STATUS OF BEAM CURRENT TRANSFORMER DEVELOPMENTS FOR FAIR

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Abstract

In view of the upcoming FAIR project (Facility for Antiproton and Ion Research) several long-term development projects had been initiated with regard to diagnostic devices for beam current measurement. The main accelerator of FAIR will be the fast ramped superconducting synchrotron SIS100. Design parameters of SIS100 are acceleration of 2×10^{13} protons/cycle to 29 GeV for the production of antiprotons, as well as acceleration and slow extraction of p to U ions at 10^9 ions/s in the energy range of 0.4-2.7 GeV/u and extraction times of up to 10 s. For high-intensity operation non-intercepting devices are mandatory, thus the developments presented in this contribution focus on purpose-built beam current transformers. First prototype measurements of a dc current transformer based on a Tunnelling Magneto Resistance sensor are presented, as well as recent achievements with a SQUID-based Cryogenic Current Comparator.

FAIR ACCELERATOR FACILITY

Presently, the technical layout of the FAIR accelerator complex is being finalized and civil construction of the accelerator tunnel will start soon. FAIR consists of the fast-ramped superconducting synchrotron SIS100, the high-energy beam transport system (HEBT) interconnecting the synchrotrons with the pBar-Target for production of anti-protons, the super-fragment separator (SFRS) for the production of rare isotopes, the collector ring (CR) for stochastic pre-cooling of rare isotopes and anti-protons, and the high-energy storage ring (HESR) for internal target experiments [1]. Existing GSI accelerators serve as injectors for the FAIR machines. Primary goal of the novel facility is the production of heavy ion beams with unprecedented intensities close to the space charge limit of the synchrotron. The workhorse of FAIR will be SIS100, designed to produce up to 5×10^{11} U^{28+} ions/s with energies of 400-2700 MeV/u. Particles will be extracted either in single bunches of e.g. 30 ns as required for the production of anti-protons, or as slowly extracted beam with extraction times of several seconds for the radioactive ion beam program of FAIR.

For effective usage of the accelerator chain a multiplexed machine operation is foreseen which will allow to provide beams to up to four different physics experiments inside one machine super-cycle. Especially the planned high-intensity operation calls for a reliable online transmission control system. Beam current transformers will be the main source of intensity signals along the accelerator chain. Each section of the FAIR complex has special requirements and, ideally, beam current transformers are purpose-built instruments for each use case.

REQUIREMENTS FOR BEAM CURRENT MEASUREMENT

The accelerator control system of FAIR will require the measurement data of beam current transformers for various applications. Besides regular transmission monitoring, operating and archiving systems will monitor the beam currents during injection, accelerating ramp and during fast and slow extraction to calculate extraction efficiencies online. This is done e.g. to prevent recurring beam losses leading to unnecessary activation of machine components. Additionally, the planned machine protection system requests the generation of a 'beam-presence flag' and a 'setup-beam flag' from the current transformer signals. The setup-beam flag identifies beam settings that are used for preliminary test runs and accelerator commissioning, typically performed at low beam intensities. A signal threshold is monitored for beam current monitors along the related accelerator chain to verify the conditions for the setup-beam flag. The beam-presence flag on the other hand identifies machine settings that have previously been validated for high-current operation of the machine. In this state the online transmission control based on transformer signals is set to very small tolerance bands to protect the accelerator chain from potential beam-induced damages.

Since many years commercial solutions for beam current transformers are available on the market. However, for special use cases, demanding e.g. for very high dynamic range of beam intensities, or the measurement with ultra-high sensitivity in the nanoampere range, purpose-built transformers are required.

TUNNELING MAGNETO RESISTANCE DC CURRENT TRANSFORMER

The goal of the research project for a novel DC current transformer (DCCT) was to create an instrument that allows for precise online measurement of accelerated and stored beams with a large dynamic range of beam intensi-

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ties (µA to 150 A) and bunch frequencies up to 5 MHz. Due to its design the present GSI-built DCCT shows faulty signals at beam currents of >70 mA with bunch frequencies around 1.2 MHz, which will be standard operating parameters for SIS100. The novel DCCT is based on the clamp-on amperemeter design, consisting of a split toroid, which facilitates dismounting, e.g. for vacuum bake-out. The toroid is made from amorphous VITROVAC 6025F and acts as a flux concentrator. In the present design a beam current of 1 A leads to an induction of 80 µT in both gaps of the toroid, cf. Fig. 1. Two magnetic sensors are placed inside the toroid gaps and give a direct measure of the magnetic field inside the toroid. A number of different B-field sensor types were studied for the usage inside the novel DCCT.

