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SUPERCONDUCTING MAGNETS FOR SUPER-FRS: PRODUCTION AND TESTING STATUS

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Abstract

The Super FRS is a two-stage in flight separator to be built next to the site of GSI, Darmstadt, Germany as part of FAIR (Facility for Anti-proton and Ion Research). Its three branches allow to carry out a wide variety of experiments. Due to the large acceptance needed, the magnets of the Super-FRS require a large aperture and therefore only a superconducting solution is feasible. A superferric design was chosen in which the magnetic field is shaped by an iron yoke. For the dipole magnets only the superconducting coils are in a cryostat. These magnets are manufactured by Elytt Energy (Spain). The multiplets, assemblies of quadrupoles and higher order multipole magnets, are completely immersed in a liquid Helium bath. They are being built at ASG (Italy). The first of two first of series multiplets, a short assembly containing 2 magnets, was tested at a dedicated test facility at CERN (Switzerland). The 2nd FoS multiplet, containing 9 magnets, and the FoS dipole will be tested soon. Series production of the multiplets has started.

In this paper we will present the status of production and testing of the different superconducting magnets for Super-FRS.

INTRODUCTION

The Super-FRS is a new two-stage in-flight separator. It will be built as part of the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany [1]. Due to its three branches (high-energy branch, low-energy branch, and ring branch) a wide variety of experiments will be possible [2, 3]. The large acceptance required and the DC operation of the magnets led to a superconducting solution. Only the very first magnets after the target have to be built as normal conducting magnets with special radiation resistant conductor, due to the high radiation levels.

From protons to uranium all sorts of ions can be accelerated in the Super-FRS up to energies of about 1.5 GeV/u and with beam intensities of 10^{12}/s.

The general layout of FAIR and Super-FRS location in it are shown in Fig. 1. Overall the Super-FRS consists out of 24 dipole magnets and 30 multiplets (containing 80 quadrupoles, 41 sextupoles, 14 steerers, and 46 octupoles).

Additional superconducting magnets are needed for the Energy Buncher in the low energy branch. These magnets are not treated within this paper.

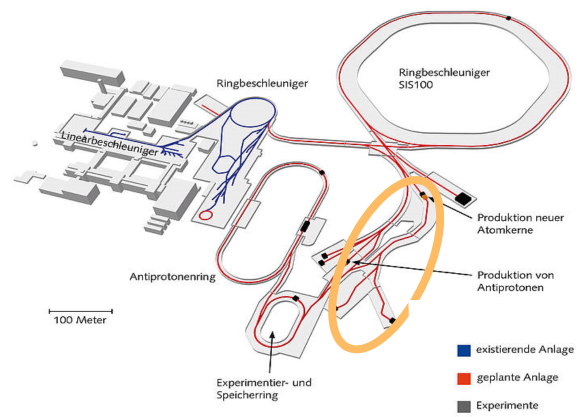

Figure 1: Layout of FAIR. On the left is the existing GSI, the position of Super-FRS with its different branched is indicated by the orange circle.

MAGNET DESIGN

The magnets of Super-FRS have several common design features. Firstly, they are of so called superferric type (with the exception of the small correction magnets steerer and octupole which are made as surface coils). The magnetic field is shaped by the magnetic iron as for normal conducting magnets, but the coils of the magnet are wound with superconductors.

Secondly, the magnets have to be self-protected, i.e. they have to survive a quench without any damage even in case the quench protection system fails. Nevertheless dump resistors are foreseen for quadrupoles and dipoles to extract as much energy as possible. The requirement of self-protected magnets leads to the use of superconductors with a high Cu/SC ratio (>9 in case of the dipoles, ~3.5 for quadrupoles and sextupoles).

Each of the magnets is powered individually and has its own pair of leads. To limit the size of the current leads and warm power cables, the maximum current of the mag- nets have to stay below 300 A. This leads to coils wound of insulated wires rather than a cable, resulting in high inductance values for the magnets (about 37 H for the long quadrupole and 23 H for the branching dipole).

