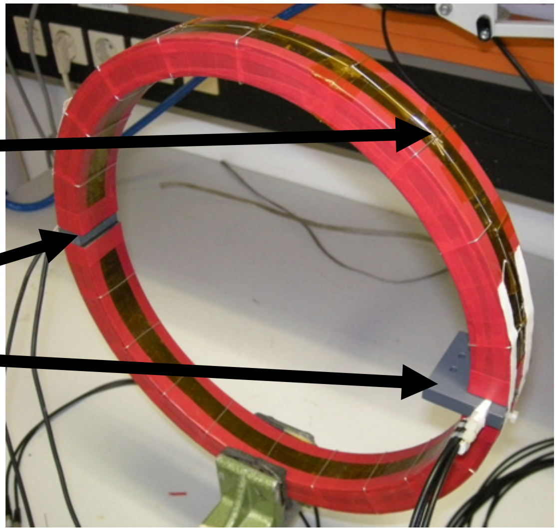


- Reasons: induced voltages in sensor material, eddy currents in NiFe-layer

SIS100: N-DCCT: Combined ACT-DCCT-System

Further NDCCT Improvements

- add single ACT-winding to core
- add high-pass filtered ACT-branch to electronics
- use 2 GMR sensors (1 sensor per gap)



New: dc and ac measurement on single core!

Pulse Response (Combined System)

Ongoing R&D

- investigation of NDCCT rf- characteristics
- design & layout of readout electronics
- ASIC design for direct digitization
- studies on radiation hardness
- improvement of loop-crossover (ACT, DCCT)

Beam Position Monitors (BPM) for SIS100

Goals

- **precise beam position measurement** in SIS 100
- closed orbit control during **RF manipulations** (bunch compression, acceleration)
- use of position data for **closed orbit feedback**

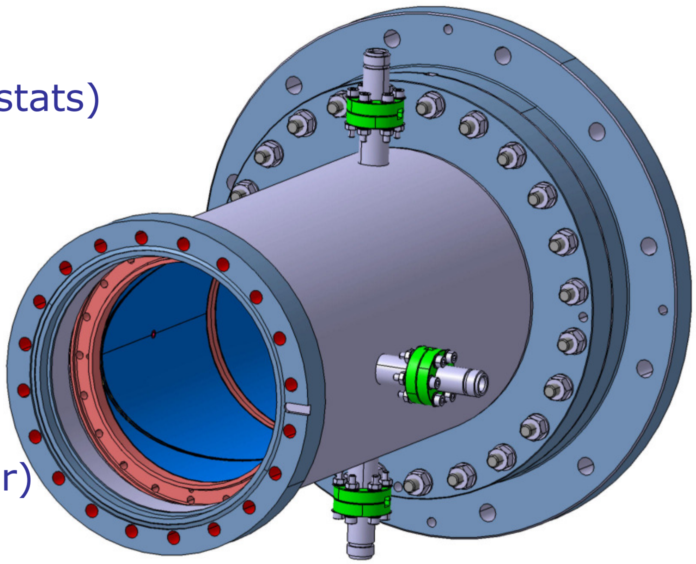
Requirements

- all BPMs installed in **cryogenic regions** (quadrupole cryostats)
- **linear-cut type BPM** preferred, because:
  - bunch length >> BPM length
  - relatively low bunch frequency: **0.5-2.7 MHz**
  - linear response even for transversally large beams
- **mechanical reproducibility** of **~50 µm** required for 0.1 mm accuracy
- all components suitable for **XHV conditions** (< 10^{-11} mbar)

→ **Development of metalized Ceramic Cylinder**

- flat response in **frequency range 0.1-100 MHz**
- **large dynamic range** (**1 µV < U_{plate} < 1.8 kV**)

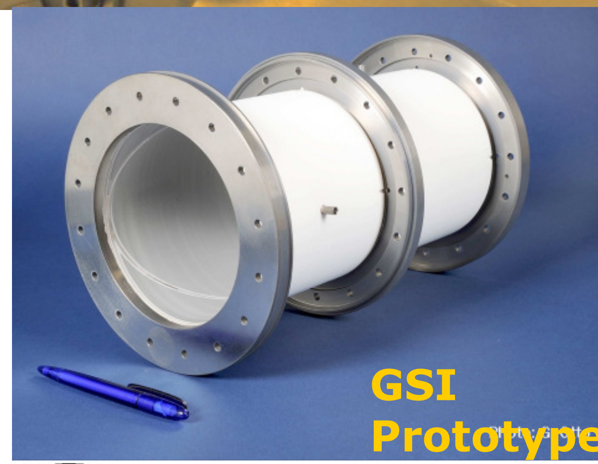
→ **Development of Amplifier / Attenuator Stage**

