DIAGNOSTIC DEVICES FOR BEAM INTENSITY MEASUREMENT AT FAIR*

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Abstract

Precise determination of beam intensity is important for any accelerator facility. At FAIR, the Facility for Antiproton and Ion Research presently in the planning phase at GSI, the requirements set by beam intensities in the various accelerators, storage rings and transport lines differ significantly. A set of beam diagnostic instruments is foreseen to detect the large variety of ion beams ranging from less than 10^4 antiprotons up to high intensity of 5×10^{11} uranium ions. This contribution presents an overview of destined current measurement devices, both intercepting, like scintillators, ionization chambers or secondary electron monitors, and non-intercepting current-transformer type devices. Ongoing developments are discussed for non-intercepting devices, i.e. a DC current transformer with large dynamic range and a cryogenic current comparator, purpose-built for the detection of lowest beam intensities at FAIR.

LAYOUT AND REQUIREMENTS OF FAIR

After the decision in October 2009 to start the FAIR project in the so-called modularized start version (module 0-3), the layout of the planned facility has been finalized and presently the technical concepts for the three modules of the FAIR start version are elaborated in detail.

The modularized start version of FAIR [1] comprises the 100 Tm heavy-ion synchrotron SIS100 (mod. 0), experimental halls for the Condensed Baryonic Matter (CBM) and the Atomic and Plasma physics, and applied sciences program (APPA) (mod. 1), the Super-Fragment Separator for the NuSTAR collaboration (Mod. 2) as well as the collector ring CR and the HESR antiproton storage ring for the PANDA experiment (mod. 3).

For the antiproton experiments of PANDA short (50 ns) pulses of high intensity (2×10^{13} particles/spill) 2 GeV-protons are supplied as primary beam for the antiproton production target. On the other hand, the plasma physics experiments (APPA) demand for slowly extracted beams of U^{28+}-ions with 4×10^{11} particles/spill, whereas the CBM program requires high energy (11 GeV/u) beams of slowly extracted U^{93+}-ions, again with high intensity of up to 10^{10} particles/spill. A major challenge of the FAIR project is the planned parallel operation of the experiments by means of a strongly multiplexed beam production scenario.

The performance of the diagnostic devices has to be matched to the requirements of the multiplexed operation of the accelerator complex on the one hand and, on the other hand, has to be seamlessly integrated in the control and timing systems. This report gives an overview of the foreseen devices for beam intensity measurement, their special requirements with regard to the intended operational modes and present developments of dedicated diagnostic equipment.

DEVICES FOR BEAM INTENSITY MEASUREMENT

Due to the requirements of the different experimental programs and the resulting operational modes with large ranges of beam intensity it is clear that all diagnostic instruments need to provide sufficiently large dynamic ranges. In many cases two different devices for intensity measurements have to be foreseen. Especially in the High Energy Beam Transport (HEBT) section special devices are required to monitor both, low and high beam intensities, of slowly and fast extracted beams. The following table presents an overview of the devices for intensity measurement foreseen at FAIR.

Table 1: Devices for Intensity Measurement

Device	Location	Typical Detection Threshold
DC Current Transformer	Synchrotron (SIS100), storage rings (CR, HESR)	~1 μA_{rms}
Novel DCCT	SIS100	~200 μA_{rms}
Cryogenic Current Comparator	High energy beam transport, CR	~1 nA_{rms}
Fast Current Transformer	Linac, synchrotron (SIS100), storage rings (CR, HESR), transfer lines	~30 μA_{rms}
Resonant Transformer	High energy beam transport	~0.5 pC_{rms}
Particle Detector Combination	High energy beam transport	Scintillator: 10 pps Ion. Chamber: 10^4 pps Secondary electron monitor: 10^8 pps

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DC CURRENT MEASUREMENT

The typical application of DC current transformers is the online measurement of the ion beam circulating in synchrotrons and storage rings. Otherwise, for the detection of slowly extracted ion beams the resolution of a standard DCT is not sufficient and a dedicated transformer type is required.