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Table 1: Main Parameters of Super-FRS Multiplet Magnets

	Quadrupole Type 3	Quadrupole Type4	Sextupole	Steerer	Octupole*
Number of magnets	44	32	39	14 (13v/1h)	
Field/Gradient range	1-10 T/m	1-10 T/m	4-40 T/m²	0-0,2 T	105 T/m³
Effective length [m]	0,8	1,2	0,5	0,5	
Radius of usable aperture [mm]	190	190	190	±190	
Field quality	$\pm1\cdot10^{-3}$	$\pm1\cdot10^{-3}$	$\pm5\cdot10^{-3}$		

*embedded in Quadrupole Type 3

The cooling of the magnets will be done by a pool boiling Helium bath. The design pressure of the Helium containers is set to 20 bars to avoid helium losses in case of quench and to be able to operate the cryogenic facility of FAIR with one common pressure.

An additional requirement is a warm beam pipe.

Despite of being operated in DC mode three consecutive triangular cycles up to maximum current with a ramp up time of 120 sec have to be possible in between the different operation cycles. This cycling is necessary to always have reproducible field conditions independent from the previous setting.

The beam height in Super-FRS is at 2 m the height of the cryogenic supply was fixed to 3.3 m over ground.

MULTIPLETS

Quadrupole, sextupole and steerer magnets, as well as octupole coils embedded in the short type of quadrupoles, are grouped together in one common cryostat, a so called multiplet. Depending on the position of the multiplet within the Super-FRS it contains from 2 up to 9 magnets. Table 1 gives an overview of the main parameters of these multiplet magnets. More details on can be found in [4, 5]. The multiplets are manufactured by ASG Superconductors in La Spezia, Italy.

Cold Test Results of FoS Short Multiplet

The First of Series (FoS) short multiplet has been delivered to CERN in September 2019 and was cold tested in a dedicated test facility, set up in frame of a collaboration contract between CERN and GSI [6]. The cold testing o

Tests performed at CERN included [7]:

- Vacuum and HV insulation tests;
- Instrumentation checks
- Cool-down and warm-up
- Magnetic measurements for each single magnet
- Ramping tests (120 seconds ramp time; 3 cycles)
- Static heat loads

The design of the magnets of the multiplet (long quadrupole and sextupole) could be verified successfully, Fig. 2 shows an example of magnetic measurement results for the quadrupole. Another parameter successfully proved was the stability of the magnetic axis position after thermal cycling. Also the cool down could be optimised to 5 days. The measured heat loads were higher than calculated, this could be ascribed to the presence of openings for windows for observation of cold mass position and for transport secures. Due to these successful measurement a release of the multiplet production of the short multiplets could be given. Only drawback for this dedicated multiplet was a leakage in the thermal shield cooling pipe, which will require continuous vacuum pumping during operation.

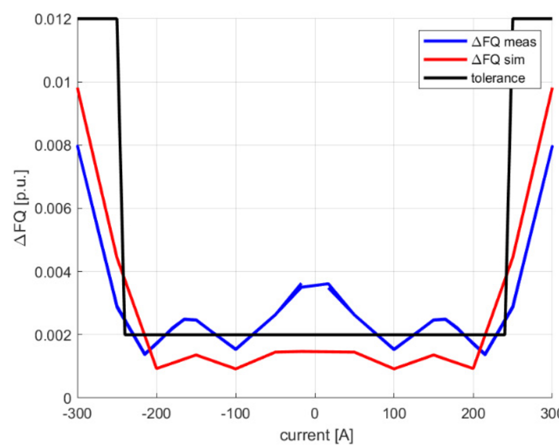

Figure 2: Field quality measurements for the long quadrupole of the FoS short multiplet. The deviations between simulated and measured values could be ascribed to the influence of the iron yoke of the neighbouring sextupole magnet which created non allowed harmonics. The steep increase in the field quality for higher currents is due to high saturation of the iron yoke.

