ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS015

DESIGN AND MANUFACTURING OF THE FIRST MULTIPLET FOR THE SUPER-FRS AT FAIR

E. Cho†, H. Mueller, K. Sugita, C. Roux, M. Winkler, GSI, Darmstadt, Germany
A. Borceto, G. Valesi, D. Ventura, G. Drago, ASG Superconductors S.p.A., Genova, Italy

Abstract

The Superconducting FRagment Separator (Super-FRS) at Facility for Antiproton and Ion Research (FAIR) is a two-stage in flight separator. It aims at production of rare isotopes of all elements up to uranium and separation of them. It consists of three experimental branches with 24 superferric dipole magnets and 170 multipole magnets in addition to few normal conducting magnets in the high radiation area. The quadrupole and the sextupole magnets are assembled with corrector magnet(s) in a common cryostat. This cryogenic module is called a multiplet. The first unit of the series (FoS) multiplet comprises one quadrupole and one sextupole magnet and its construction was completed in Q1, 2019. The design challenges of the multiplet are to fulfil the field quality requirement of the quadrupole magnet at a large good field region despite strong iron saturation and to design the multiplets for high design pressure. This contribution presents the magnetic and the mechanical design and manufacturing status of the FoS multiplet.

INTRODUCTION

The Super-FRS is a part of FAIR, which is currently being built in Darmstadt, Germany [1]. Its capability of separating rare isotopes within some hundred nanoseconds will enable an efficient study for very short-lived nuclei [2]. It is designed for large momentum acceptance ($\Delta p/p = \pm 2.5$ %) and angular acceptance ($f_x = \pm$ 40 mrad, $f_y = \pm$ 20 mrad). The maximum beam rigidity is 20 Tm. For large acceptance and high rigidity, the superferric magnet design was adopted except for the octupole and the steering dipole magnet.

In a multiplet, two to nine magnets (at maximum) will be arranged depending on the requirement of beam optics. The magnets will be cooled in a common liquid helium (LHe) bath. Figure 1 shows a cross section of the FoS multiplet. Dimensions and weight of the multiplet are 2.6 m x 2.7 m x 4.2 m (W x L x H) and 28 tons, respectively. The magnet column consists of one sextupole and one quadrupole magnet with a 250 mm distance between the yoke ends. The weight of the cold mass is 19 tons. The design pressure of the LHe vessel and the maximum volume of LHe are 20 bars *abs* and 800 liters, respectively [3]. It corresponds to PED (Pressure Equipment Directory) 97/23/EG category IV. According to the regulation, design of the vessel needs to be verified and approved by an authority.

MAGNETIC DESIGN

The main parameters for magnets are summarized in Table 1. The field requirement for the quadrupole magnet is defined differently for two regions due to high iron saturation.

A vacuum impregnated race track coil with a square cross section is used for all the magnets. The feature of Nb-Ti superconductor is a Cu/Sc ratio of 3.5 ± 0.3 and RRR = 100. For the quadrupole magnet, the operating current of 300 A at 10 T/m is 37 % of the critical current. For the sextupole magnet, the operating current of 291 A at 40 T/m^2 is 15 % of the critical current. The temperature margin is more than 2 K.

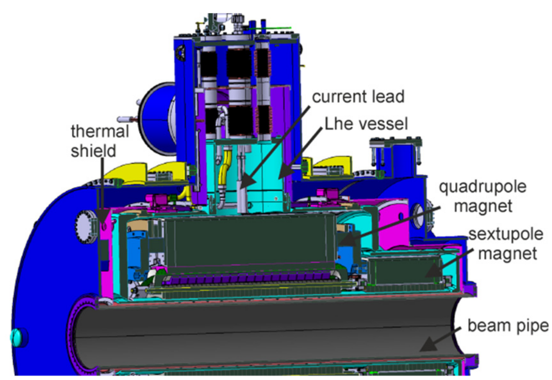


Figure 1: Cross section of the FoS Multiplet.

