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STATUS OF SUPERCONDUCTING MAGNETS FOR SUPER-FRS AT FAIR

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Abstract

The first experiment at newly constructed FAIR accelerator facility will be conducted with a beam provided through the Super Fragment Separator (Super-FRS) as FAIR Early Science program. Super-FRS superconducting magnets having a large aperture are key elements, which determine performance of the separator. 15 dipole magnets and 20 multiplets are required for the High Energy Branch of Super-FRS for execution of the Early Science program. The dipole magnet is a super-ferric type magnet with a warm iron yoke, providing 1.6 T. A mechanical array of various combinations of quadrupole, sextupole, octupole, and steering dipole magnets is integrated in a cryostat, which is the multiplet generating magnetic fields fulfilling beam optics requirements. Production of the dipole magnets as well as the multiplets is ongoing. The produced magnets are being delivered and tested at a cryogenic test facility at CERN. This paper gives an overview of the superconducting magnets in Super-FRS, status of the production and the testing.

FAIR EARLY SCIENCE AND SUPER-FRS

The first physics experiment with a newly constructed accelerator facility FAIR will be carried out with secondary beams, produced and separated using High Energy Branch of Super-FRS [1]. This strategy have been reviewed and reconfirmed by the FAIR council recently. The civil construction for the Super-FRS cave is in the advanced stage as well as the procurements of the Super-FRS components.

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For the Early Science, besides some radiation-resistant normal conducting magnets placed just after the target, 15 wide aperture superconducting dipole magnets and 20 multiplets, which contain superconducting quadrupole and corrector magnets are required. 2 out of 15 dipole magnets shall be a branch type dipole magnet so that the Super-FRS can provide a beam to the Low Energy and the Ring Branches as full completion of Super-FRS. 3 dipole magnets after the target have a longer length and a larger deflection angle of 11°, with respect to the other dipole magnets with 9.75°. 3 long multiplets are used for final focusing of the primary beam on the Super-FRS target, 7 short multiplets follow after the target, most of the long multiples are installed at front and rear of the bending sections, each consisting of 3 dipole magnets. Figure 1 shows the magnets along the Super-FRS.

LARGE APERTURE SUPERFERRIC DIPOLE MAGNETS

The large aperture dipole magnet having warm H-type iron yoke is being manufactured at Elytt Energy, Spain [2]. CEA/Saclay, France is contributing technical follow-up of the dipole magnet as French in-kind contribution to FAIR. The superconducting coil in the cryostat is cooled down to 4 K with liquid helium thermo-syphon cooling. A race track coil with 560 turns is wound from a rectangular cross-section NbTi superconducting conductor with an electrical isolation carrying about 240 A. It is used to generate magnetic field from 0.16 to 1.6 T in the aperture with a good field region 380 mm × 140 mm. Different requirements for the dipole magnets, such as already mentioned deflection angles or

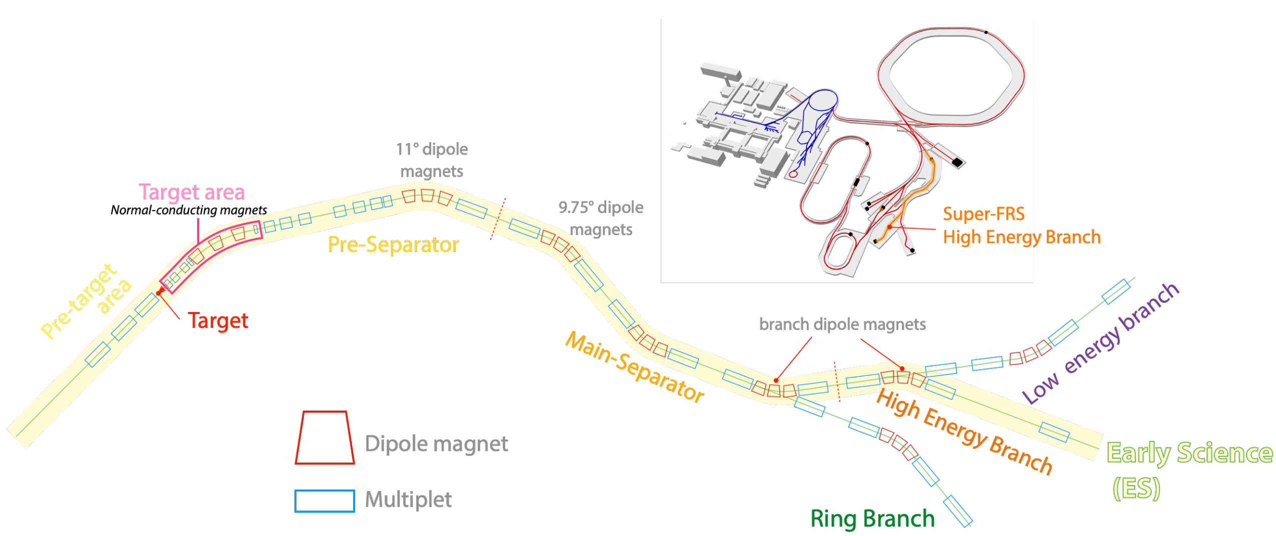

Figure 1: Superconducting magnets in Super-FRS at FAIR

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branching types, but also locations of the cryogenic interfaces, result in total in 8 different types of the dipole magnets for the High Energy Branch As spare, assembled cryostats for the 9.75° and the 11° dipole magnets will be produced. Magnet parameters are summarized in Table 1 and a picture of the 11° dipole magnet is shown in Fig. 2.

