BEAM DIAGNOSTICS CHALLENGES AND INNOVATIONS FOR FAIR*

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Abstract

The planned FAIR facility will consist of two heavy ion synchrotrons for high current operation and four large cooler storage rings. A complex operation scheme with multiple use of the transport lines is foreseen. The facility demands an exceptional high dynamic range from the beam instrumentation. Due to the large beam power, non-destructive methods are mandatory for high currents. Precise measurements of all beam parameters and automatic steering or feedback capabilities are required. Due to the ultra-high vacuum condition and the demanding measurement accuracy, novel technical solutions are foreseen. An overview of the challenges and projected innovative solutions for various diagnostic installations is presented.

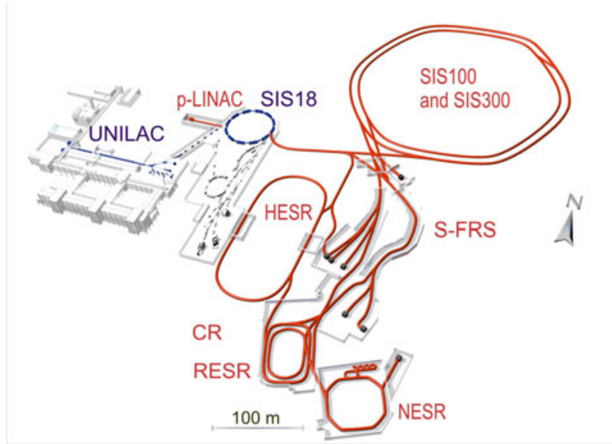

Figure 1: Layout of the existing (blue) and new (red) FAIR facility.

DEMANDS FOR FAIR-DIAGNOSTICS

The Facility for Anti-Proton and Ion Research FAIR, as shown in Fig. 1, will be a very versatile accelerator complex for all ion species from protons up to Uranium [1]. Beside a new proton-LINAC, the existing UNILAC and SIS18 will serve as injectors, but up-grades for high current operation are under way. High currents of primary beams, even in low charge states, will be stored and accelerated with a large in-coherent tune spread up to $\Delta Q \simeq 0.5$ in the super-conducting SIS100. The design cases are $5 \cdot 10^{11}$ U^{28+} ions at an energy of 1.5 GeV/u and $4 \cdot 10^{13}$ protons at 29 GeV. SIS300 serves as a stretcher ring or, after further stripping, as an accelerator for heavy ions up to GeV/u. Radioactive ions can be generated either for investigations at fixed targets or injection into the storage rings. They are stochastically cooled in CR and RESR and electron cooled in NESR. Further beam manipulations including deceleration are possible there. The NESR also serves as an experimental tool for cooled stable ions. The anti-protons are pre-cooled in the CR and accumulated in the RESR, before being accelerated up to 14 GeV in the HESR. Here high energetic electron cooling enables spectroscopic investigations at an internal target. Pulse-to-pulse operation with different ion species and beam parameters is an integral part of the facility.

Deduced from the accelerator parameters, the following main demands for beam diagnostics are challenging and require detailed R&D, which is partly started:
Common realization: Although the beam parameters of the FAIR synchrotrons and storage rings are quite different, common realizations for all accelerators are mandatory to save man-power during the R&D phase and to reduce the costs during construction.

Large dynamic range: The central characteristic of FAIR is the large dynamic range, demanding about a 120 dB measurement possibility. A wide variation of beams will be stored, accelerated or decelerated, ranging from low current secondary beams up to space charge limited intensities of heavy ions with quite different time structures. In the transfer lines this high dynamic range of ion species, intensities and energies requires destructive diagnostic methods for low currents and, in parallel, non-destructive devices for high currents to prevent material melting by the large beam power.
Precise beam alignment: Because the acceptance is limited to about 3×emittance (KV-Distribution) in the synchrotrons and 2×emittance in the transfer lines, a precise alignment of the beam is strongly advised. The beam diagnostic systems have to provide the capability for online feedback with respect to closed orbit, betatron tune, chromaticity and coupling.
Beam losses: Because the loss budget in the superconducting synchrotrons is only a few percent, current measurements with high relative accuracy of $\sim 10^{-4}$ are mandatory. This also applies for the transport lines, which are partly equipped with superconducting magnets.
Background radiation: The radiation level in some parts of the accelerator will be high, calling for radiation-hard electronics or special shielding.
Compactness and vacuum conditions: Additional constraints have to be fulfilled: compact installation due to the limited insertion space, partly in the cryogenic regions and the UHV condition with a pressure down to $5 \cdot 10^{-12}$ mbar.
Parallel operation: The versatile parallel operation scheme demands a highly flexible data acquisition.
On this background, a variety of challenges concerning the beam diagnostics have to be dealt with and five recent developments are summarized below.

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Table 1: The foreseen diagnostics and the most frequent applications in synchrotrons and storage rings.