Table 1: Main Parameters of the Quadrupole and the Sextupole Magnet

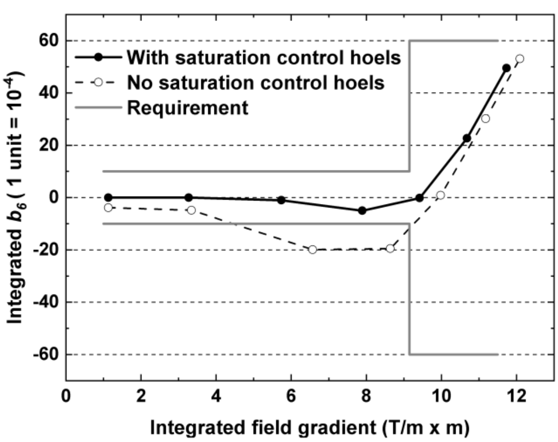
Parameters	Quadrupole	Sextupole
n	2	3
Length of iron (mm)	1200	500
Pole tip radius (mm)	250	238
Warm bore radius (mm)	190	190
Outer radius of yoke (mm)	700	420
Gradient, g (T/m^{n-1})	10	40
Max. current, I_{max} (A)	300	291
Inductance @ I_{max} (H)	21	0.88
Stored Energy @ I_{max} (kJ)	952	37
Integral field quality requirement @ 190 mm	$\pm 1 \times 10^{-3}$ $< 0.8\ g_{max}$ $\pm 6 \times 10^{-3}$ $> 0.8\ g_{max}$	$\pm 5 \times 10^{-3}$

† e.j.cho@gsi.de

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS015

Each magnet is equipped with a pair of 300 A DC vapour cooled current lead (CL). In case the quadrupole magnet quenches, its stored energy will be partly dissipated at a dump resistor (2.8 ohm). The magnets are self-protecting. Even if the quench protection system does not work, the hot spot temperature of the quadrupole magnet is expected to be 140 K. During operation, the pressure in the LHe vessel is 1.3 ± 0.1 bars and the maximum voltage between the coil and the ground could be 1.6 kV at the quench. The distance between the voltage tap feedthrough pins are less than 2 mm (minimum required space in order to avoid Paschen effect), the pins are insulated with Stycast® [4].

The sextupole magnet meets the field quality (FQ) requirement with a good margin. However, achieving the required FQ for the quadrupole magnet at the reference radius of 190 mm was challenging. The FQ did not meet the requirement especially between the integrated field gradient 5 and 8 T/m·m where most of the quadrupole magnets will be operated. 2D and 3D magnetic field analysis were performed with commercially available software [5]. From the results, it is concluded that this is due to strongly localized iron saturation (at the end portion of the pole) starting already at 50 A (corresponding to 3 T/m·m).



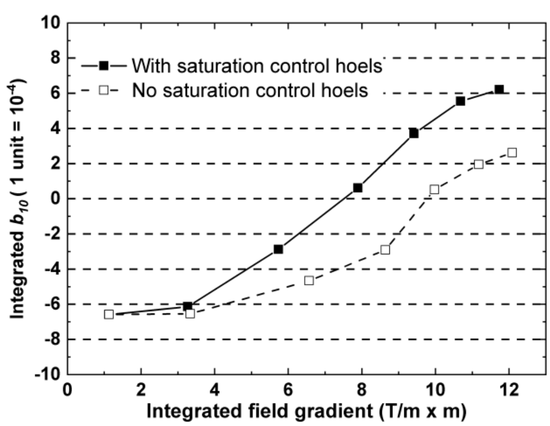


Figure 2: b_6 as a function of integrated gradient (top). The solid lines indicate the field quality requirement. b_{10} as a function of integrated gradient (bottom).

After extensive investigation about the impact of position, size, shape and the number of saturation control holes on the FQ [6], three saturation control holes were introduced around the pole in order to achieve more homogeneous iron saturation. The integrated b_6 and b_{10} are compared depending on the presence of the saturation control holes in Fig. 2. Significant reduction of b_6 and b_{10} at the aimed gradient is clearly visible due to the holes.

The magnetic field interference between the quadrupole and the sextupole magnet was analyzed with a half-full 3D model. At worst case ($I_{quad.}$ = 300 A and $I_{sext.}$ = 150 A), the dominant forbidden multipole, b_4 is slightly higher than the field quality requirement (4×10^{-4}), which is still acceptable.

