Superconducting Magnet Testing for FAIR

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***Abstract*—The FAIR project is now heading in its realisation phase with the first series of magnets being procured and the others on the tendering process. The superconducting magnets will be tested at GSI or its partner institutes. In addition the collaborative R&D work on the SIS300 main magnets proceeds to be ready for the second project phase without delay that requires additional test preparation for the already built prototypes. All the magnets within their total installation must be tested at cold to prove their functionality and production accuracy. The different test facilities are currently set up and the test procedures established. We report on the testing strategy and the progress of the test preparation together with testing challenges already derived from the first SIS100 series dipole as well as for the Super-FRS and SIS300.**

I. Introduction

Large scale projects aim for procuring components by suppliers able to auftreten as a competent partner, who will oversee the full implementation process including the test of the components at operating conditions. Superconducting magnets, however, require dedicated resources to bring them in operating conditions, in particular high current power converters of high stability, dedicated measurement systems and a cryo-infrastructure to cool the magnets down and keep them cold. All these resources are not commonly found in industry nor the technology readily available.

Therefore, similar to previous accelerator projects, the cold test was decided to be made within the research lab. The international character of the FAIR project made the planning a bit different: not a single facility is erected but the testing is spread over different partner institutes.

II. Test Facilities

Two machines of the start version FAIR project will utilise superconducting magnets the heavy ion synchrotron SIS100 and the super fragment separator Super-FRS, with the synchrotron SIS300 foreseen as a first upgrade.

While the magnets of SIS100 and SuperFRS are iron dominated, the magnets of these two types differ significantly. The former ones are of rather smaller bore ($110 \cdot 68$ mm for the dipole, 50 mm pole dip radius for the quadrupole), with a maximum pole dip field of 1.9 T for the dipole and XXX for the quadrupole. Further these magnets are of the fast ramped type. The SuperFRS, on the contrary, uses magnets with a large bore ($220 \cdot 80$ mm for the dipole and 250 mm for the quadrupole), with pole dip field of 1.6 (dipol) to 2.3 T (quadrupole). Further the SuperFRS magnets provide a warm bore, while the SIS100 magnets utilise a cold bore and cold vacuum chamber to meet the stringent requirements of this high intensity beams.

Given the variety of the magnets and the collaboration character of the FAIR project, the limited space on campus, together with many capable partners at hand, led to split the testing effort to different partner institute.

A. Testing SIS100 Dipoles at GSI

GSI committed itself to build one of the test facilities. Its equipment is dedicated to

- conduct the series tests of the SIS100 dipoles
- allow the installation and execution of the SIS100 string test
- provide the cooling capacity later on for SIS300,
- allow retest of all superconducting accelerator magnets for SIS100, SIS300 and SuperFRS together with
- the cooling capacity for a cw-linac.

All these requirements let to the decision to build the facility in an hall close to the existing linear accelerator. The following tests will be executed:

- tests ensuring the machine safety,
- tests proving that the magnets are compliant with the specified performance and
- tests to obtain the parameters required for operating the machine.

The required tests are then (as typically applied for qualifying superconducting magnets) measurements of the electrical insulation, leak tightness, thermodynamic and mechanical cool down behaviour of the cold mass together with its effect on the suspension system. Further the quench performance will be measured together with the magnetic field. Given that SIS100 is a fast ramped synchrotron (periodically cycled with a frequency of up to 1 Hz) additionally the AC loss is measured, the field on the ramp and its dynamic effects due to eddy currents in the yoke and in the vacuum chamber [1], [2]. The AC loss will be determined using the VI-method (i.e. determining the loss measuring the electrical power required during ramp up and deducing the power retained during ramp down). All SIS100 dipoles are cooled by parallel channels, therefore the hydraulic resistance of each magnet must be measured to ensure proper functioning of the two phase cooling as already demonstrated by the predecessor of SIS100 the Nuclotron [3], [4].

