A CRYOGENIC CURRENT COMPARATOR FOR FAIR*

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Abstract

At present the Facility for Antiproton and Ion Research FAIR is designed and planned for realization at GSI [1]. The FAIR accelerators will deliver beams of unprecedented intensity for nuclear experiments and for the production of rare isotope beams or antiprotons. The availability of high intensity, high energy beams of ions and rare isotopes will be world-unique. Apart from high intensity beams produced by fast extraction from the synchrotrons, also slowly extracted beams have to be transported to the experiments. This operational mode demands for devices which allow for online measurements of beam currents in the nA-regime. To monitor slowly extracted beams a sensitive cryogenic current comparator (CCC) is currently developed in collaboration with FSU Jena and MPI-K Heidelberg. This contribution presents the actual state of the CCC developments for the FAIR beamlines and reports on recent improvements of the device.

GSI AND THE FAIR PROJECT

In November 2007 the FAIR project celebrated its kick-off event, with representatives of the international partners signing a communiqué on the imminent start of the FAIR project. Meanwhile the layout of the future facility and all of the technical subsystems has been further refined and GSI entered into the final planning phase [1]. Fig. 1 presents an overview of the future facility. The existing GSI machines (UNILAC, SIS18) will act as an injector (blue beamlines in Fig. 1, left part) for the new FAIR accelerators (red lines). As part of the FAIR project a proton Linac is planned for the production of high-current proton beams as needed for effective production of antiprotons. It is foreseen that in its final stage FAIR comprises two heavy ion synchrotrons (SIS100 and SIS300), the antiproton production target, the Super-Fragment Separator (Super-FRS) and four storage rings (CR, RESR, NESR and HESR). The FAIR accelerator complex is designed as a flexible, multi-purpose facility with the following goals:

- acceleration of all ion species from proton to uranium
- production of high-current primary beams
- generation of radioactive beams for fixed target or storage ring experiments
- production, accumulation and storage ring experiments with antiprotons

From the experimentalist's view 14 large experiments have been approved for installation at FAIR. The FAIR research programme is organized in four scientific pillars: APPA (Atomic, Plasma Physics and Applications), CBM (Compressed Baryonic Matter), NuSTAR (Nuclear Structure, Astrophysics and Reactions) and PANDA (AntiProton ANnihilation in DArmstadt).

As a consequence of a severe cost overrun of the estimated realization costs it was decided in fall 2009 to reorganize the planned facility into modules and to start FAIR in a reduced "Modularized Start Version". The six modules are colour-coded in Fig. 1: Module 0: heavy ion synchrotron SIS100 (green), Module 1: experimental hall for CBM (ochre), Module 2: Super-FRS (yellow), Module 3: p-Linac, antiproton Target, CR, HESR (orange), Module 4: NESR (light blue) and Module 5: RESR (red). The FAIR start version presently consists of modules 0 to 3, whereas modules 4 and 5 are foreseen to follow in the future. It is important to note that all international partners, as well as the scientific steering committee, endorsed the new modularized attempt and great care had been taken to retain the physics case for all scientific communities involved.

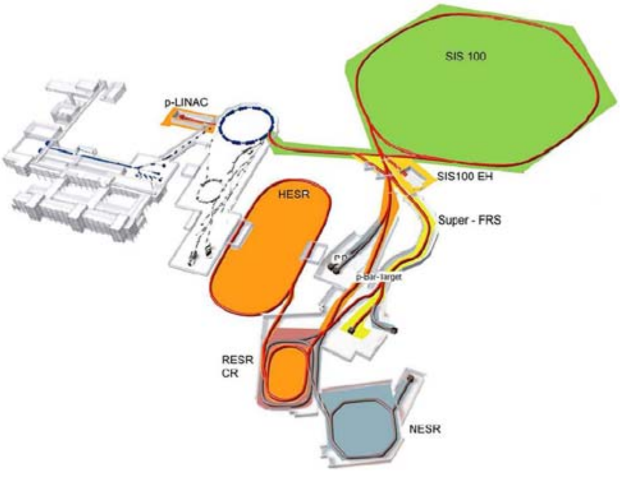

Figure 1: Present layout of GSI and the upcoming FAIR facility. The modules of the "Modularized Start Version" are colour-coded, see text.

BEAM CURRENT MEASUREMENT

This contribution focuses on beam current measurement in the extraction beamline of the fast ramped superconducting synchrotron SIS100 and in the high energy beam transport (HEBT) section of FAIR.