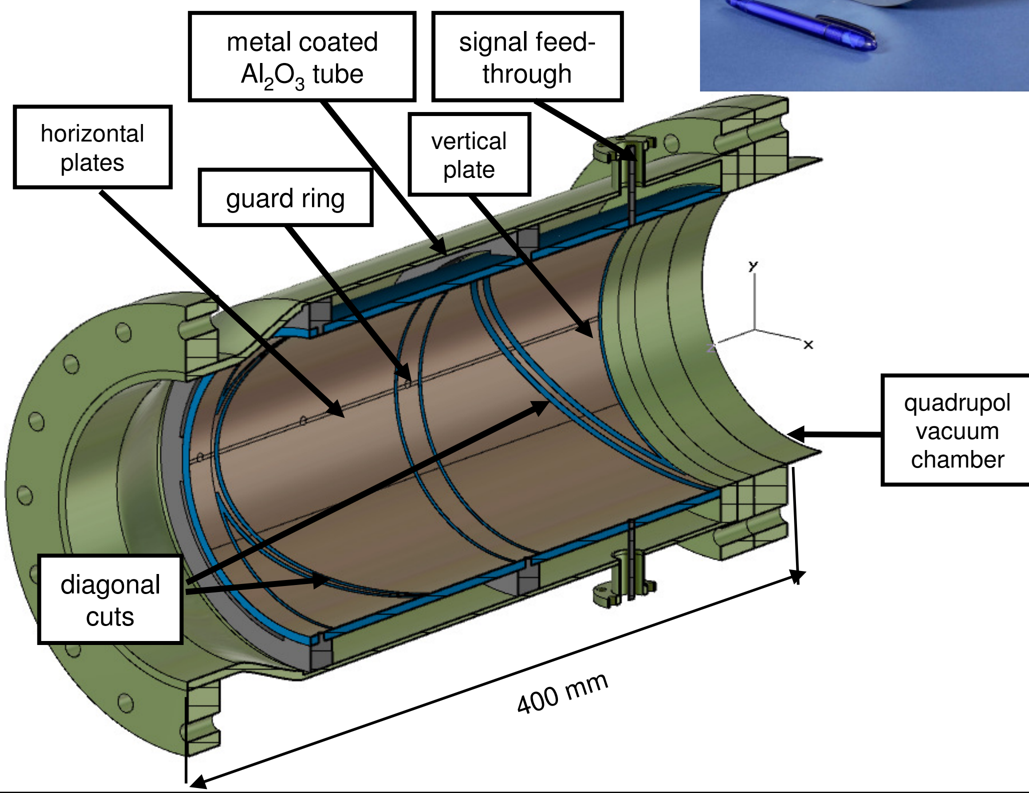


SIS100 BPMs – Development of Ceramic Pick-Up

Technical Design

- pick-up material: metal-coated Al_2O_3
- cylindrical ceramics structure
- circular aperture 135 mm

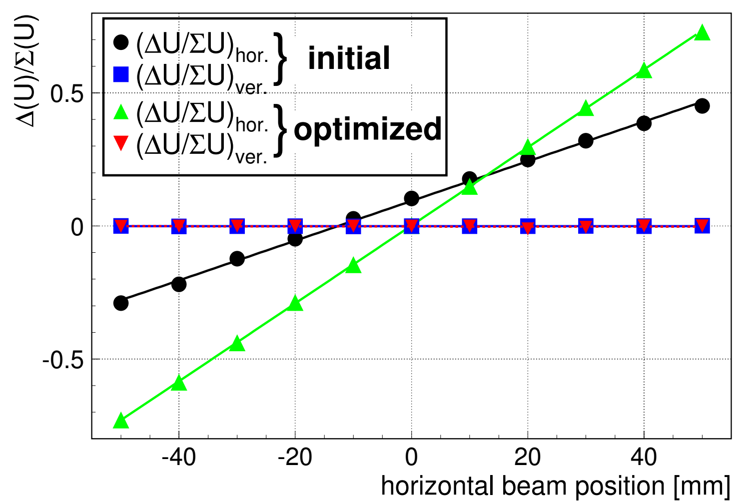




FEM-Simulations:

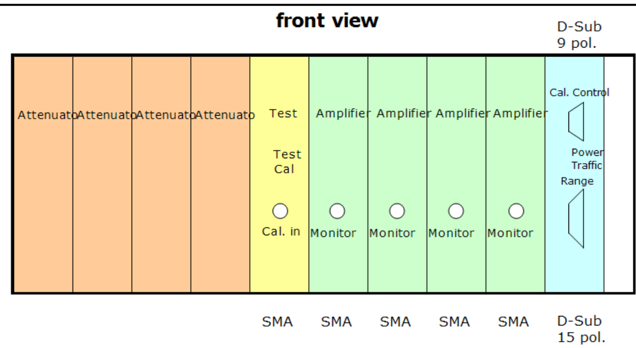
- increase sensitivity
- reduce plate-to-plate crosstalk
- reduce offsets
- suppress fringe fields

Simulation Results:



SIS100: Development of BPM Pre-Amps

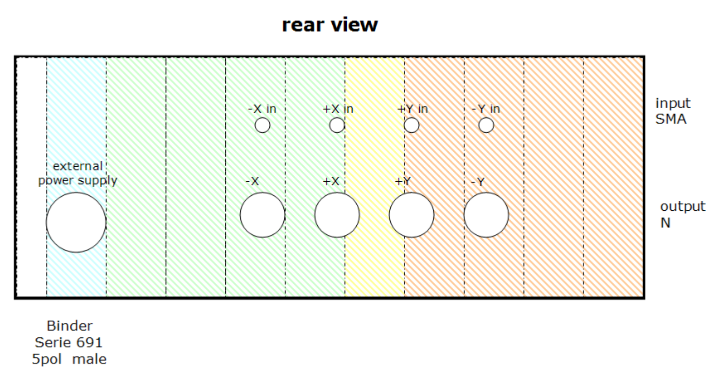
Development of:
Non-inverting, low noise amplifier quartet with control interface and built–in test generator



Main Requirements

- ▲ **bandwidth** (-3dB): **400kHz....55MHz**
- ▲ input sensitivity: (S+N)/N = 6dB @ -90dBm
- ▲ input voltage: max 230V peak
- ▲ **gain error** between channels: **max. 0.1dB**
- ▲ **gain switching time**: max. **100µs**
- ▲ power off condition: attenuation 40dB min.

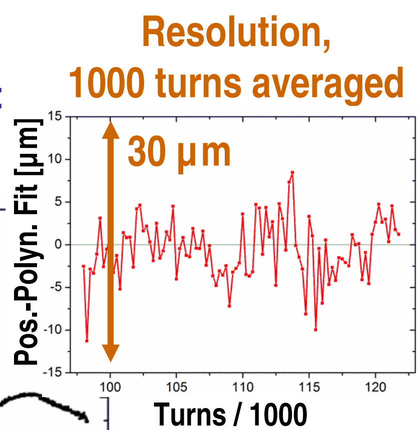
- ▲ important: **common mode behaviour** in amplification (gain errors between channels would cause wrong beam position evaluation)
- ▲ internal **test generator** for every gain range
- ▲ **calibration input**, **monitor outputs** for external network analyzer.
- ▲ truth table for "range control", gain matching and test signal levelling via EIA-485 port.
- ▲ flexible truth table "range control" (might change)
- ▲ All parameters stored in non-volatile memory.
- ▲ radiation dose up to **1000 Gy during 2 years**