B. Testing SIS100 quadrupoles and correctors

The SIS100 machine uses a doublet focusing concept. Each quadrupole together with associated correctors and beam monitors are mounted in units [5], [6] (see Fig. 1). Two units are then, together with the cryocollimator, mounted on a

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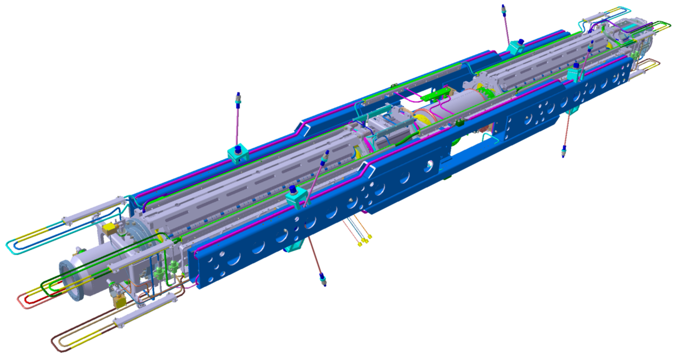

Fig. 1. One quadrupole doublet (without cryostat). It consists of the quadrupole, the associated correctors or beam position monitors mounted on them and its bus bars, which cover the length of one doublet.

common girder and finally inserted in its cryostat. The vacuum chamber is of elliptic shape, necessary for the aperture covered by the beam. Here a central cold rotating coil probe with an outer radius slightly smaller than the pole radius will be used for measuring the field quality. As the vacuum chamber must be mounted in the unit before the doublet is assembled, the magnetic measurement must be performed during the unit test, thus demanding, together with the measurement of its hydraulic resistance, a cold test of the unit. During this test

- the magnetic field properties of the magnets will be measured: the central and end field for the main quadrupoles and the integrated total fields for the correctors.
- All other tests required to ensure the proper functioning of superconducting components will be executed: high voltage tests, quench training . . . . Further the loss of each hydraulic cycle has to be measured and adjusted [4], owed to the efficient two phase cooling.

Only after these tests the beam vacuum chambers will be inserted, the BPM mounted, and the whole doublet assembled. Currently only random tests are planned on the integrated module, to be validated on the first doublets produced, which are to be tested at cold conditions.

The magnetic measurement will be based on a long rotating coil probe. It is to be made of compensation coil probes, which allow suppressing the dipole and quadrupole component. Longitudinally it will be split in three parts: the middle part to cover the central field of the main quadrupole, the other ends to be either used to measure the correctors field or the end field of the main quadrupole. The axes of the magnets will thus be located in the frame of this rotating coil probe. It will be mounted precisely on the unit magnets and then its mechanical references used to mount it on the girder. The magnetic measurement will then only be a correction to the mechanical axis; the difference will be corrected when the magnet is mounted on the girder.

C. SuperFRS Magnets at CERN

The large SuperFRS magnets are to be measured at CERN. CERN is currently refurbishing its facility in building 180, along with intensive preparations in particular:

- a refurbishment of the cryogenic infrastructure of the hall
- new power converters will be procured, which are foreseen to be used for testing the SuperFRS magnets and then later on for some of the new insertion quadrupoles.
- Electronics, developed for detecting quenches in the SuperFRS magnets, when installed in the machine, shall be get ready on the time scale imposed by the delivery of the first magnets of the SuperFRS. This has the advantage that the electronics will be in use for several years on a frequent basis, which allows gaining operation experience.
- As the SuperFRS magnets are spectrometer magnets, precise information on the magnet quality is required. Therefore CERN is adapting existing systems or building new systems for measuring the magnetic fields of the dipoles and all other magnets assembled to a multiplet.

D. SIS300

The first SIS300 magnets are being built. While the main focus of testing is laid on getting the SIS100 and SuperFRS magnets tested and the series productions approved, still SIS300 dipole and quadrupoles have been fabricated and will be tested. The prototype test facility at GSI has the necessary power converter and can provide the high flow of saturated helium [7]. While dipoles and quadrupoles have been tested already [8], [9], only the test at GSI will be with the same cryogenic conditions and ramp rates as demanded for the SIS300 machine. The magnetic field of the dipole will have to be measured as well.