DC Current Transformer

For online intensity measurement of the circulating ion beam inside the FAIR synchrotrons and storage rings DC current transformers (DCT) are foreseen. DCTs allow monitoring the bunched beam during the acceleration process, the coasting beam on the extraction flat top, as well as its decreasing intensity during extraction. The measurement principle is based on the fluxgate or magnetic modulator principle. A DCT includes two ring cores with a set of opposite windings, which are typically modulated with a frequency of 1-30 kHz. With a secondary winding the induced sum signal is detected. When a DC ion beam penetrates the two toroids with perfectly identical magnetic characteristics, the hysteresis curves of the ring cores become asymmetric, because of the beams magnetic field. This asymmetry is corrected for by a feedback loop, and the compensation current is a measure for the beam current. Main technical challenges of this DCT are the perfect matching of the magnetic characteristics of the toroids, the feedback loops high frequency stability and a sophisticated design of the modulator with excellent amplitude stability and spectral purity. Figure 1 depicts beam current measurements with four different transformer types.
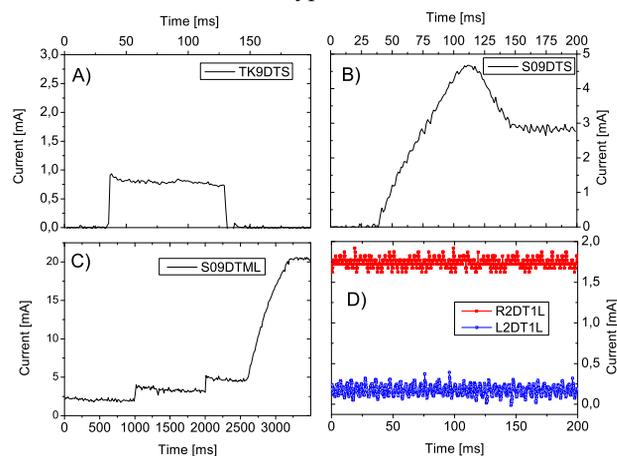

Figure 1: $^{209}Bi^{68+}$-beam at GSI: a) ACT of transfer line to SIS18 synchrotron , b) ACT (single injection) and c) DCT inside SIS18 (multi-turn injection, acceleration to 403 MeV/u); d) data acquired with commercial DCT behind ion sources of Heidelberg Ion Therapy Centre HIT for 96 keV proton- (red) and ^{12}C-beam (blue).

The GSI-built DCT [2] has a resolution of ~2.5 μA_{rms} at a bandwidth of DC to 20 kHz (Fig. 1c). The offset drift, mainly given by environmental temperature changes and magnetic imperfections of the core material is in the order of 20 $\mu A/day$, but is corrected for by an electronic auto-zero function. Commercially available DCTs, as used for the measurement shown in Figure 1d), achieve a current resolution of 1 $\mu A_{rms}/\sqrt{Hz}$ [3].

Novel DCCT

Especially for the application inside SIS100 a novel type of DCT has been designed in the past years at GSI. The GSI-built DCT had shown that for high beam currents (>70 mA) and bunch frequencies around 1.2 MHz the output signal gets disturbed. This lack of performance in the range of standard operation for SIS100 lead to the development of a novel transformer based on two sensitive GMR-sensors (Giant Magneto-Resistance) attached to a split ferrite toroid. The GMR signals are fed into a differential pre-amplifier and, additionally, the signal is treated in a second AC transformer path to detect also high frequency contributions with the same device. The target values for the dynamic range are 100 μA-150 A at bunch frequencies up to 5 MHz. It is planned to further optimize the existing prototype electronics with regard to long-term offset stability, as well as high absolute accuracy. Up to now the prototype shows a resolution threshold of ~220 μA_{rms}, but so far without sufficient shielding against known electromagnetic interferences [4]. We expect that improvements of the EMC behaviour and the development of an integrated analog electronics board will again substantially enhance the resolution and frequency response of the Novel DCCT.

Cryogenic Current Comparator

For the precise determination of low beam intensities of DC ion beams, as in the case of slow extraction from SIS100, cryogenic current comparators (CCC) are foreseen in the HEBT beam lines of FAIR. The sensitivity of ~1 $\mu A_{rms}/\sqrt{Hz}$ [2,3] of standard DCTs is too poor by approximately two orders of magnitude for single pass measurements of slowly extracted beams. Only the CCC allows non-intercepting current measurements with sensitivity in the nA-range.