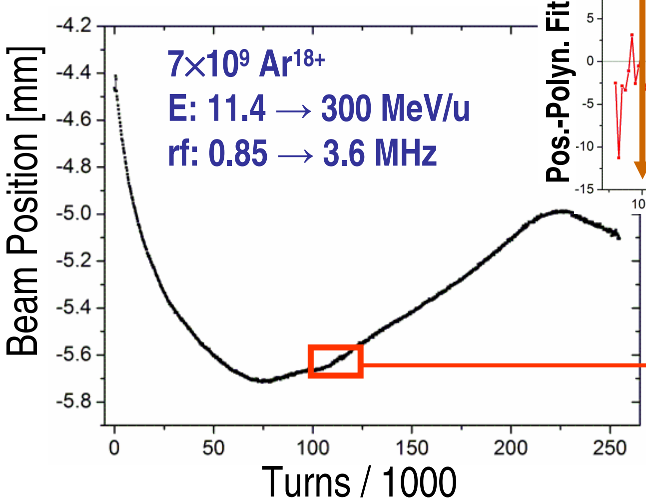


SIS100: Development of BPM Data Acquisition

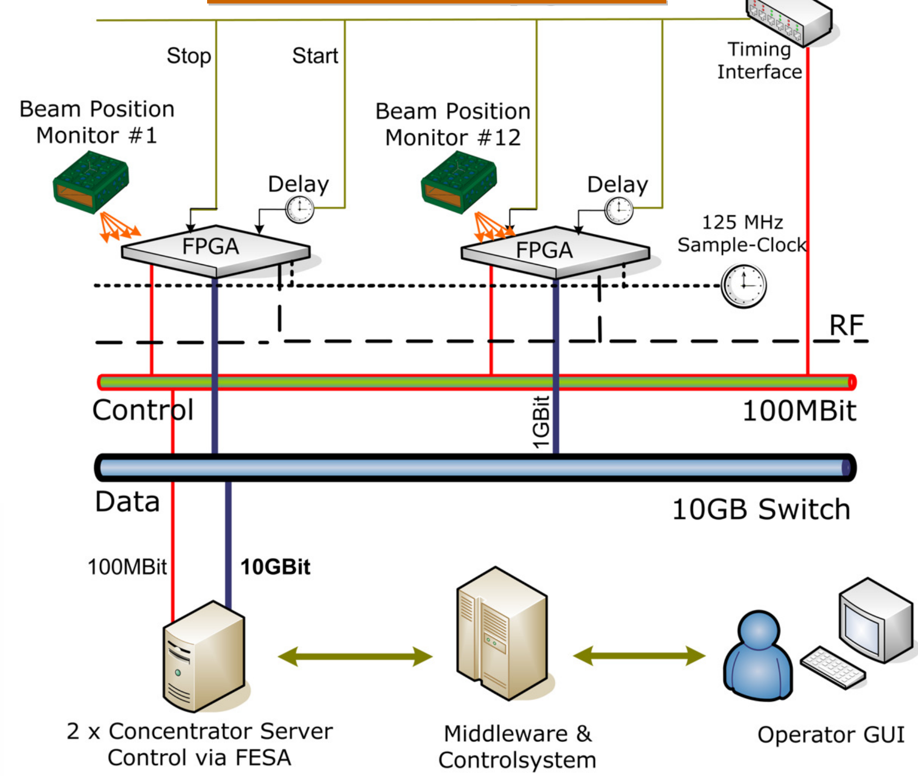
Direct Baseband Digitization

- digitization: 4 ADCs, **125 MSa/s**, 14 bit using LIBERA Hadron (I-Tech), 256 MB RAM, 1 Gbit interface
- **sample-synchronous** processing in FPGA
- development of **FPGA algorithm** for noise reduction, integration-gate, baseline reconstruction
- **bunch-by-bunch position measurement** on synchrotron ramp:





SIS18 BPM Upgrade



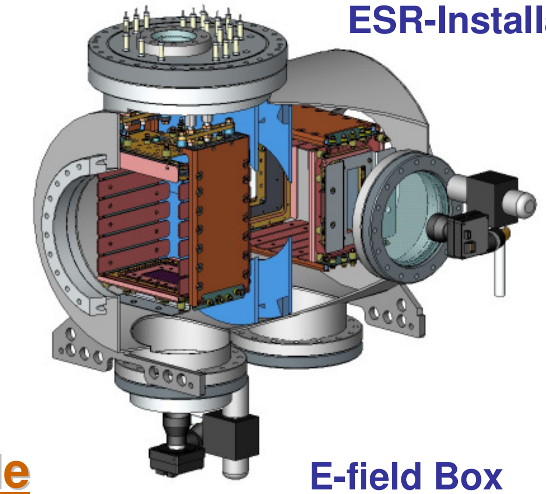
- 12 BPMs, 12 LIBERAs, 2 concentrator servers
- 10 GBit Network, high data rate: 720 MB/s
- DAQ software: FESA classes (Cosylab)
- online tune evaluation (FFT)

Ionization Profile Monitor (IPM) for SIS100

Goals

- measurement of **transverse beam profile**
- emittance determination, evolution and changes due to **RF manipulations**
- detection of emittance growth
- monitoring of **fast profile changes** in turn-by-turn mode

ESR-Installation



Requirements

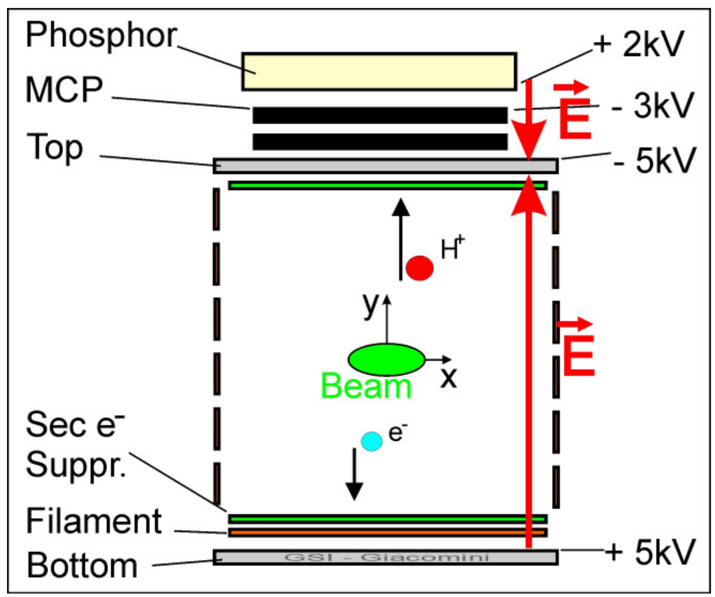
Electrons or ions detection:

- E-field (extraction) (E≈±50 V/mm, 1% inhomog.)
- B-field (guidance) (B≈30 mT, 1% inhomog.)