The unique beam parameters of the FAIR machines require carefully designed diagnostic equipment. E.g. the extreme UHV condition down to 5×10^{-12} mbar in the SIS100 is a strict requirement for all vacuum installations inside, or in close vicinity to SIS100. The fast-ramped heavy-ion synchrotron SIS100 will be the working horse of the whole facility, allowing to store and accelerate high currents (up to the space charge limit) of primary beams in low charge states. For the HEBT sections the main goal is to achieve a high resolution and low detection limit for all diagnostic devices, because both, slow and fast extracted beams have to be monitored, casually changing in a pulse-to-pulse manner. In order to prevent destruction of devices by high-intensity ion beams and to allow for online measurements non-intercepting beam diagnostic devices, like e.g. beam current transformers for current measurements, are preferred as standard devices.

Especially the production of rare isotope beams requires slowly extracted primary beams from the SIS100 synchrotron. To monitor slowly extracted beams with maximum values in the order of 10^{12} particles/s, corresponding to 4.5 µA for U^{28+}, instrumentation with maximum sensitivity is ultimately required. The only non-intercepting current measurement device capable of measurements down to the nA-range is the SQUID-based CCC. Altogether six installations of the CCC are foreseen in the HEBT section, for direct measurement of the beam current and, secondly, to monitor transmission between machines or between accelerator and experiments.

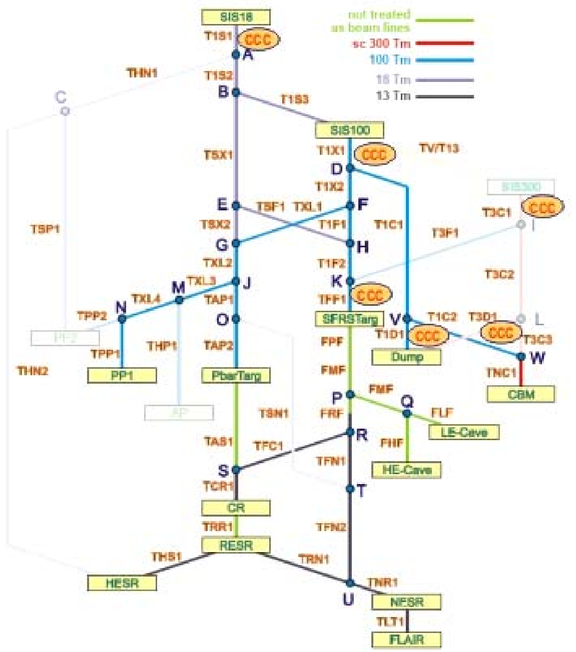

Figure 2: Schematic view of the high-energy beam transport section of FAIR [1], interconnecting the accelerators and experiments (yellow rectangulars). Yellow ellipses indicate the installation locations of the CCCs. The total length is 2.6 km

A schematic view of the HEBT beamlines is depicted in Fig. 2. CCCs are foreseen at the following positions: 1. in beamline T1S1 connecting the synchrotrons SIS18 and SIS100, 2. in SIS100 extraction section T1X1, 3. in T1D1 before the SIS100 beam dump (to verify complete beam extinction), 4. in beamline TFF1, i.e. the entrance of the Super-Fragment Separator. The two installations in beamlines T3C1 and T3D1 belong to FAIR modules 4 and 5, and thus will be realized at a later stage.

CRYOGENIC CURRENT COMPARATOR

A SQUID-based cryogenic current comparator is a sensitive device for the measurement of the azimuthal magnetic field of a flux of charged particles.

Measurement Principle

The basic physical effect deployed by a CCC is that for an ideal superconductor the magnetic flux is expelled from the bulk material by shielding currents on the materials surface (Meissner-Ochsenfeld-effect). A schematic view of a CCC sensor is presented in Fig. 3. As depicted, the ion beam longitudinally penetrates a superconducting cylinder and induces screening currents in the surface of the niobium cylinder, which contains a toroidal pick-up coil with ferromagnetic core [2]. The pick-up coil detects the magnetic field of the induced screening currents and the current signal is transferred via a superconducting loop to an LTS DC SQUID. The SQUID electronics is connected to a Josephson-junction and generates an output voltage proportional to the number of magnetic flux quanta applied.

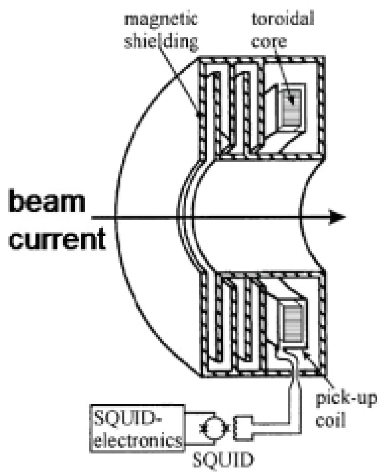

Figure 3: CCC sensor principle

In order to suppress disturbing external magnetic fields a meander-shaped superconducting niobium shield covers the pick-up coil and effectively suppresses non-azimuthal components of magnetic stray fields from outside the CCC. This is of course important if the device is installed in an accelerator environment, e.g. near fast ramped magnets of the beam transport system. In 1994 a CCC prototype was built at GSI in collaboration with FSU Jena. The prototype achieved a current resolution of ≤ 250 pA/sqrt(Hz) and was successfully tested for the measurement of high-energy ion beams in the nA-range [3]. A more recent development of a CCC for the measurement of dark currents in superconducting cavities in the frame of the CHECCHIA test stand achieved a higher resolution of 40 pA /sqrt(Hz) [4].

