INSTRUMENTS AND METHODS FOR THE MAGNETIC MEASUREMENT OF THE SUPER-FRS MAGNETS

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Abstract

The Super-FRS is a new fragment separator to be built as part of the Facility for Antiproton and Ion Research (FAIR) [1] at Darmstadt. The acceptance tests and magnetic measurements of the superferric separation dipoles and multiplets (containing quadrupole and higher-order magnets) will be performed at CERN in collaboration with GSI/FAIR [2]. This paper presents the methods and challenges of the magnetic field measurements, and the required instruments for measuring the transfer function, field quality, and magnetic axis. A prototype for each system has been produced in order to validate the measurement methods, the instruments, and the mechanical integration. In this paper will present the design and production of the prototypes, the design of the instruments for the series measurements, and the results of the metrological characterization.

INTRODUCTION

Super-FRS is a two stage, in-flight separator that will be built as part of FAIR, the Facility for Antiproton and Ion Research. Super-FRS is composed of all-together 205 magnets: 24 dipoles, 80 quadrupoles, 41 sextupoles, 14 steerer magnets and 46 octupoles. Due to the high momentum acceptance (±2.5%) and large angular acceptance ($\phi_x = \pm 40$ mrad; $\phi_y = \pm 20$ mrad), large-aperture magnets are required [3].

CERN has recently designed and built a cryogenic test facility for these superconducting magnets. Within this project, the magnetic measurement section of CERN's Technology Department is in charge of the development and production of the measurement systems needed for the assessment of the field quality of the dipoles and multiplets [2]. The main challenges result from the large measurement volume, that is, a reference radius of 170 mm for the multiplets and a good-field region of 400 x 140 mm for the dipoles, and the need for measuring the local field profiles along the dipole magnets. We have designed a system based on induction-coil sensors that are translated in the bore of the dipole magnet, in the following called the translating fluxmeter, and a rotating-coil system for measuring the multipole field errors in the multiplets. This system is based on an array of printed-circuit coils supported by a carbon-fiber shaft.

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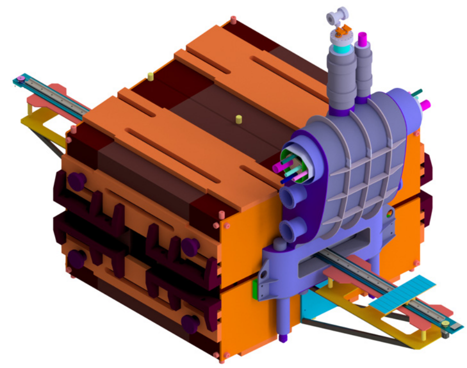

Figure 1: The translating fluxmeter setup in the main Super-FRS dipole.

THE MAGNETIC-FIELD MEASUREMENT PROGRAM

The Super-FRS dipoles are H-type, superferric magnets with warm iron yoke and superconducting coils operated at 4 K, for more details see reference [4]. The series is composed of 23 magnets of two types that differ in integral field strength, featuring yoke lengths of 2.4 m and 2.3 m. The standard measurement program foresees measurements, at several current plateaus, of the integral field over 3.5 m length and the field homogeneity over three different longitudinal sections inside the good field region. The longitudinal field profile must be measured because the large fringe-fields affect the particle trajectory. These fringe-fields depend on the iron saturation and hysteresis, and are therefore dependent on the excitation current level and history. The slow ramp rate of 0.016 T/s would make the standard fluxmeter methods [5], often used to test fast ramped H-type dipoles, extremely challenging. This is because a large number of coil turns would be required to obtain a reasonable signal to noise ratio.

The focusing quadrupoles and multipole correctors are integrated in so-called multiplets; common cryostats containing from 2 to 9 magnet elements [4]. Like the dipoles, these magnets are superferric but the iron yoke is also cooled to 4 K. The multiplets are grouped in 2 families: the short multiplets, containing one quadrupole and a sextupole corrector and the long multiplets (up to 7 m long) containing two short quadrupoles with embedded octupole corrector coils, one long quadrupole, two or three sextupole correctors, as well as superconducting, coil-dominated steerer dipoles. All the

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magnet elements have the same good field region (0.17 m radius) and are powered individually; the longitudinal distance between them is fixed to 1 m. The series measurement program foresees 10 days of testing per multiplet to verify cryogenic and electrical integrity and the production conformity in terms of field quality and alignment of the magnet elements within the cryostat. Thus, the measurement program foresees the magnetic axis localisation and fiducialisation of the quadrupoles and sextupole by mean of single stretched wire measurements [6], as well as the integral field strength and homogeneity measurement using a rotating coil system [7].