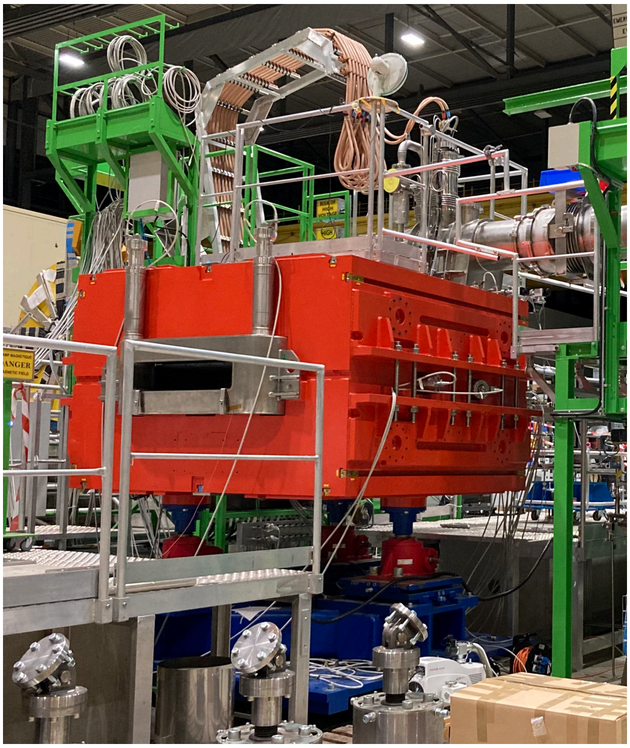

Figure 2: The large aperture superferric dipole magnet placed in a test bench at CERN.

SUPERCONDUCTING MULTIPLETS

In contrast to having a warm iron yoke for the dipole magnet, the magnets of the multiplets are immersed in liquid helium in a vessel in the cryostat, which has a beam pipe at room temperature with a diameter of 380 mm.

The multiplets are being produced by ASG Superconductors, Italy [3]. The different types of magnets in multiplets are long and short quadrupole magnets, having 1.2 m and 0.8 m yoke length, a sextupole and a steering dipole magnet, both having 0.5 m long yokes and an octupole coil embedded in the short quadrupole magnet. Whereas both quadrupole magnet types having identical cross-sections, as well as the sextupole magnet are designed on the principle of a superferric magnet with race-track coils, the steering dipole and the octupole coil have cosine-theta design. A common NbTi conductor is used for all the coils. The steering dipole magnet and the octupole coil are a cosine-theta type. Since the octupole coil is powered in the short quadrupole magnet yoke, the conductor positions in the coil is arranged like a quadrupole and octupole combined function magnet coil in order to compensate effects from the quadrupole symmetric yoke. The cross section of the superferric magnets and the overview of the cosine-theta coils are shown in Figure 3. The parameters of the magnets are shown in Table 1.

The multiplets are composed of different combinations of the magnets, mentioned above. In front of the target, 3 multiplets, which contain, in total, 8 long quadruple magnets and 2 steering dipole magnets, are installed. Between the target area and the 11° dipole magnets, 7 multiplets with a shorter length will be placed. The 7 multiplets contain, in total, 4 long quadrupole magnets, 7 sextupole magnets, and 2 short quadrupole magnet with the octupole coil, 1 steering dipole magnet. After the 11° dipole magnets, all 10 multiplets have a triplet of short-long-short quadrupole magnets combination. All the short quadrupole magnets house the octupole coils. In these multiplets, at the front and/or the rear of the triplet magnet array, and/or between the quadrupole magnets, sextupole magnets, and/or a steering dipole magnet are integrated depending on the type of a multiplet. Due to the variation of the combination, there are 16 types for the 20 multiplets in the High Energy Branch.

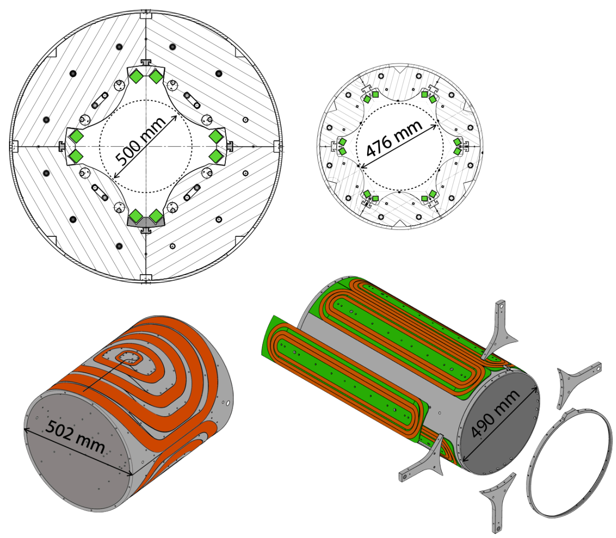

Figure 3: Cross section of the quadrupole and the sextupole magnets and overview of the steering dipole and the octupole coils.