Apart from an optimized magnetic shielding the overall system noise defines the resolution of CCC. Therefore a detailed study of the various noise contributions of the CCC system was carried out at FSU Jena. As a result it turned out that the choice of the ferromagnetic core material is of major importance for a good resolution. The noise performance could be improved by using core materials with highest possible relative permeability μ_r, since the signal to noise figure is proportional to the square root of μ_r (I_N: noise current, I_S: signal current, cf. [5]):

$$B, L \propto \mu_r \Rightarrow \frac{I_s}{I_n} \propto \sqrt{\mu_r}\,.$$

Sensor Improvements

In search of a maximum relative permeability, various materials have been studied with respect to their μ_r as a function of temperature and frequency. The frequency behaviour is of course important to achieve a high analog bandwidth of the device and thus to allow for sampling rates in the kHz range.

The studies of different core materials revealed especially nanocrystalline alloys like Vitroperm [6] and Nanoperm [7] as good candidates for the CCC core. Fig. 4 epitomises the relative permeability of ferromagnetic core materials as a function of temperature. For these measurements the temperature has been defined by an automated dip-stick setup that sets the sample temperature by positioning the test item in the gas phase above the liquid helium inside a cryostat.

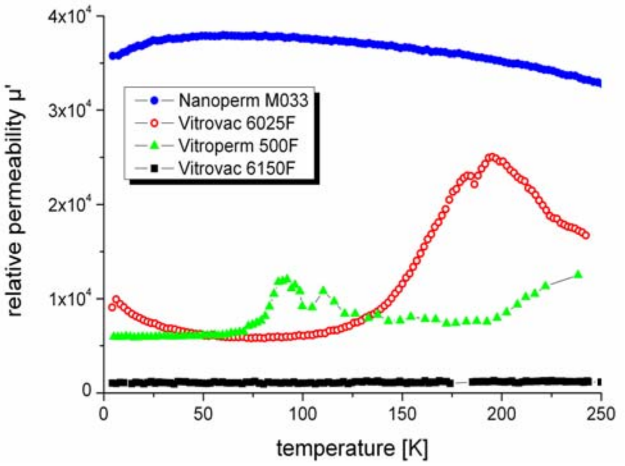

Fig. 4: Relative permeability μ_r at 100 Hz for various ferromagnetic core materials as a function of temperature

The plots in Fig. 4 clearly indicate that over the whole temperature range (4 K to 250 K) the relative permeability of the ferromagnetic alloy Nanoperm M033 exceeds the Vitrovac and Vitroterm samples by a factor of ~4, resulting in a factor of 2 for the signal-to-noise ratio. Thus Nanoperm presently is the preferred core material for the FAIR CCC. More details on the materials analysis regarding μ_r can be found in [5] and [8].

Next Steps

As a next step Nanoperm cores of adequate diameter will be purchased for further system tests in the cryostat. Secondly an improved magnetic shielding with a greater number of meanders will be manufactured. Both components are designed to fit to the mechanical layout of the CCC for the cryogenic storage ring.

CCC FOR CRYOGENIC STORAGE RING

Presently the Cryogenic Storage Ring is developed and realized at MPI-K Heidelberg. The CSR will be an electrostatic storage ring with a circumference of 35 m dedicated for molecular and atomic physics experiments [9]. Special features of CSR are the operation at L-He temperature, extreme vacuum conditions in the 10^{-13} mbar regime and beam intensities between 1 nA and 1 µA. The cryogenic environment of the CSR facilitates the installation of a SQUID-based CCC for the measurement of lowest beam intensities [10]. To minimize noise and zero drift of the SQUID all components of the CCC have to be cooled down to L-He temperature, with a stability of 50 mK. Currently, as part of the collaboration between FSU Jena, MPI-K and GSI, the mechanical layout of the superconducting shielding of a CCC for CSR is finalized and detailed design work for the CCC chamber has started.

OUTLOOK

At the moment the beamline instrumentation and thus all installation locations for the CCC inside the HEBT beamlines of FAIR are being determined and user demands for the required CCC performance are collected. These requirements will be included in the design of the CCC prototype. It is planned to manufacture a prototype coil structure and to implement it in a cryogenic system. The installation of a CCC prototype inside the CSR will be an ideal test bench for the development of the FAIR CCC.

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