Device	*Measurement*	*Application*
DCCT	dc-current	stored current, lifetime
GMR-DCCT	dc-current	for high currents
CCC	dc-current	for low currents
ACCT	Pulsed current	injection efficiency
BPM	center-of-mass	closed orbit & feedback turn-by-turn lattice functions
Exciter+BPM	center-of-mass	tune, BFT, PLL
Quad. BPM	quad. moment	BTF, matching
Schottky	longitudinal: transverse:	$\Delta p/p$, cooling tune, chromaticity
WCM or FCT	bunch structure	matching, bunch gymnastics
IPM	beam profile	cooling, matching
BLM	beam loss	matching, halo, scraper, losses
Grid/Screen	beam profile	first turn

SYNCHROTRON DIAGNOSTICS

The foreseen diagnostic devices for the high current synchrotrons and the cooler rings are presented in Table 1. Nearly all devices require R&D to extend the existing realizations toward the technical limits for either high intensities in the synchrotrons or high resolution and low detection threshold in the cooler rings.

Current Measurement by GMR-DCCT

The expected dc and bunch currents should be measurable with a standard current transformer like the NPCT from company Bergoz. But bunches with only a few MHz repetition rate can heavily disturb the feedback loop of such a device, which in the case of the GSI-designed DCCT looses control above I_{dc}~100 mA at f_{bunch}~1.2 MHz, corresponding to I_{peak}~1 A [2]. For the Bergoz NPCT this threshold is probably higher. This will be tested at GSI in fall 2006. An alternative device is under consideration, which is based on the idea of a clip-on Amperemeter with a Ø230 mm flux concentrator made of VITROVAC 6075F. Two gaps are foreseen with an estimated induction of ~1 mT for a 10 A peak current. The parameters of most suitable, commercially available GMR (Giant Magneto-Resistance) sensors for the magnetic field have a noise limited resolution down to 10^{-9}T/$\sqrt{\text{Hz}}$ and a saturation field of up to some mT, which fits to the assumed magnetic parameters for a bandwidth of 10 kHz. A test set-up for SIS18 is under construction [3].

The Layout for the BPM system

The requirements for the BPMs at SIS100 are:

- The BPM has to fit in the cryogenic modules.
- For impedance matching, the shape of the BPM should be elliptical like the beam pipe.

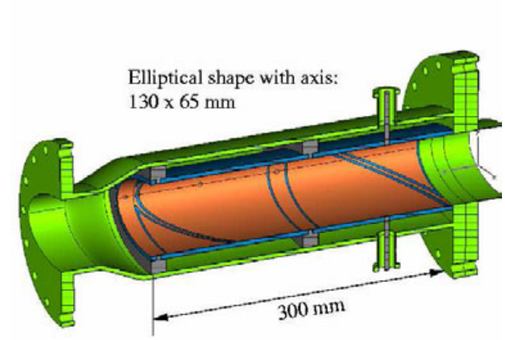

Figure 2: Sketch of a BPM for the cryostat of SIS100.

- The materials have to be compliant to the UHV.
- The aspired position resolution is < 100 μm, leading to a mechanical stability better than 50 μm.

A linear-cut BPM is well suited for non-relativistic beam energies and offers the best linearity. To guarantee the mechanical stability within 50 μm under cryogenic conditions, a metal coated ceramic tube is proposed, as shown in Fig. 2. Based on finite element calculations by CST Microwave Studio, guard rings between the electrodes are necessary for the desired position resolution [4].

The signal will be treated by a low noise amplifier/attenuator chain with 120 dB dynamics and a bandwidth of 50 MHz for best utilization to the 14 bit ADCs. It will be digitized with 125MSa/s to enable base-band processing. We chose a Libera from Instrumentation Technology as hardware platform. The raw data are transfered to a Xilinx Virtex II Pro FPGA, where digital filtering and dedicated algorithms for position calculations are performed [5]. In particular, during the bunch forming phase at the beginning of the acceleration an optimized bunch detection scheme with baseline reconstruction is important to improve the position accuracy. Bunch-by-bunch data could be evaluated and stored for the full cycle. An accuracy of 150 μm has been demonstrated at SIS18 in this mode. A better accuracy can be achieved by a reduced time resolution and a closed-orbit feedback capability is foreseen using this error signal.

Ionization Profile Monitor

The determination of the transverse emittance and its evolution during acceleration and cooling will be performed by an Ionization Profile Monitor (IPM). It is based on a secondary electron detection using a MCP combined with a phosphor-screen for the readout, see Fig 3. In a high resolution mode, the phosphor is read by a CCD camera at a rate of about 100 fps. For the cooler ring application, a spatial resolution of 50 μm should be reached. A device test is planned for fall 2006. A fast mode with a turn-by-turn profile determination, mainly for the synchrotron application, is foreseen to control the injection matching and to visualize any possible emittance enlargement during acceleration. Because of the short revolution period, a profile determination within less than 1 μs is a challenge and will be performed by an array of 100 sensitive light detectors. These detectors can be either Avalanche Photo Diodes

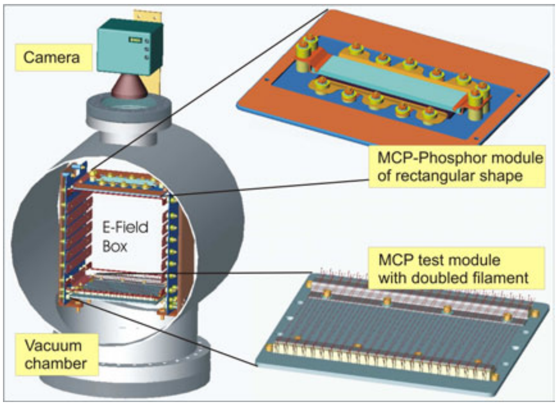

Figure 3: Sketch of the IPM of clearance 175×175 mm^2.

