BEAM DIAGNOSTIC DEVELOPMENTS FOR FAIR*

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Abstract

The FAIR (Facility for Antiproton and Ion Research) accelerator complex is currently designed and projected at GSI. The unique features of the main machine SIS100, like e.g. the acceleration of high intensity beams of 2.5×10^{13} protons and 5×10^{11} Uranium ions, the operation close to the space charge limit leading to a large tune spread and the extreme UHV conditions of the cryogenic system for fast ramped superconducting magnets, impose challenging demands on the beam diagnostic components. This contribution describes the general concept of beam diagnostics for FAIR and reports on the present status of prototype studies. Exemplarily the achievements for a novel type of dc transformer, beam position monitors and the ionization profile monitor are discussed and first measurements with prototype setups are presented.

FAIR ACCELERATOR COMPLEX

Presently GSI entered the final planning phase for the international FAIR project [1]. The existing GSI accelerators, UNILAC and SIS18, together with a new high-current proton LINAC will act as injectors. In its final stage FAIR will consist of two heavy ion synchrotrons (SIS100, SIS300) and four storage rings (CR, RESR, NESR, HESR). The main features of FAIR are: acceleration of all ion species from protons to Uranium, high currents of primary beams, generation of radioactive beams for fixed target experiments or injection in storage rings, as well as antiproton production, accumulation and storage ring experiments. For the planned large variety of physical experiments the multiplexed operation of the whole facility with different settings for ion species, energy etc. on a pulse-to-pulse basis, has been an important design criterion. In this contribution we focus on diagnostics for the fast ramped superconducting synchrotron SIS100 and the high energy beam transport section of FAIR.

REQUIREMENTS FOR DIAGNOSTICS

A set of general strategies has been considered in order to facilitate the construction of the facility with world-unique complexity. A main paradigm is the facility-wide standardization of diagnostic devices. Even though the requirements of the synchrotrons and storage rings differ, it is planned to use identical diagnostic installations wherever applicable. Standardization also covers the front-end software FESA [2] as an integrative platform for all diagnostic devices at FAIR. Concerning the hardware it is planned to use commercially available components to a maximum extent, in order to reduce manpower and spares inventory.

FAIR beam parameters impose strict requirements for all diagnostic devices. A strong constraint with regard to mechanics is the extreme UHV condition down to 5×10^{-12} mbar in SIS100. In this main synchrotron, high currents (up to the space charge limit) of primary beams in low charge states will be stored and accelerated with a large incoherent tune spread of up to $\Delta Q\approx0.5$. An important prerequisite is the precise beam alignment since in certain locations the synchrotron acceptance is limited to 6 times the rms beam width. For the High Energy Beam Transport section of FAIR the acceptance is even lower, four times the rms beam width. The goal for diagnostics in transport lines and storage rings is to achieve a high resolution and low detection limit. Additionally, the HEBT diagnostic devices have to deal with slow and fast extracted beams, respectively. Due to the requirement for online measurements and in order to prevent device destruction at high beam intensities, non-intercepting diagnostics is preferred and focused on in this contribution.

BEAM CURRENT MEASUREMENT

Novel DC Current Transformer (NDCCT)

For the GSI-built synchrotron DCCT, it was found that at high beam currents (>70mA) and bunch frequencies around 1.2 MHz the feedback loop of the DCCT loses control and the setting of the correct working point becomes unreliable. Therefore an alternative device based on state-of-the-art sensor technology is presently under development at GSI [3]. The NDCCT makes use of integrated GMR sensors (giant magneto-resistance) inside the gap of a split flux concentrator (amorphous alloy or ferrite toroid). The GMR signals are corrected and amplified by a differential pre-amplifier. Additionally, an AC transformer path is implemented by a secondary winding. Special requirements for the NDCCT are: low noise characteristic, high resolution (~100 µA), capability to measure beam currents from 100 µA to 150 A (2 A DC), bunch frequency up to 5 MHz, long-term zero-point stability and high absolute accuracy.

The utilized GMR sensor (AA-0002, Nonvolatile Electronics Co.) consists of 4 meandered resistors and 2 flux concentrators, building up a Wheatstone bridge. Studies on the frequency response revealed that the sensor circuitry spans inductive loops and, above a certain threshold frequency, the frequency response of the GMR sensor becomes disturbed. The upper frequency threshold was found to be a result of macroscopic effects like unwanted induced voltages in the sensor, eddy currents and skin effects in the GMR's NiFe-layer, leading to a reduced bridge voltage above the cut-off frequency of 1 MHz, as depicted in Fig. 1. The GMR frequency response is shown for different core materials (CMD5005,

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VITROVAC6025F) and different magnetic remanences. An important goal for the NDCCT design is to reach an overall resolution in the 100 µA region. The NDCCT resolution is dominated by system noise, while the noise contribution of the passive ACT-part is negligible with respect to the GMR noise. The lower resolution limit was estimated by detection of the broadband sensor noise (GMR+pre-amp). For S/N=2, the measurement of the minimum power spectrum density yields 88 nV/√Hz.