Two photo-detector types:

- **High spatial-resolution mode:** CCD readout (100 µm resol.)
- **Turn-by-turn mode:** array of photo-multiplier tubes (~1 µs time resolution)

Detection Principle

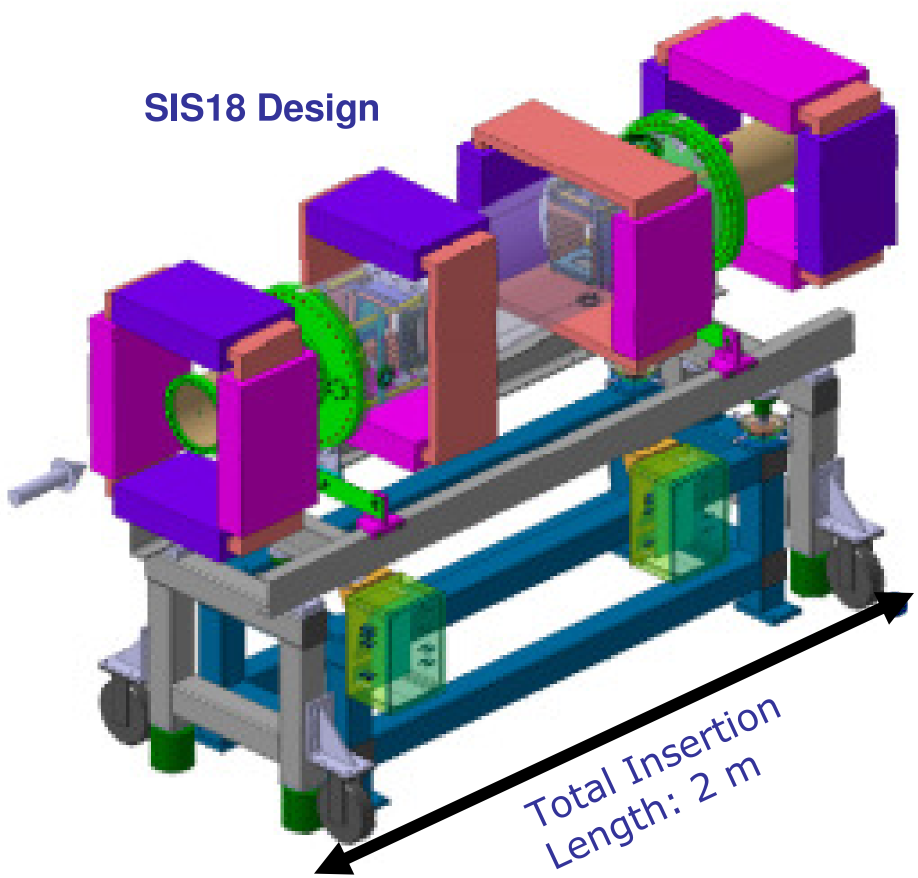


E-field Box

Advanced IPM (Turn-by-Turn Measurements)

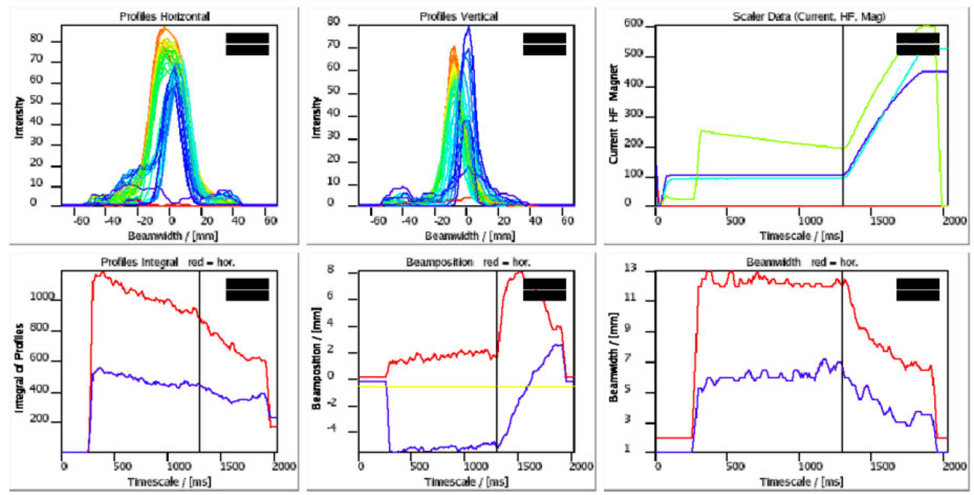
Mechanical Construction

SIS18 Design



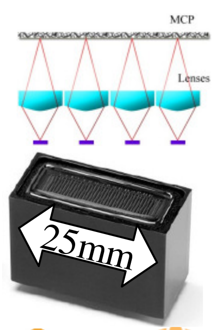
(Magnet Design by iThemba Labs, South Africa)

Measurement of Transverse Profile



Ongoing R&D

- **fast readout for turn-by-turn mode**:
  - development of digitizer board for PMT array (ITEP, Moscow)
  - FPGA, DSP electronics for high time resolution: **1 profile each 100 ns**
- **PMT array:**



High Energy Beam Transport (HEBT) Section

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

High Dynamic Range

- **low** and high intensities (10^4-10^{13} /pulse)
- **slow** and fast extraction (μs – s)