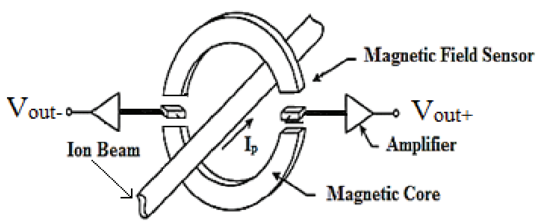

Figure 1: Schematic layout of the novel DCCT.

The DCCT development consists of three major steps. Firstly, different types of commercially available magneto-resistance (MR) sensors were tested and an amplifier PCB was developed for the most appropriate sensors. In a subsequent step the MR sensor signal was used as input for a zero flux feedback loop.

MR Sensor Study and Noise Analysis

For the detection of low magnetic fields two main types of MR sensors are available: Giant Magneto-Resistance (GMR) and Tunnel Magneto-Resistance (TMR) sensors. The functional structure is identical for all MR sensors and the field measurement is based on the change of the electrical resistivity of a thin film structure in the presence of an external magnetic film. In the standard layout four thin film resistors form a Wheatstone bridge. Whereas the GMR has two shielded resistors in the bridge causing unipolar output, the TMR has a bipolar output. For the application inside a novel DCCT the bipolar output is desirable because it facilitates to upgrade the device with a 'zero-flux' feedback loop.

For a theoretical noise analysis the performance of MR sensors was evaluated using the detectivity D as optimization parameter: $D \coloneqq \sqrt{S_V}/R_{BV}$, where S_V is the output noise power spectral density [V/√Hz] and R_{BV} is the sensitivity of the magnetic field sensor [V/T]. The total output noise power spectral density S_V is given by the summation of all uncorrelated noise contributions, i.e. thermal shot noise, flicker noise, thermal magnetic noise and magnetic flicker noise. Separate PCBs were produced for each MR sensor and noise spectra were measured inside a magnetic shield. Best results were obtained with an MMLP57FD TMR-sensor [2] with a measured detectivity of D=15.6 nT/√Hz, thus the novel DC current transformer was named tunnelling magneto resistance DCT (TDCT).

Stretched Wire Tests

Three different PCBs were selected for a test setup consisting of a stretched wire carrying a DC current placed in the center of the split toroid. The sensors were mounted inside the 10 mm air gaps of the split toroid and the whole setup was covered with a mu-metal box to attenuate external magnetic fields. Figure 2 depicts the measurement results for the selected MMLP57FD sensor leading to a minimum detectable DC current of 62 µA [3].

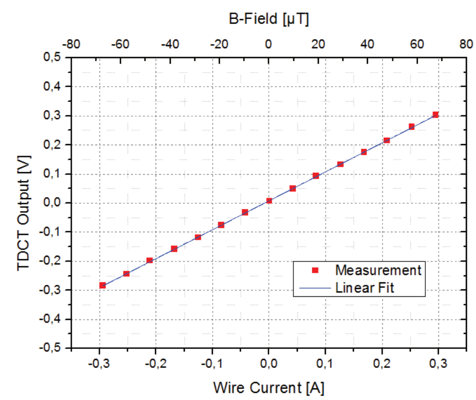

Figure 2: Stretched wire measurement with TMR-sensor MMLP57FD, note the good linear response.

Closed-Loop TDCT

In order to further increase the current sensitivity of the TDCT a feedback-loop was implemented. The principle of this 'zero-flux' instrument is to convert the amplified sensor voltage to a proportional current and to feed it to a coil wound around the toroid. The feedback current produces a magnetic field opposite to the field generated by the ion beam. As a result, the total magnetic field inside the air gap becomes zero. Therefore, the bipolar nature of the TMR sensor is preferred in order to set a proper working point and to counteract the magnetic flux in both polarities. For the closed-loop system two TMR sensors are placed inside the two air gaps of the split toroid. Purpose-built PCBs were manufactured to amplify the TMR voltage signal by a factor of 10. Using commercially available operational transconductance amplifiers (OTA) the amplified voltage is transformed to a proportional current, thus generating a sufficiently high feedback current. In addition n windings are wound around the toroid to further increase the magnetic field. First tests with the closed-loop system yielded promising results and are presently ongoing.