The basic measurement principle of the CCC is the determination of the beams magnetic field with utmost sensitivity using a DC-SQUID (DC Superconducting Quantum Interference Device). The CCC sensor consists of four main parts: a magnetic alloy toroid acting as flux concentrator, a superconducting pickup coil, an effective superconducting magnetic shield and a high-precision SQUID system. Figure 2 presents the schematic layout of the CCC sensor. For operation at 4.2 K all components are installed inside a liquid He dewar with two warm holes for the connection to the beam line vacuum system. The magnetic flux induced by the passing ion beam is concentrated by a magnetic alloy ring core. Detailed materials science studies of various ferromagnetic materials revealed that nano-crystalline Nanoperm is best suited for the CCC because it shows a very high relative permeability of 40,000 up to a cut-off frequency of

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100 kHz at 4.2K [5]. The azimuthal magnetic field of the ion beam generates screening currents on the surface of the cylindrical magnetic shield. The magnetic field of these screening currents is detected by a single-turn pickup coil around the ferromagnetic core. The pickup signal is measured by means of a high-precision DC-SQUID. To effectively suppress disturbing non-azimuthal components of external magnetic fields a superconducting shield with sophisticated geometry is required. The first CCC prototype developed at GSI in the 1990's [6] had been equipped with a meander-shaped lead shield. Since the SQUID sensitivity is noise dominated the present development foresees a Niobium shield with greater amount of e.g. 10 meanders. Presently simulations of the magnetic shield are carried out with the goal to further increase the attenuation of non-azimuthal contributions.
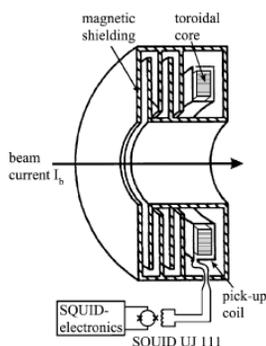

Figure 2: Schematic layout of the CCC sensor.

In combination with the enhancements achieved at FSU Jena for the SQUID electronics [7] and the optimized core material [8], an improvement of the current resolution by a factor of 5-10 is envisaged as compared to the former GSI prototype with a resolution of 250 pA_{rms} /$\sqrt{Hz}$ [6].

DEVICES FOR PULSED BEAMS

Fast Current Transformer

In order to control e.g. the injection efficiency into SIS100 a set of two commercial Pulse Current Transformers with a bandwidth of ~600 MHz and an overall dynamic range of 80 dB will be installed in the injection beam line to SIS100 and inside the synchrotron. With a current resolution of ~30 μA_{rms} the evolution of individual bunches will be detectable. The FCTs are passive devices with (for the GSI-built transformer) 100 Ohms termination and a switchable gain amplifier. The GSI-FCT has a resolution of 5 μA_{rms} at a bandwidth of ~1 MHz. Since the FCT is also foreseen for installation along the HEBT the number of instruments becomes rather large. Thus it is envisaged to purchase rather than to develop and build the FCTs for FAIR.

Resonant Transformer

For the online measurement of beam current during fast extraction resonant transformers (RT) developed at GSI are foreseen. The basic principle of the RT is that a bunch of charged particles excites a damped oscillation in the electronic circuit of the RT secondary winding. The peak amplitude of the first oscillation is proportional to the total charge of the particle bunch. To record the signal a peak detector is applied and the output signal is sampled with a 16 bit ADC. Main advantages of this transformer type are its high charge resolution of ~10^7 electrical charges and the very large overall dynamic range of about 120 dB. Comparative tests with a fast current transformer are ongoing. An FCT could principally replace the RT if the bunch signal is integrated and digitally processed. The prospective task is to define the maximum charge resolution of an FCT as compared to the RT.

Particle Detector Combination

For slowly extracted beams intercepting particle counters are typically used as diagnostic devices. In order to cover the full range of intensities of slowly extracted beams the so-called particle detector combination (PDC) has been designed at GSI. This detector type serves as a standard tool in the existing GSI accelerator facility. The PDC consists of three different particle detectors mounted on a single pneumatic feed-through. Particle currents below 10^6 particles/s (pps) are detected using a plastic scintillator. An ionization chamber is used for the measurement of medium beam currents between 10^4 and 10^{10} pps. A gas-filled stainless steel cylinder contains both the ionization chamber and the plastic scintillator. The cylinder is accessible from outside the vacuum. For currents above 10^8 pps a Secondary Electron Monitor (SEM) is mounted inside the vacuum. For the IC and SEM signals a current-to-frequency converter is used to provide scaler pulses proportional to the particle number. Equally, the scintillator pulses are fed to the scaler board.

CONCLUSION AND OUTLOOK

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