THE MEASUREMENT SYSTEMS

The translating fluxmeter is a coil array that is moved parallel to the magnet axis, intercepting the B_y component of the magnetic flux density, see Fig. 1. Because of the difficulty to measure DC or slow-ramped fields along curved paths, it has been agreed to measure along straight paths, but with a coil array wide enough to cover the entire pole surface. Fig. 2 shows the prototype installed in CERNs reference dipole magnet. The fluxmeter is composed of a carriage holding a linear encoder head and the coil array, which is guided by an aluminium rail installed on a machined base plate. The longitudinal displacement is measured by a linear encoder, reading the position over a 5-m-long, non-magnetic tape scale. The encoder output is used as a trigger for the acquisition of the coil signals. The carriage is connected to a stepper motor with a non-magnetic traction cable and a free pulley. During the coil translation, the voltage generated at its terminal is given by $u_s = -\frac{d\Phi_s}{dt} = -\int_{\partial s}(\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{r}$, where Φ_s is the magnetic flux through the surface $\mathbf{a}$, $\mathbf{v}$ is the velocity vector field, and $d\mathbf{r}$ vectorial line element along the coil rim. The flux increments $\Delta\Phi_i$ on the elements $i \in [1, n]$ defined by the spatial resolution of the encoder, yields the magnetic flux density profile by

$$B_y(n) = \frac{\sum_{i=0}^{n} \Delta\Phi_i}{A_c} \tag{1}$$

where A_c is the equivalent coil surface. Because of the finite length of the coils, the measured signal is the convolution of the field distribution with the coil sensitivity function. The Fubini theorem can be used to calculate the integrated field, multiplying the integral of the measured signal by the length of the coil array.

For the multiplets, a rotating coil system has been designed to fulfil the following requirements: a) the length of the shaft should cover at least the integral field of the longest quadrupole (2.6 m); b) the measurement radius should be larger than the good field region; c) the shaft weight must be lower than 60 kg. The conceptual layout of the system is shown in Fig. 3. The shaft can be moved longitudinally inside the bore in order to measure the different magnets assembled in the multiplet. The large aperture of the magnet permits to have the shaft and motor-drive unit inside the bore. An extension tube allows to keep the drive unit sufficiently far from the powered magnet. This solution was chosen because the accuracy of the measured field harmonics depends on the precision of the angular position measurement in the rotating unit. Minimising the distance between the angular encoder and search coils will reduce the uncertainty due to torsional deformations. The search coils are made using printed-circuit board technology, with 5 radial coils (1.4 m^2 equivalent surface) equally spaced by 85 mm transversally. The circuit board is a 10 layers construction that guarantees a high compensation factor of the main field component (~ 1000) and the possibility of radius calibration [8] due to the geometrical precision of the traces. To cover the total length of 2.6 m we have assembled in one support structure two boards of 1.3 m each that are easier to produce than longer multilayer circuit boards. The boards are sandwiched between two carbon-fibre shells filled with low density foam that guarantees torsional and bending stiffness. The shaft is supported on a carriage that can be adjusted in the transversal and longitudinal directions. It was decided to produce first a prototype of smaller dimensions to be compared with the standard shafts and to be calibrated in CERNs dipole calibration magnet.

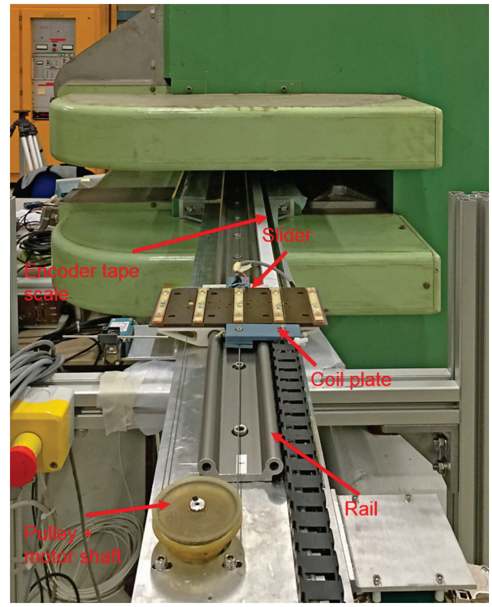

Figure 2: The prototype version of the translating fluxmeter installed on CERNs reference dipole for magnetic measurements.