(APD) or multi-anode photo-multipliers. The analog and digital readout electronics for a single-channel has been developed [6]. As an innovative alternative we investigate the recently developed Silicon Photo-multiplier (SiPM), where an array of small APDs are biased for Geiger-mode operation to overcome the temperature sensitivity of APDs and the count-rate limitation of PMs [7].

For the intense beams at the synchrotrons, a magnetic field of 30 mT is required to guide the secondary electrons toward the MCP-detector. A field uniformity of 1 % is necessary for a magnet with an exceptional large clearance of 480 mm. We designed solutions based on electromagnets and on permanent magnets made of rod with an azimuthal varying magnetization [8]. Accompanied to the main dipole, magnets with reversed field orientation are foreseen to compensate the beam offset during the passage. The whole assembly should fit into the limited insertion length of $\sim$2.5 m.

TRANSPORT LINE DIAGNOSTICS

For the transport lines the wide variation of beam species and currents as well as the different demands for fast and slow extraction lead to various devices, as listed in Table 2. Beside the large dynamic range of all devices, dedicated developments have been started for non-destructive devices.

Cryogenic Current Comparator

Non destructive, low dc-current measurement is required for slow extraction monitoring and transmission control. Even for the highest intensities, the dc-current in the transport lines are well below the $\sim$1 μA detection threshold of a regular dc-transformer. Some years ago we demonstrated the applicability of slow extraction monitoring with several nA resolution by a Cryogenic Current Comparator (CCC) [9]. The very low magnetic field of the beam is detected with a SQUID connected to dedicated electronics, which requires careful shielding against external fields and high temperature stability to prevent offsets and drifts. With an improved version, a resolution of 0.25 nA/$\sqrt{\text{Hz}}$ is achieved [10]. For FAIR the CCC will be installed behind the synchrotrons and in front of the high current targets. Moreover, the low current of RIB or stable beams inside the storage rings can be determined in an absolute manner.

Table 2: The foreseen transport line diagnostics and their applications for fast and slow extraction.

Device	*Measure*	*Extr.*	*Application*
Resonant Trans.	pulse charge	fast	transfer eff.
CCC	current	slow	transfer eff., high currents
Particle Detect.	current	slow	transfer eff., low currents
WCM or FCT	bunch struc.	fast	transfer eff.
BPM	center	fast	position
SEM-Grid	profile	fast	profile
MWPC	profile	slow	profile
Screen	profile	f&s	profile
IPM or BIF	profile	f&s	profile, high currents
BLM	beam loss	f&s	matching interlock

Beam Induced Fluorescence Profile Monitor

For the profile measurement of intense beams the Beam Induced Fluorescence BIF was investigated [11]. Within a vacuum bump of N_2 the fluorescence in the blue wavelength region is detected in 'single photon mode' by an image intensified CCD camera. The applicability was demonstrated. In particular, it will offer a compact installation with short insertion close to the targets. But a careful shielding of the image intensifier might be required due to the large amount of neutrons, as figured out for the test installation close to a beam dump.

Acknowledgment

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REFERENCES

[1] P. Spiller et al., *Proc. EPAC06 Edinburgh*, p. 24 (2006).
[2] H. Reeg, 2ndCARE-HHH-ABI Workshop, Lyon, 2004, http://adweb.desy.de/mdi/CARE/Lyon/ABI-Lyon.htm.
[3] M. Häpe et al., *Proc. DIPAC05 Lyon*, p. 102 (2005).
[4] P. Kowina et al., *Proc. EPAC06 Edinburgh*, p. 1022 (2006).
[5] A. Galatis et al., *Proc. DIPAC05 Lyon*, p. 184 (2005) and A. Galatis et al., *Proc. EPAC06 Edinburgh*, p. 1019 (2006).
[6] D. Liakin et al., *Proc. DIPAC05 Lyon*, p. 154 (2005) and D. Liakin et al., *Proc. DIPAC05 Lyon*, p. 150 (2005).
[7] S. Barabin et al.,*Proc. EPAC06 Edinburgh*, p. 1172 (2006).
[8] V. Skachkov et al., *Proc. RuPAC06 Novosibirsk* (2006).
[9] A. Peters et al., *Proc. DIPAC99 Chester*, p. 109 (1999).
[10] W. Vodel et al., *Proc. EPAC06 Edinburgh*, p. 1070 (2006).
[11] F. Becker et al., *Proc. EPAC06 Edinburgh*, p. 10 13 (2006).