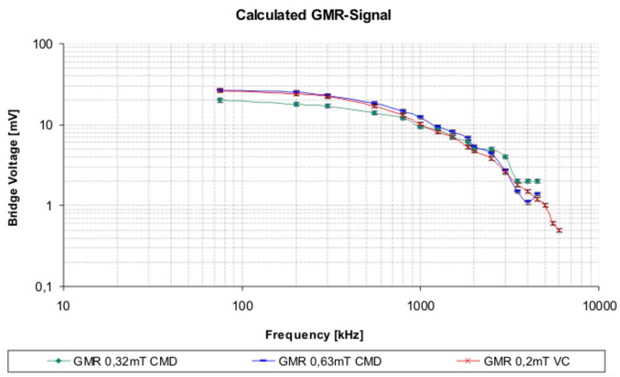

Figure 1: GMR signal vs. frequency.

Due to the system cut-off frequency of 1 MHz, the sampling rate has to be 2 MHz leading to signal amplitude of ~88 µV. Thus, the calculated minimum detectable beam current is as low as 220 µA. The electromagnetic interference of the unshielded test setup was found to be quite high and reduction of the interfering signals will be studied after the design of the readout electronics has been finished.

Cryogenic Current Comparator (CCC)

Because the CCC allows non-intercepting beam current measurements down to the nA-range [4] its installation inside HEBT beamlines is foreseen. The measurement principle of a CCC is based on the effect that for an ideal superconductor the magnetic flux is expelled from the bulk material through shielding currents on the materials surface. The magnetic field of a passing ion beam is measured by a superconducting toroid including a single winding pick-up coil with a ferromagnetic core. The coil signal is fed into a DC SQUID and digitized. In order to achieve a high current resolution in the nA-range both, the SQUID and the pick-up coil, have to be effectively shielded against external magnetic fields. A detailed investigation on noise contributions of the ferromagnetic core material was carried out. The theoretical calculations have shown that, apart from a good attenuation of external fields, the CCC resolution strongly depends on the choice for the coil material. Thus a wide range of ferromagnetic materials has been investigated with respect to their permeability as a function of temperature (down to 4.2 K) and frequency (dc to 10 kHz) [5]. The best choice for the core material is NANOPERM (Magnetec GmbH). The next step is to manufacture a prototype coil structure and to implement it in a vacuum chamber with cryostat. Further details of the CCC prototype development can be found in [6].

PROFILE MEASUREMENT

Ionization Profile Monitor

The ionization profile monitor (IPM) allows non-intercepting detection of transverse beam profiles. Profiles of the circulating beam inside the synchrotron are monitored by detection of the ionized residual gas molecules (e.g. H_2). Here a transverse electric field is applied to accelerate either (depending on polarity) the ionized gas atoms of the residual gas or the emitted electrons towards a spatial resolving Micro-Channel Plate phosphor module. An electric field of 50 V/m is realized with an inhomogeneity of less than 1% by dedicated field forming electrodes to ensure position preservation. Additionally, if electrons shall be detected, a guiding B-field of ~30 mT is required, as calculated using FEM simulations.

The IPM installation in SIS18 is operative since 2003 and the device has become almost a standard tool for beam tuning. Exemplarily, Fig. 2 shows measurement results for the beam profile evolution at different levels of noise excitation leading to significant emittance blow-up.

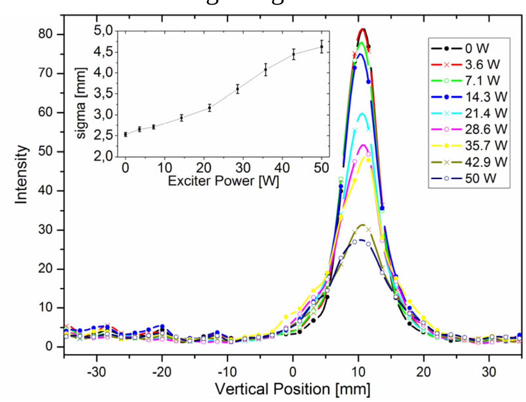

Figure 2: IPM measurements of vertical beam profile for different exciter settings. Insert: beam width sigma (Gaussian fit to beam profiles) vs. exciter power.