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

Dedicated Developments

- non-intercepting high-sensitive intensity measurement

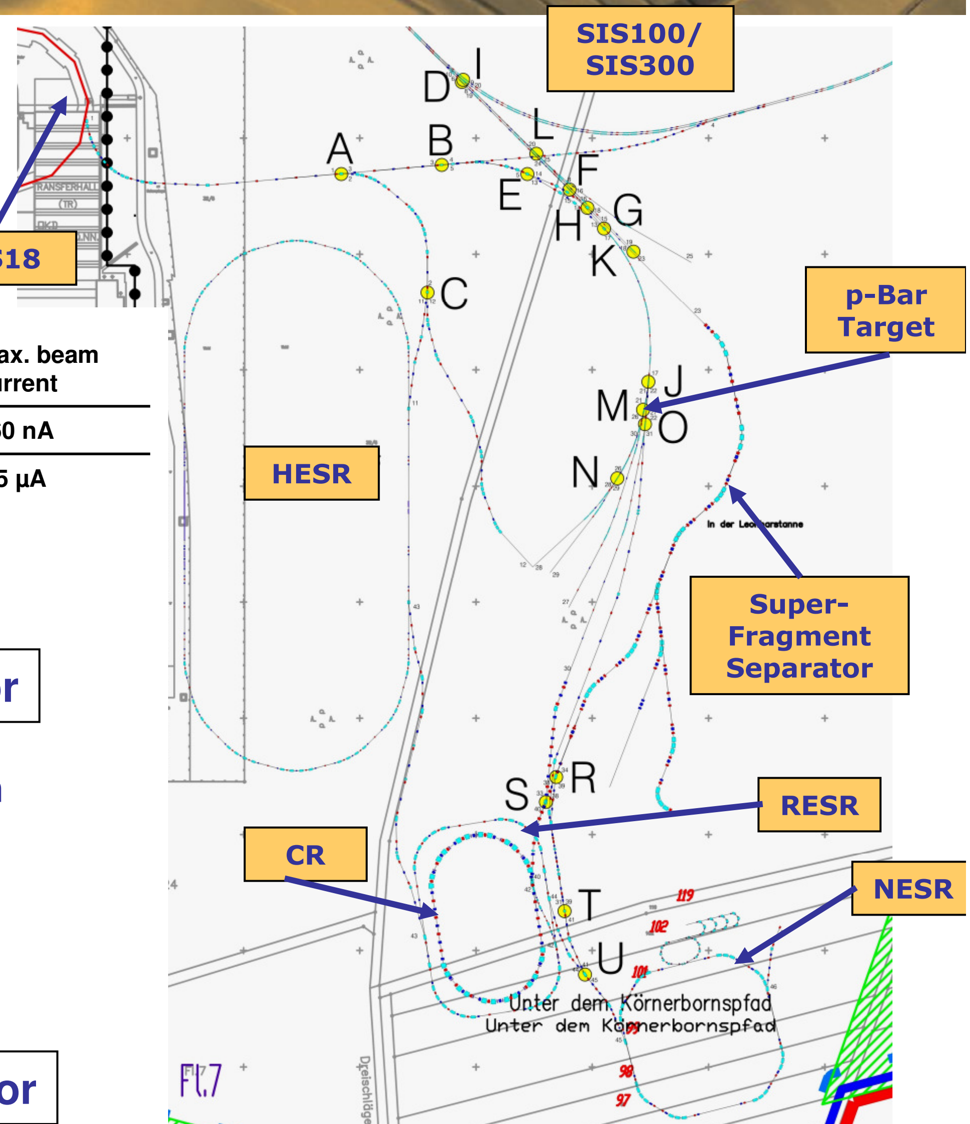
  → **Cryogenic Current Comparator**

- electronics for sensitive, time-resolved beam profile measurement

  → **Charge-to-Frequency Conv. QFW**

- non-intercepting Beam Profile Measurement

  → **Beam Induced Fluorescence Monitor**



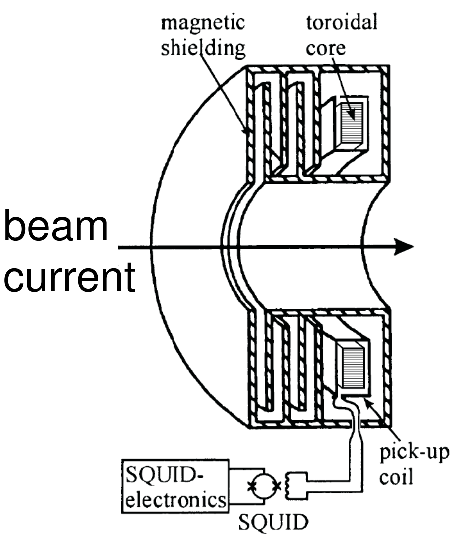
Cryogenic Current Comparator CCC (HEBT)

Role in HEBT Section

- online current monitoring for **slow extracted beams**
- beam current **below threshold of regular transformers**

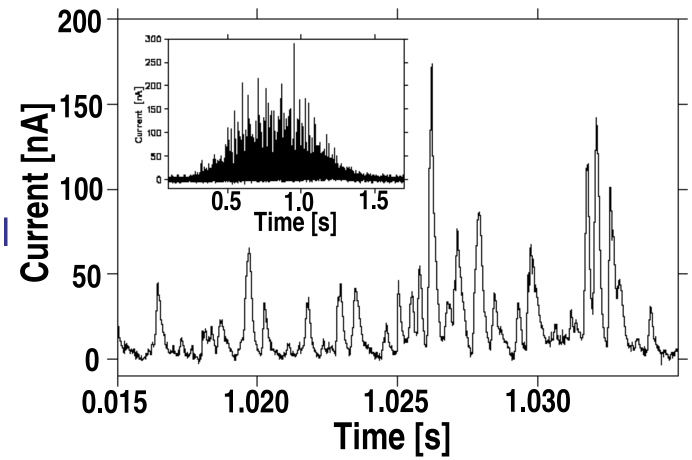
GSI prototype in 1997:

Measurement Principle



- high-resolution detection of the **beam's magnetic field**
- **superconducting pick-up coil** with ferromagnetic core
- **SQUID** for sensitive detection of coil magnetic field
- collaboration: Univ. Jena, MPI-K Heidelberg, HIT Heidelberg, GSI
- resolution improvement by optimal **selection of core material**

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



- GSI prototype resolution:

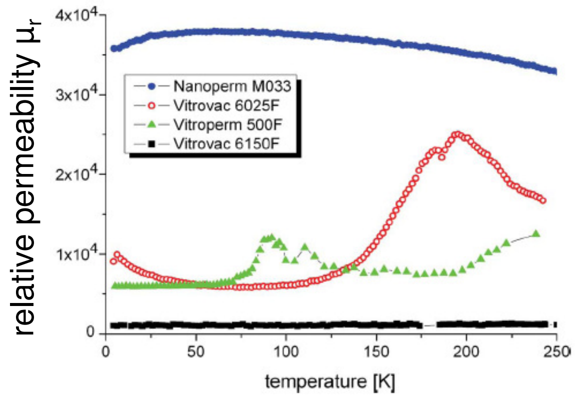
  8 nA (1 kHz readout) $\longrightarrow$ **2×10^{9} U^{28+}/s**

Special Requirements / Challenges

Possible Optimizations to Improve CCC Sensitivity / Reduce System Noise

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

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



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

3. ferromagnetic core material

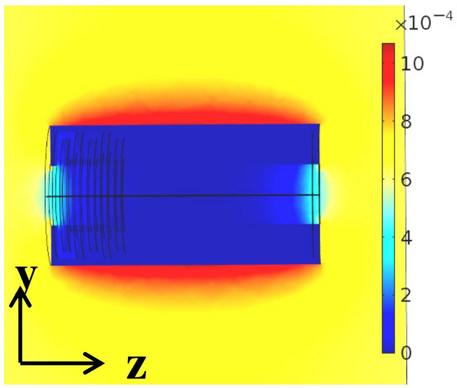
$$\frac{I_S}{I_N} \propto \sqrt{\mu_r}$$