III. Challenges

Testing superconducting magnets is a tedious task to ensure that these will work correctly. The standard methodes and procedures are known to the community, so here only the new approaches will be given, in particular measuring harmonics of curved accelerator magnets.

A. Field description for curved magnets

The SIS100 and SIS300 magnets are curved, but harmonics are to be derived. It has been shown in previous publications (e.g. [10]) that harmonic coil measurements at different locations can be combined to a set of cylindric (2D) circular and elliptic harmonics. Previous research (see [11]–[13]) showed that these fields can be described with local toroidal circular or elliptic coordinates next to a outlook on how to measure them with a rotating coil. Here now the picture is closed, and shown that the cylindric approach is sufficient for treating the fields of SIS100 and SIS300 if proper corrections are applied. Only a brief concise treatment is given here, the interested reader is referred to [14]. This description and correction has to be applied to any beam dynamics calculation if the trajectory of the beam and beam aperture is similar to SIS100 or SIS300 even if the magnets are straight.

The potential equation in local toroidal coordinates is given by

$$\Delta\Phi = \left[\frac{\partial^2}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial^2}{\partial\vartheta^2} + \frac{\varepsilon}{h}\left(\cos\vartheta\frac{\partial\Phi}{\partial\rho} - \frac{\sin\vartheta}{\rho}\frac{\partial\Phi}{\partial\vartheta}\right)\right]\Phi = 0.$$

with ρ and θ the radius and angle within the small circle of the torus, $\varepsilon = R_{Ref}/R_C$ with R_{Ref} the reference radius and R_C the radius of the large circle of the torus. This equation is solved approximately by replacing Φ with $\sqrt{h}\Phi$, which will transform the original term in ε to a term dependent in ε^2; this term is then neglected, thus the standard equation of cylindric circular coordinates is obtained [11], [14]. $\sqrt{h}\Phi$ means that the basis functions are changed and thus the potential ansatz is given by

$$\bar{\Phi}_m^{(1)} = \mathbf{z_s}^{|m|} - \frac{\varepsilon}{4}\left[\mathbf{z_s}^{|m|+1} + |\mathbf{z_s}|^2\,\mathbf{z_s}^{|m|-1}\right], \qquad (1)$$

with $\mathbf{z_s} = \mathbf{z}/R_{Ref}, \mathbf{z} = x + \mathtt{i}y$. y is normal to the plane of the big circle, x selected to be a right hand system. The basis functions for the field are derived from the basis functions of the potential using $\nabla\Phi$. These calculations have to be made in x and y as $|\mathbf{z}|$ is not analytic. The basis functions obtained for the different terms can be combined substituting $\mathbf{z_s}$ with $\rho/R_{Ref}\exp\mathtt{i}\phi$ one obtains

$$\begin{pmatrix}\tilde{\bar{\mathbf{T}}}_{\mathbf{m}}^{(\mathbf{n})}\\ \tilde{\bar{\mathbf{T}}}_{\mathbf{m}}^{(\mathbf{s})}\end{pmatrix} = \rho^{m-1}e^{\mathtt{i}(m-1)\phi}\left(1 - \frac{\rho\epsilon}{4m}\left\{\left[(m+1)\,e^{\mathtt{i}\phi} + (m-1)\,e^{-\mathtt{i}\phi}\right]\right.\right.$$
$$\left.\left. +2e^{-\mathtt{i}m\phi}\begin{bmatrix}e^{\mathtt{i}\pi/2}\sin\left((m-1)\,\phi\right)\\ \cos\left((m-1)\,\phi\right)\end{bmatrix}\right\}\right). \qquad (2)$$