CRYOGENIC MAGNET TESTING AT CERN

GSI and CERN have been established a collaboration on the Super-FRS superconducting magnet testing since 2012 [4]. After 7 years of investment into the cryogenic facility renovation as well as three test bench installations and related activities, commissioning of the facility and testing of the first magnet modules are started in 2019. In the operation phase, in general, CERN colleagues are working for keeping the facility operational, and GSI colleagues stationed at CERN are coordinating and executing the tests. There are three test benches, which are compatible for all type of both the dipole magnets and the multiplets.

Since the first magnet module, namely the First-of-Series (FoS) short multiplet, so far, 4 out of 20 multiplets for the

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Table 1: Magnet Specifications

	11° Dipole	9.75° Dipole	Long Q.	Short Q.	Sextupole	Steering D.	Octupole
n, $2n$-pole	1	1	2	2	3	1	4
$\int B_n dL$ (T/m$^{(n-1)}$ m)	3.8	3.4	11.8	8.1	20.4	0.1	82.9
B_n at center (T/m$^{(n-1)}$)	1.6	1.6	9.7	9.7	36.1	0.2	98.5
Effective length (m)	2.40	2.13	1.22	0.83	0.56	0.48	0.84
Iron yoke length (m)	3.23	2.96	1.2	0.8	0.5	0.5	(0.8)
Nominal current (A)	260	237	268	275	291	293	160
A·turns/pole (kA·turns)	145.6	132.4	334.5	343.2	138.5	57.1	17.3
Inductance (H)	26	15.8	42	30	1.0	0.07	0.1
Stored energy (MJ)	0.5	0.5	1.1	0.77	0.037	0.0026	0.0013

Early Science were delivered to GSI after the tests at CERN. These include the FoS long multiplet containing 9 magnets, which is the largest configuration multiplet. Its overall testing was successful, especially it was proven that the 9 magnets can be powered in the same time. However, magnetic measurements revealed that the octupole coils were installed 45° rotated into the short quadrupole magnets, mistakenly. After evaluation of the magnetic field quality by beam optics simulations, the long multiplet was accepted exceptionally and will be installed into the Ring Branch. Since the magnet designs are common for all identical type of the magnets in the multiplets, the criteria on the field quality is set to meet the most demanding magnets in the Super-FRS. However, practically, the field quality requirement would vary along the beam line. Therefore, even non conformity on field quality is detected, evaluation with beam optics simulations is performed and the acceptance decision are being made for individual cases.

The other delivered 3 multiplets are the shorter multiplets. Besides the steering dipole magnet, all the other magnet types are intensively tested and the designs and the manufacturing technology of the magnets had been confirmed. Since unexpected error of the field quality of the steering dipole magnet was detected, investigation and analysis are ongoing. Further two short and two long multiplets were manufactured and delivered to CERN. One short multiplet is being prepared for the tests, one is waiting for a shipment to GSI after the testing and both long multiplets are currently being tested.

In February 2021, the FoS 9.75° dipole magnet was delivered to CERN. However, due to leakage from the thermal shield cooling pipe, the magnet could not be subjected to the cryogenic testing and had to be sent back to the manufacturer for repairing. In January 2022, FoS 11° dipole magnet had been delivered and the cryogenic tests were executed. During the testing, movements of the chamfer blocks of the iron yoke was observed. It was considered as a possible reason of the measured non-conformity of the magnetic field quality. Therefore, the chamfers were re-placed in the correct positions and dedicated support reinforcement structures were implemented. As results, the magnetic field quality fulfills the requirement and the cryogenic test program had been completed. The magnets was sent back to the manufacturer for some repair operations, then it will be delivered to GSI in middle of this year. The dipole magnet manufacturer identified a potential weakness of brazing joints of the thermal shield piping. Intensive investigations and R&Ds on the joints are being completed and the improved technology will be implemented from the next dipole magnet on. In order to catch up the schedule, the manufacturer is planning increase of production rate of the dipole magnets.

PRE-ASSEMBLY OF THE MAGNET MODULES

The magnet modules delivered to GSI/FAIR will be subjected to incoming inspections first. The inspection passed modules are subjected to pre-assembly operations like installation of facility interface parts such as power cables and helium return gas valves. For the dipole magnet, a beam pipe will be installed at GSI. Fully equipped modules are placed in a storage place, where the temperature and the humidity are monitored and controlled, and wait installation to the cave.

SUMMARY

The High Energy Branch of the Super-FRS was assigned as facility for FAIR Early Science is under construction. The large aperture dipole magnets and the multiplets are in the series production phase. Testing of the magnets is ongoing in a full swing mode. Delivered modules are prepared for the installation and properly stored. The present pace of the production and testing is in line with the installation schedule, thus the modules, required for the Early Science are going to be ready for the installation in 2025.

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