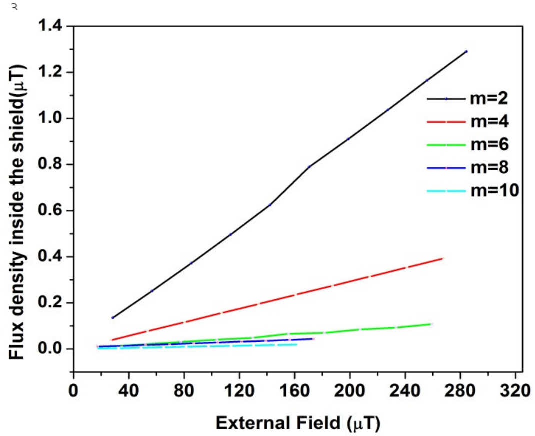
→ search for core material **with highest relative permeability**

Engineering Challenges:

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

FEM Simulations of Magnetic Shield



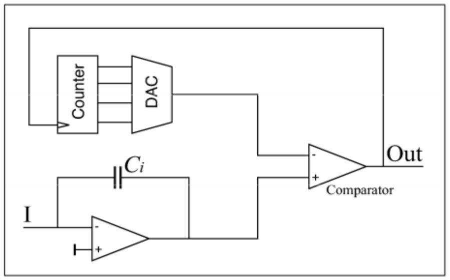


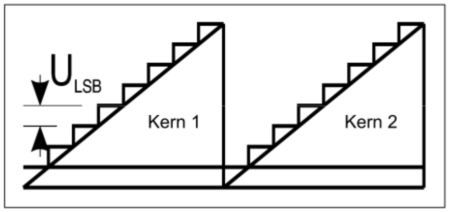
HEBT: Profile Grid Readout

QFW: Charge-to-frequency conversion

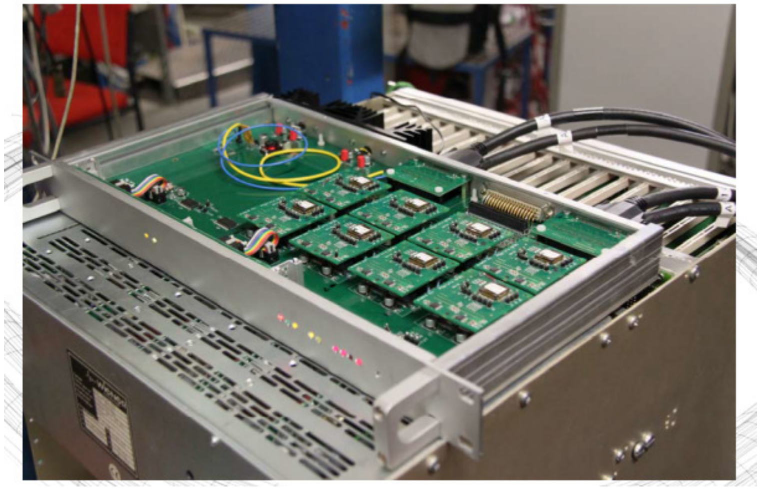
QFW ASIC Working Principle

- 2 QFW cores / channel
- 1st core: integration of input charge
- comparator: U > U_thres increase counter
- at overrun: activate 2nd core, delete 1st core
- linear dependance of output freq. and input current f=I/Q



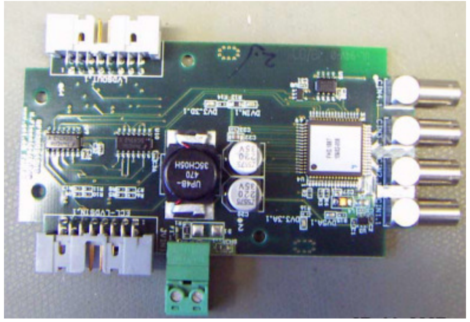


Setup with 8 QFW-ASICs (32 Chan.)



QFW-Module (H. Flemming, Dep. EE)

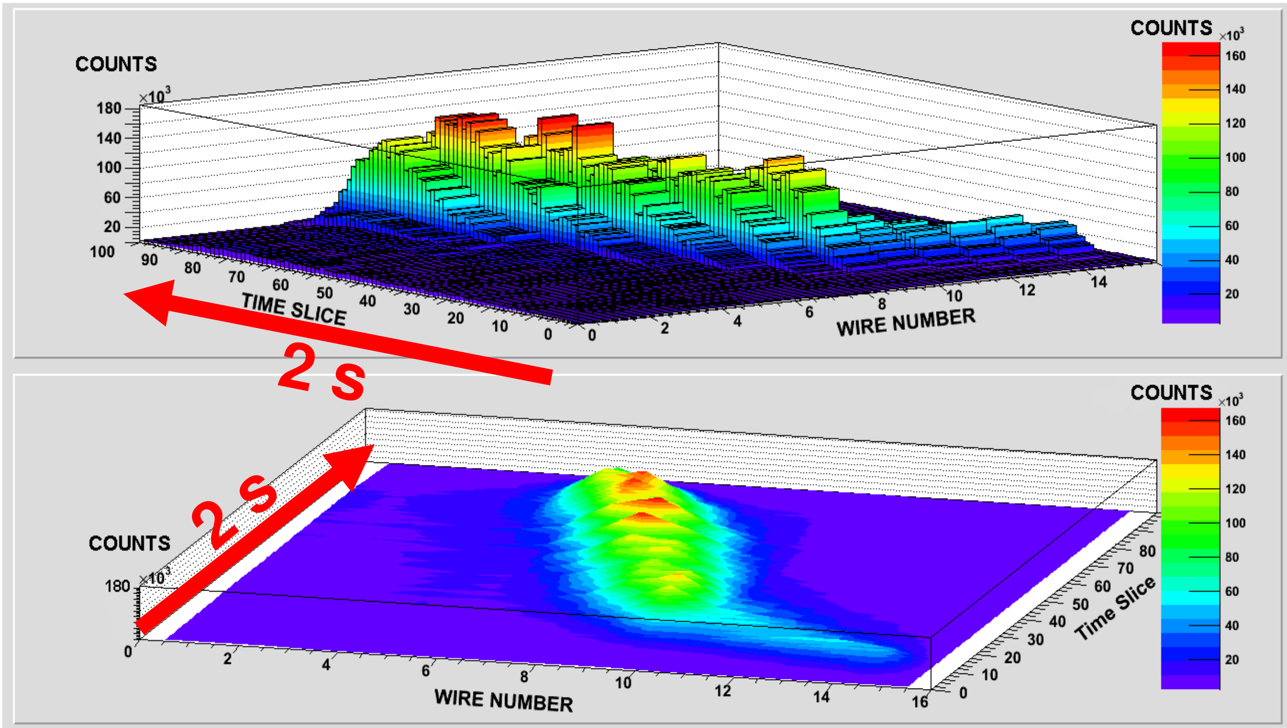
- 4 input channels
- ASIC with two ranges (0.24 / 2.4 pC/Pulse)
- large dynamics (300 fA – 180 µA)
- output frequency 4 / 40 MHz
- full digital interface