Equation (2) shows that the basis functions for the normal coefficients ($\vec{\bar{T}}_m^{(n)}$) and the skew coefficients are different ($\vec{\bar{T}}_m^{(n)}$) contrary to normal circular harmonics. One can see that the perturbation term (dependent on ε) depends linearly in ρ, decreases for higher orders of m. The last term shows that the field is decreasing with increasing x. The field expansion is then given by

$$\tilde{\mathbf{B}}(\mathbf{z}) = \sum_{m=1}^{M}\left(r_m\;\tilde{\bar{\mathbf{T}}}_{\mathbf{m}}^{(\mathbf{n})} \;+\; \mathtt{i}s_m\tilde{\bar{\mathbf{T}}}_{\mathbf{m}}^{(\mathbf{s})}\right), \qquad (3)$$

with r_m and s_m the expansion coefficients.

B. Rotating coil probes in curved magnets

Rotating coil probes are considered to be used for measuring the SIS100 and SIS300 magnets so here the limits will be derived based on the coordinates given above. The integrations are made similarly as for a straight magnet, but now one has to take into account that a field integration versus the longitudinal coordinate s has to be made [11], [14], assuming that the field is independent of the angle of the big torus.

Circular harmonic coefficients $b_n + \mathtt{i}a_n$ are derived from the rotating coil probe measurement which are translated to the appropriate toroidal circular ones by

$$a_n = -\sum_{m=1}^{M}\bar{s}_m\;C_{mn}, \qquad b_n = \sum_{m=1}^{M}\bar{r}_m\;D_{mn}. \qquad (4)$$

These matrices C_{mn} and D_{mn} are obtained integrating the field induced by a single toroidal harmonic ($\bar{r}_m$ or $\bar{s}_m$) and processing it up to the circular multipoles. Thus C_{mn} and D_{mn} are linear mappings of toroidal multipoles to circular ones, so the toroidal multipoles are derived by the inverted C_{mn} and D_{mn}. $D_{mn} = \varepsilon\left(\frac{d}{2R_{Ref}}\right)^m + C_{mn}$ with d a horizontal shift of the axis (i. e. in the plane of the torus to the outside), therefore only C_{mn} is treated further on. The conversion matrix (C_{nm}) can be written in the following form

$$C = I - \epsilon\big(U + \underbrace{\mathcal{D}' + \mathcal{L}^{co} + \mathcal{L}^{dr2}\big) + \mathcal{L}^{dr}}_{f(d)}. \qquad (5)$$

The matrix consists of four submatrices whose magnitude depend on the ratio $\epsilon = R_{Ref}/R_C$. Considering that $R_C =$ 52.625 and R_{Ref} is 40 mm for SIS100 and 35 mm for SIS300 and setting d to be 1 mm (based on practical measurement experience), two terms depending on ε are dominant [12], [14]. D' is given by

$$\mathcal{D}' = \frac{d}{4R_{Ref}}\;\delta_{nm}\cdot\begin{cases}2 & n = 1\\ n+2 & n > 2\end{cases} \qquad (6)$$

and $\mathcal{L}^{co}$ which is defined by

$$\mathcal{L}^{co} = \binom{n-2}{n-m-1}(n-1)\left(\frac{d}{R_{Ref}}\right)^{n-m-1} S^m \qquad (7)$$

$$S_m = \frac{l^2}{24R_{Ref}^2} - \frac{K_{m+2}}{4\,(m+1)\,K_m} \qquad (8)$$

with K_m the complex coefficients, describing the sensitivity of a coil probe to the m harmonic and

$$\mathcal{L} = \lambda_{nm} = \begin{cases}0 & n \le m\\ \neq 0 & n > m\end{cases}. \qquad (9)$$

A practical limit for defining a coil for measuring a curved machine is based on the requirement that the dominant terms $\mathcal{L}^{dr}$ (the "feed down effect") and $\epsilon\mathcal{L}^{co}$ of (5) shall be of equal size [12], [14] . This yields the criteria for the coil length l

$$l \le \sqrt{\frac{24\,d}{\epsilon\,R_C}}. \qquad (10)$$

For SIS100 one obtains $l \le 775$ mm, therefore the used coil probe with a length of 600 mm is appropriate.