Besides the short multiplet, also the magnetic measurement equipment and other parts of the test facility have been commissioned successfully.

Multiplet Production Status

The FoS long multiplet, containing the maximum configuration of 9 magnets had its succesfull factory acceptance test at ASG in September 2020 and was deliverd to CERN. It is installed at the bench, cooled down and tests are ongoing. Figure 3 shows the 2 multiplet installed at 2 test benches at CERN.

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Figure 3: Long (in the front) and short multiplet mounted on test benches at CERNLayout of FAIR.

Series production of the short multiplets has started and is progressing smoothly. All short multipets are planned to be produced within this year.

DIPOLES

Two types of dipoles, differing in their magnetic lengths, are required in the Super-FRS. From the 21 dipoles of so called type 3, three magnets must additionally provide holes for a straight beam tube at the splits of the different branches. The main parameters of the dipoles are given in Table 2; The dipoles are H-type magnets with racetrack coils, and only the coils are cold while the iron yoke is at room temperature as for a normal conducting magnet. Based on a prototype built in China [8] a conceptual designs for standard and branched dipoles were developed by CEA, Saclay. In frame of this design work the cooling concept was changed to of two independent thermosiphon loops for upper and lower coil, respectively [9].

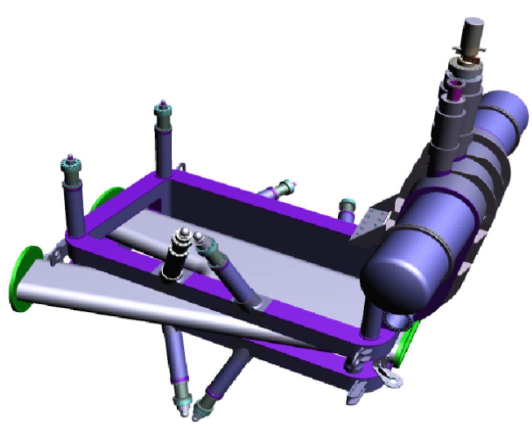

Figure 4: Cryostat and vacuum chamber of the branching dipole. Due to the opening for the chamber the coil casing supports have to be inclined to be able to cope with the magnetic forces.

Also for the 3 branching dipoles the conceptual design was developed by CEA, Saclay [10, 11]. To provide the high mechanical strength of the cold mass needed, the final design consists of a C-shaped cryostat with inclined cold to warm supports (which also have to be fixed on the yoke) as can be seen in Fig. 4.

Standard and branched dipoles are built by Elytt Energy, Spain. The First of Series type 3 magnet was finished in December 2020, and delivered to CERN for testing (see Fig. 5). The FoS type 2 dipole is in its final manufacturing steps and should be ready for shipment in July.

The design of the branched dipole is verified and the production of these magnets also has started.

Table 2: Main Parameters of Super-FRS Dipoles. Three of the magnets of type 3 are branching dipoles with an additional straight exit

	Type 2	Type 3
Number of magnets	3	21
Dipole field [T]	0.15-1.6	0.15-1.6
Bending angle [°]	12,5	9,75
Curvature radius [m]	12,5	12,5
Effective straight length [m]	2,4	2,13
Good field region [mm]	±190	±190
Pole gap height [mm]	170	170
Integral field quality (relative)	±3*10-4	±3*10-4

Figure 5: First of Series dipole ready at Elytt to be packed for shipment.

STATUS AND OUTLOOK

All superconducting magnets of Super- S are contracted and in production. The site acceptance test of the FoS short multiplet is finished and due to the satisfactory results the release for series production of the short multiplets was

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given. The FoS long multiplet is under test at CERN right now. Also the first type 3 dipole has arrived at CERN and testing will start soon. For the testing of the FoS magnet an extended measurement period of about 6 months is foreseen. After that the series testing will start using the three parallel test benches of the facility that allow testing of a magnet assembly every two weeks. Series testing will run until 2024.

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