QFW: Prototype Measurements

Example for Prototype Test Measurement:

- First Test Measurements using Multi-Wire Proportional Chamber (MWPC)
- Test Setup in GSI HEBT Section



Beam Parameters:

- $^{40}Ar^{18+}$ ion beam at 300 MeV/u
- vertical time-dependent beam profiles for 1/2 MWPC x-plane (16 out of 32 wires).
- spill duration: 1.8 s, time slices of 20 ms
- for this measurement: beam mismatched on purpose

Details: see poster of M. Witthaus, S. Löchner

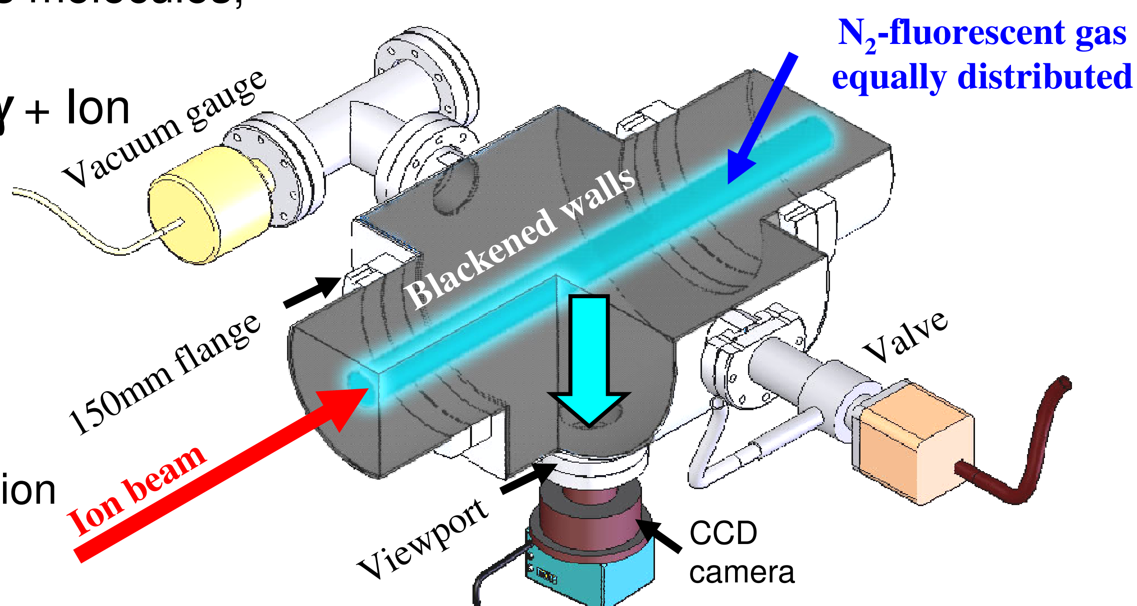
Beam Induced Fluorescence Monitor

Detecting ***photons*** from working gas molecules,
e.g. Nitrogen

$N_2 + \text{Ion} \rightarrow (N_2^+)^* + \text{Ion} \rightarrow N_2^+ + \gamma + \text{Ion}$

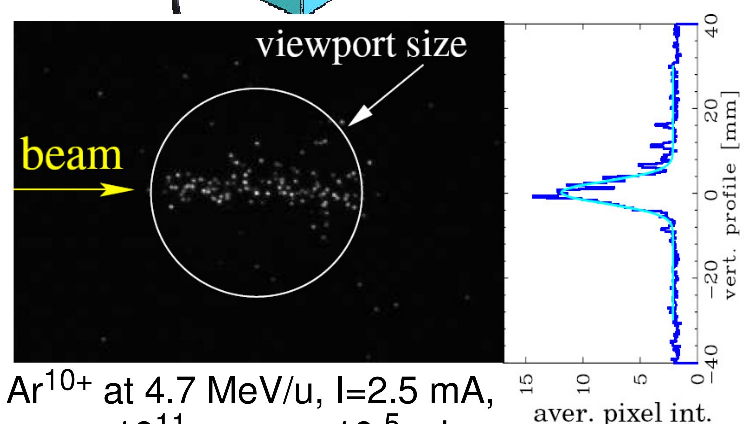
390 nm< λ< 470 nm

emitted into solid angle Ω to camera
single photon detection scheme



Features:

- Transv. profile: projection in z-direction
- High resolution (here 0.2 mm/pixel) can be matched to application
- Single pulse observation possible down to ≈10 µs time resolution
- Commercial Image Intensifier
- Less installations inside vacuum as for IPM