SYSTEMS VALIDATION AND FIRST MEASUREMENT RESULTS

Several tests have been carried out on the translating fluxmeter prototype in order to check the repeatability of the motion system and of the encoder pulses at different speeds. Cross-checks of the positioning were done with a laser interferometer, and the measurement were compared to a scan with an NMR (nuclear magnetic resonance) probe.

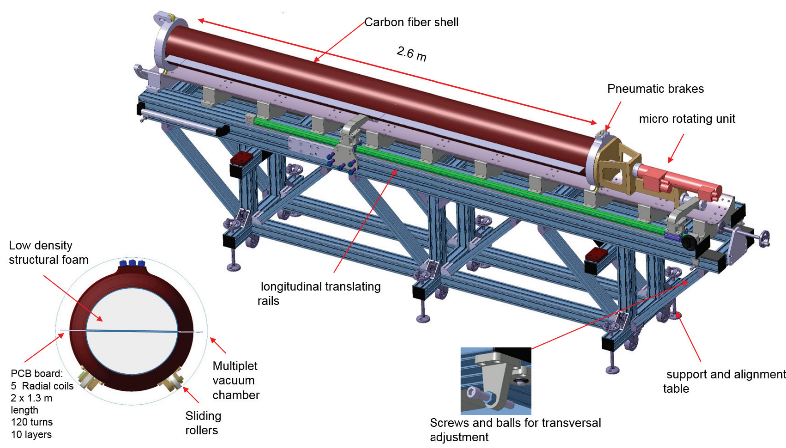

Figure 3: The rotating coil shaft assembly.

The field quality, defined by

$$B_I(x, y) := \frac{\int_a^b B(x, y, z)\mathrm{d}z - \int_a^b B(0, y, z)\mathrm{d}z}{\int_a^b B(0, y, z)\mathrm{d}z} \quad (2)$$

is shown in Fig. 4 for fluxmeter and NMR measurements at different transversal positions in the magnet bore. The uncertainty is ± 5 10^{-5} T at 1 σ which takes into account the error propagation of the central coil measurements with respect to the others 4 coils. Further tests are needed to estimate the uncertainty introduced by the in-situ coil calibration, and to verify whether the use of a compensation scheme can reduce this uncertainty.

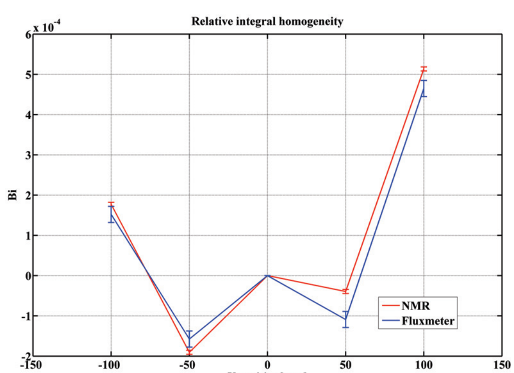

Figure 4: The integral field homogeneity as a function of the transversal position in the magnet.

The rotating coil prototype with its PCB coil array has been calibrated in the CERN reference dipole and quadrupoles. The typical calibration performed at CERN can achieve accuracies of few units in 10^{-4}. The calibrated surfaces are 1.5‰ smaller than the design values, while the radii are systematically larger by 2‰ . Even though the cause of this is not yet understood, the spacing between coils and the coil's relative surface variation remain within the calibration accuracy. Therefore good compensation (bucking ratios) can be achieved, ~ 1000 and ~ 600 for the dipole and the quadrupole bucking ratios.

CONCLUSIONS

The testing of the Super-FRS magnets requires a large scan width of ± 200 mm x 140 mm for the dipoles and 170 mm radius for the multiplets. A prototype of translating fluxmeter for the dipoles and a prototype of rotating coil for the multiplets have been completed. The measuring principle and the materials have thus been validated. The first results, validated by comparison of measurements with standard systems, have shown the requirements can be met for the series testing and magnet characterisation.

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