C. Field representation

Up to now the principle measurement method was sketched, leaving over the question if the terms dependent on ε in (3) are required. Here it is assumed that any contribution of a single term, which is less than a 1 ppm can be neglected. So the coefficients of the matrices $C_1 = U + \mathcal{L}^{co}$

$$C_1 = U + \mathcal{L}^{co} = \begin{pmatrix} \cdot & \frac{1}{2} & & \\ \frac{l^2}{24R_{Ref}^2} & \cdot & \frac{3}{8} & \\ \frac{dl^2}{12R_{Ref}^3} & \frac{l^2}{12R_{Ref}^2} & \cdot & \frac{1}{3} \\ \frac{d^2l^2}{8R_{Ref}^4} & \frac{dl^2}{4R_{Ref}^3} & \frac{l^2}{8R_{Ref}^2} & \cdot\;\frac{5}{16}\end{pmatrix}. \qquad (11)$$

were calculated and the parameter given in section III-B for SIS100 were inserted which yields then

$$C_1 = I + \frac{1}{10000}\begin{pmatrix} \cdot & 4 & & \\ 71 & \cdot & 3 & \\ 4 & 143 & \cdot & 3 \\ & 11 & 214 & \cdot\;\;2\end{pmatrix}, \qquad (12)$$

if all elements of the matrix smaller than one unit are set to 0. The coefficients are quite similar for SIS300.

The field is calculated from the coefficients using (3). For accelerator magnets one can safely assume that all higher order harmonics are well below 10 units. So one can conclude that the effect of this matrix can be neglected for all measured harmonics except the main one if an field description accuracy of not better than $\frac{\varepsilon}{4}\frac{10}{10\ 000}$ is required; a condition safely fulfilled for SIS100. Not the contribution of the main component is left to consider. The perturbation term of the basis function is 0 for the normal part, so the dominant term does not generate any perturbations. This means that the standard circular harmonics will give sufficient precision for the field representation if the quadrupole and sextupole are recalculated.

D. Combining lateral measurements

The measurement of rotating coils at different lateral positions are to be combined if elliptic harmonics are to be derived (see [10], [14]). It was shown above that for a SIS100 and SIS300 the standard multipoles will represent the field with sufficient precision if the recalculations are made. Assuming a lateral shift of the coil probe of $\delta x = \pm\ 30\,mm$ and associating a torus with each position the different radii are given by

$$R_C^{\pm} = R_C \pm \delta x \qquad \text{and} \qquad \epsilon^{\pm} = \frac{R_{Ref}}{R_C \pm \delta x}. \tag{13}$$

and epsilon to

$$\epsilon^{\pm} = (7.6009 \pm 0.0043) \cdot 10^{-4}. \tag{14}$$

The change of ϵ is at the 7^{th} digit and is thus significantly smaller than the measurement accuracy obtainable with rotating coil probe systems. Thus cylindric elliptic multipoles can be used to describe the field for the SIS100 dipoles.

IV. Conclusion

Facilities are erected or refurbished for testing the superconducting magnets of the FAIR project: for the SuperFRS magnets, for the quadrupoles and correctors of SIS100, and for the SIS100 dipoles and later for SIS300.

The preparation of the facilities is in progress and the measurement programs defined. Many measurements are standard ones as applied to qualify any superconducting magnet. The losses of the fast ramped SIS100 magnets have to be measured together with the hydraulic resistance to verify their value to warrant safe cooling in the parallel channels. The dipole curvature follows the trajectory of the beam but harmonics shall be measured. Local toroidal multipoles showed that rotating coil probes can be used for that purpose for SIS100 and SIS300. Using appropriate recalculations 2D circular multipoles can represent the fields of the curved dipoles with sufficient accuracy.

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