Beam: Ar^{10+} at 4.7 MeV/u, I=2.5 mA, 10^{11} ppp, p=10^{-5} mbar

P. Forck, Proc. IPAC'10

F. Becker et al., Proc. DIPAC'07, DIPAC'11

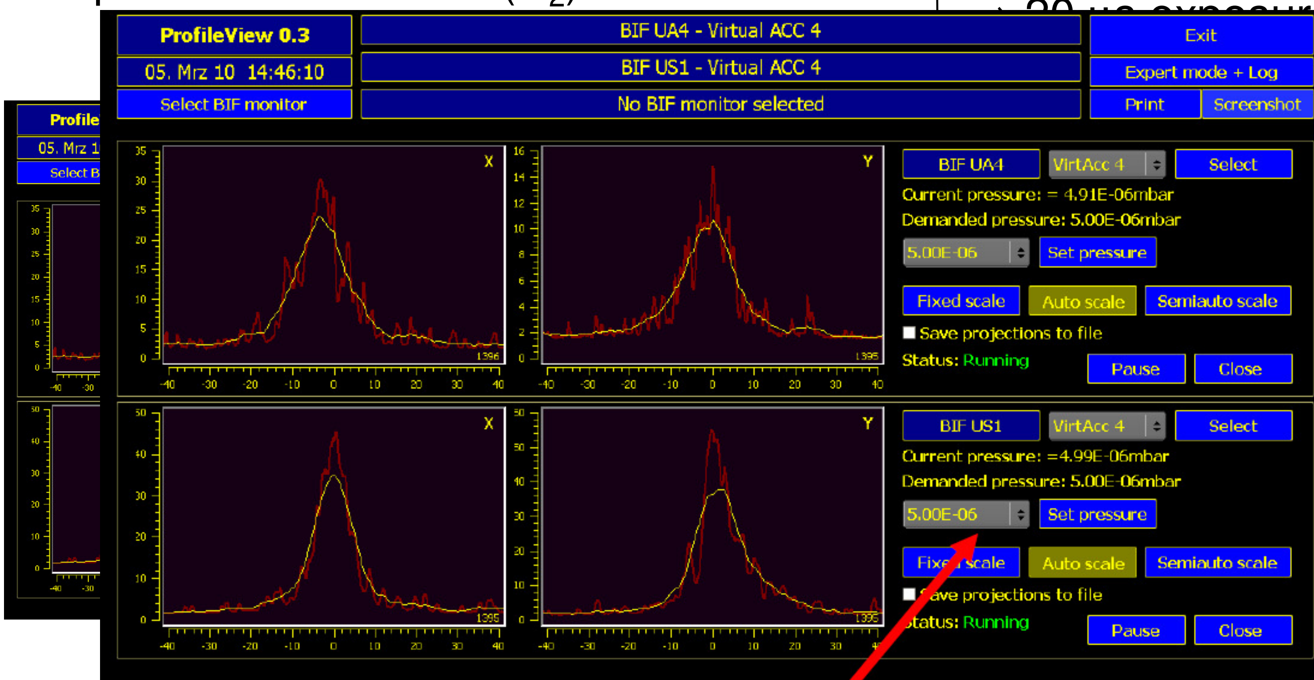
Examples from Ion LINAC at GSI

Single pulse observation

One single macro pulse of 200 µs

Typical vacuum pressure*:*

$p=10^{-6}$ to 10^{-5} mbar (N_2)



System ready for operational usage:

Presently at 4 locations along UNILAC

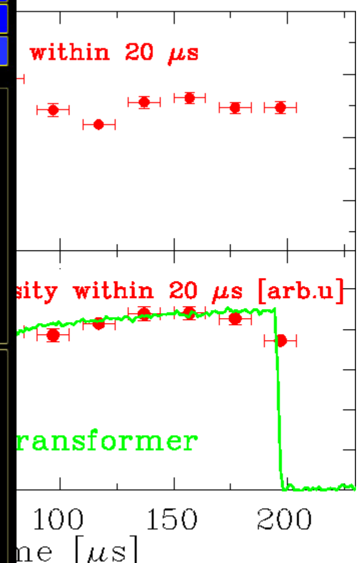
3 more in preparation.

Time resolved observation

Variation ***during*** the macro pulse detectable:

Switching of image intensifier (within 100 ns)

→ 20 µs exposure window during macro-pulse



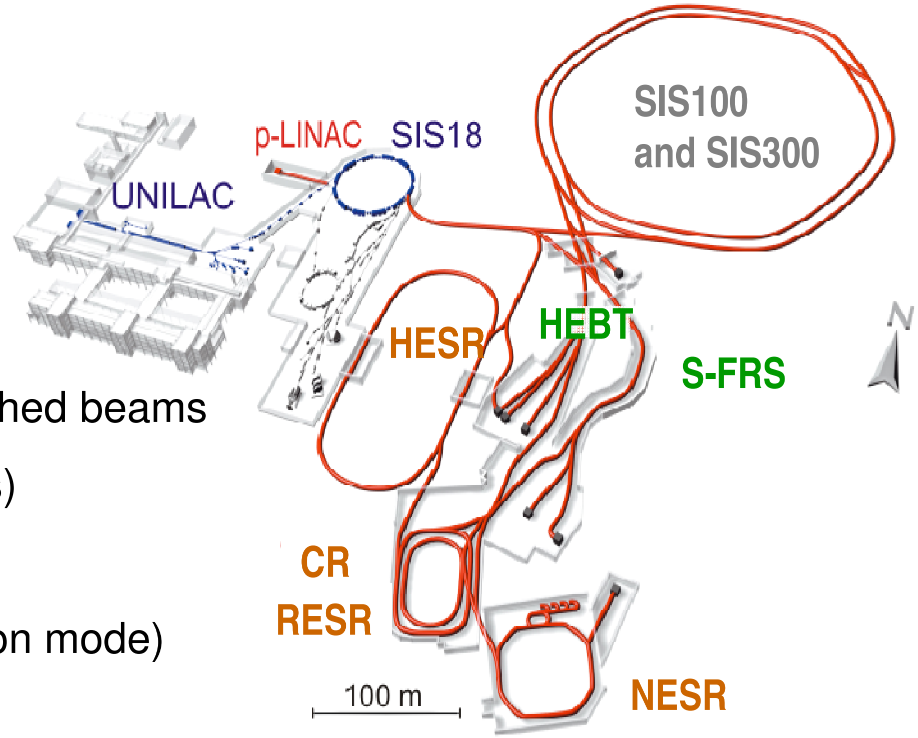
8 mA Ar^{10+}
at 11 MeV/u

…roportional to beam current

Further application: Background suppression by matching the exposure to beam delivery

Summary

- FAIR
  - ▲ multi-national large-scale accelerator project as 'Modularized Start Version'
- SIS100
  - ▲ novel DC Current Transformer for MHz-bunched beams
  - ▲ mechanical BPM design (metalized ceramics)
  - ▲ development of BPM pre-amplifier quartet
  - ▲ Ionization Profile Monitor (fast / high resolution mode)



- HEBT
  - ▲ Sensitive current measurement using Cryogenic Current Comparators
  - ▲ QFW for time-resolved transverse beam profiles
  - ▲ Beam Induced Fluorescence for non-intercepting beam profiles

Acknowledgements

- **Beam Position Monitor**
  - D. Liakin, ITEP, Moscow
  - CERN-CO, CERN-BI for the FESA-Collaboration
  - Kyocera, Japan
  - Instrumentation Technologies, Slovenia
  - Cosylab, Slovenia
  - Jozef Stefan Institute, Slovenia
- **Cryogenic Current Comparator**
  - W. Vodel, R. Neubert, R. Geithner, Friedrich-Schiller-University Jena
  - R. v. Hahn, MPI-Kernphysik, Heidelberg
  - A. Peters, HIT, Heidelberg
- **QFW-Electronics**
  - Colleagues from Experiment Electronics Department: J. Adamczewski-Musch, H. Flemming, J. Frühauf, S. Löchner, P. Skott
- **Ionization Profile Monitor**
  - J. Dietrich, V. Kamerdzhiev, FZ Jülich
  - D. Liakin, ITEP, Moscow, Russia
  - G. de Villiers, L. Conradie, iThemba Labs, South Africa

Thank you for your attention!

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