CRYOGENIC CURRENT COMPARATOR

Even though the FAIR facility is designed to provide ion beams with highest beam intensities, during slow extraction with long extraction times of up to 10 s the mean beam current drops to the nanoampere range. Thus special instruments are required to allow online beam

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monitoring of beam currents well below the detection threshold of standard DC current transformers [4]. Recently, the long-term development project of a Cryogenic Current Comparator (CCC) at GSI yielded very promising results with a sensitivity of 120 pA/√Hz, i.e. three orders of magnitude lower than the sensitivity of a standard flux-gate DCCT. The detection principle of the CCC is based on the precise measurement of the beam's azimuthal magnetic field. In the CCC setup shown in Fig. 3 the ion beam passes a toroidal sensor assembly that consists of a high-permeability magnetic alloy toroid acting as a flux concentrator. This toroid is enclosed in a superconducting pick-up coil connected to a high-precision DC-SQUID with readout electronics. Both, the pick-up coil and the toroid are encapsulated inside a meander-shaped magnetic shield to effectively attenuate any disturbing external magnetic field. The whole CCC sensor has to be embedded inside a lHe-cryostat because the DC-SQUID, as well as the magnetic shield require operation at 4.2 K [5].

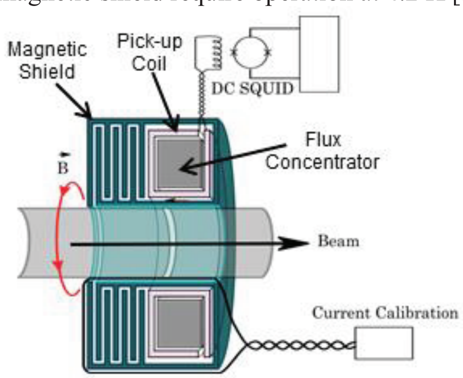

Figure 3: Schematic view of the CCC sensor assembly.

The aim of the CCC development was to further improve the current sensitivity and frequency behaviour of the CCC setup. Since the CCC current resolution is limited by the overall system noise, the electromagnetic noise contribution of each sensor part had been studied. To increase the attenuation of any disturbing non-azimuthal field component the superconducting magnetic shield was geometrically optimized using FEM simulations [6]. In addition, the magnetic permeability of various toroid materials was studied at lHe temperature, and finally nano-crystalline Nanoperm material was selected due to its high permeability and constant frequency response [7]. Also the noise figure of the DC-SQUID sensor was significantly improved by replacing the formerly used but meanwhile outdated UJ-111 SQUID with a commercial DC-SQUID and readout unit. Thus, all constituents of the CCC sensor setup underwent significant upgrades, however, beam tests with the existing CCC prototype setup revealed additional sources of distortions that had not been investigated so far. During beam tests with a 600 MeV/u Ni^{26+}-beam spurious flux jumps of the SQUID signal were observed, that deteriorate the intensity measurement. An example is depicted in Fig. 4. The blue curve shows the long-term CCC signal for three successive spills, where the baseline shift for the first two spills is clearly visible. The inserts show the spill signals with higher time resolution. Obviously, the red intensity signal was strongly disturbed by a flux jump, caused by strong high frequency noise exceeding the slew rate of the SQUID flux-locked loop electronics. Because of the periodic nature of the SQUID V-ϕ characteristic, a flux jump causes a sudden baseline offset in the intensity plot, corresponding to integer multiples of ϕ_0 (ϕ_0=h/2•e, elementary flux quantum). For the given setup the beam current corresponding to 1 ϕ_0 is 69.53 nA.

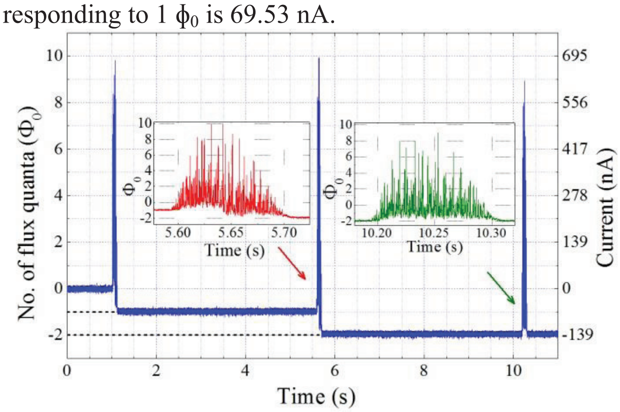

Figure 4: Flux jump of the SQUID signal observed during slow extraction of 5×10^9 Ni^{26+} with 125 ms extraction time, i.e. an average current of 60 nA (see text).

Another challenge for stable long-term CCC operation is the extreme sensitivity of its superconducting elements to temperature fluctuations. During beam tests with the CCC prototype small pressure variations in the liquid helium surface and the resulting temperature fluctuations were found to cause long-term drifts as well as short term fluctuations in the CCC baseline. Detailed investigations of these effects are presently ongoing [8].

CONCLUSION

Online beam current measurements for the upcoming FAIR facility make special demands for purpose-built beam current monitors. The development of a TDCCT yields promising results and the system will be upgraded to a zero-flux instrument. Investigations on the CCC performance and several optimization steps gave important input for the advanced CCC system, which is presently under construction for FAIR.

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