As part of an EU-FP6 project the new development of an advanced IPM for SIS18 was launched as a prototype for FAIR IPMs. As a first step a test bench was constructed to investigate a new concept for MCP installation. The test bench includes an UV lamp for calibration of the MCPs (100×48 mm^2), including a phosphor screen for the conversion of the electron signal to blue light. This P47 screen has a decay time of 100 ns. For the advanced IPM two measurement modes are foreseen: 1) high spatial resolution by CCD, 2) turn-by-turn readout by PMT. In mode 1 the goal is to reach a high spatial resolution of 0.1 mm at the cost of a lower time resolution of typically 10 ms. For this mode a triggered GigE CCD camera (framerate 200 frames/s) digitizes the fluorescent image of the MCP. The standalone front-end software for CCD readout exists and is presently tested. The proof of principle of this measurement mode was achieved by successful beam tests with protons at the COSY synchrotron (FZ Jülich, Germany, cf. [7]). For the turn-by-turn measurement a multi-anode photo-multiplier with 32 channels will be used. The read out of the anodes is performed using a dedicated digitizer board, including purpose built FPGA and DSP electronics (framerate: 10 MSlices/s), designed and manufactured by the collaboration partner ITEP (Moscow) [8]. The goal of this measurement mode is to reach a time resolution of 100 ns at a reduced spatial resolution of 0.8 mm. The novel electronics has been manufactured and the prototype is presently tested.

BEAM POSITION MONITORS

The development of beam position monitors (BPM) in SIS100 is subdivided into five subprojects: 1) pick-up design for BPM installation inside cryostats [9], 2) cryogenic signal feed-throughs, 3) design of transformers for impedance matching, 4) low noise, 50 Ohm input impedance amplifiers [10] and 5) data acquisition using LIBERA digitizer boards [11]. Since a comprehensive description of all subprojects is out of the scope of this contribution, we focus on impedance matching and data acquisition. Because of the required resolution of the BPM system inside the cryogenic environment (accuracy 100 µm, mechanical stability 50 µm) metalized ceramics were preferred for the pick-up plates instead of bulk metal electrodes. Details on the FEM simulations for optimization of shoe-box BPMs are given in [9].

The BPM signals are fed into matching transformers because a direct mounting of pre-amplifiers inside the cryostat would exceed the allowed thermal load. Secondly, the expected radiation level close to the BPM (some ten kGy/yr) is too high. Therefore the cable length will reach approx. 5 m, calling for 50 Ohm cables in connection with low impedance amplifiers. To fulfil these requirements transformers for impedance matching have to be used, which have been investigated with respect to their frequency dependent transfer function. After extensive studies of various materials in the frequency range 0.1-100 MHz VITROPERM500F (Vakuumschmelze GmbH&Co.KG) was chosen. Additional measurements of transfer functions at liquid Nitrogen and liquid Helium temperatures have shown no saturation effects [12].

As a second parallel subproject the new data acquisition system has been designed and is currently being tested. As shown in Fig. 3, each of the 12 BPMs of SIS18 is now connected to a LIBERA digitizer (4×14 Bit ADC, 125 MSa/s, [11]). For the broadband analysis of bunch signals by calculating the integrals of the sampled difference and sum data, two steps are implemented in the FPGA: a) window generation [13] and b) baseline restoration [14]. Whereas the algorithm for direct base-band digitization resides in the FPGA, raw data as well as calculated beam positions can be transmitted via 1 GbE Rocket I/Os to data concentrators. This concept allows investigating the position data on a bunch-by-bunch manner. To handle the data rate of 700 MB/s for the 12 BPMs a dedicated network connects the LIBERAs to 2 high performance concentrator servers (Intel quad core PC).

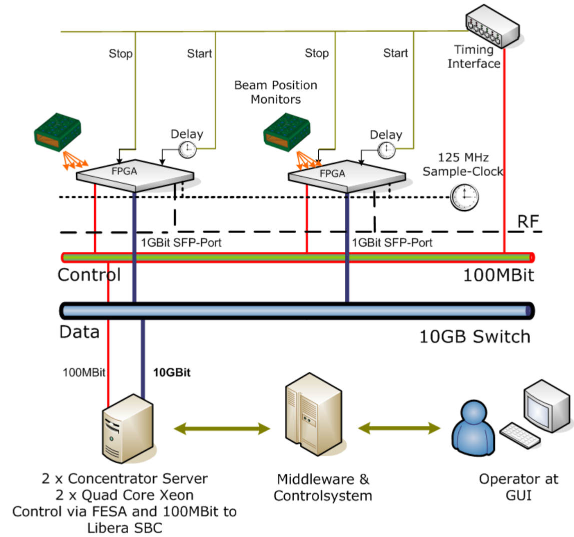

Figure 3: Layout of the new BPM data acquisition system for SIS18.

An industrial partner [15] was contracted to implement the data path from the FESA-controlled LIBERA, via middleware to a JAVA based GUI. Additionally, the system is also capable of online tune measurements by FFT calculation on the position data. The new BPM system is now installed at SIS18 and first tests with beam have been successfully completed.

CONCLUSIONS

We have shown that the demanding beam parameters of FAIR require in many cases advanced diagnostic devices that are currently being developed at GSI. First prototype tests at existing accelerators yield encouraging results. The authors acknowledge W. Vodel, R. Geithner, T. Sieber and A. Peters for the CCC collaboration, U. Raich, J. Belleman for fruitful discussions on the BPM layout and J. Dietrich and D. Liakin for the collaborative work on the IPM.

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