Figure 3 shows the complete assembly of the quadrupole and the sextupole magnet. After pre-alignment of these two magnets on an alignment bench, these magnets are connected with interface flanges. Cernox sensors are installed on the coils and the yokes in order to monitor the temperatures. During cool down, the maximum temperature gradient of the cold mass shall be maintained below 40 K in order to avoid mechanical stress. The fillers made of High Density Polyethylen (HDPE) in the sextupole magnet are visible in Fig. 3. They fill an empty volume between the LHe vessel inner pipe and the magnets.

Figure 3: Quadrupole magnet assembly (top). The coil position is being checked with a laser tracker. Sextupole magnet assembly (bottom left) and magnet column on an alignment bench (bottom right).

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS015

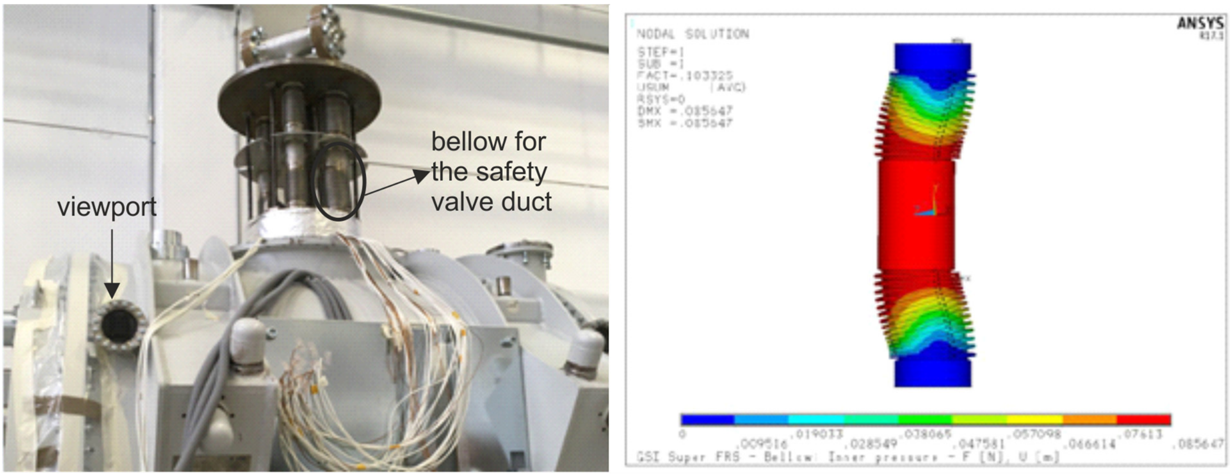


Figure 4: Deformation of the (lower) bellow containing the safety valve duct (in a circle) is clearly visible. This was observed after a pressure test at 8.3 bars. The viewports on the vacuum vessel are installed to measure cold mass movement during cool down (left). The FEM analysis result of the bellow buckling (right).

MECHANICAL DESIGN

The cold mass is supported by tie rods which are anchored to the multiplet vacuum vessel. The tie rods are made of hardened Inconel 718 providing good stiffness and yield strength. There are longitudinal tie rods and radial tie rods. The four longitudinal tie rods are preloaded to compensate the lateral contraction of the cold mass during cool down. The radial tie rods are designed to withstand the gravitational load (via major tie rods) and pre-load (via minor tie rods). They are equipped with spherical washer/conical seat couples for compensating angular displacement. During cool down, cold mass movement will be checked through the viewports on the vacuum vessel [7]. The dedicated targets are installed on the LHe vessel for the measurement.

The LHe vessel is designed according to AD 2000-Merkblatt in consideration of its design pressure of 20 bars *abs*. It is made of stainless steel 1.4571. The design of the vessel was verified by FEM analysis for three accumulative loads, self-weight, cool down and 20 bars *abs* on all the inner surfaces of the He vessel.

The CLs, an instrument flange, a safety valve and a rupture disk are assembled with a turret. The turret has four universal axial joints, i.e. two bellows are connected with pipe ends. This can allow compensating greater axial, lateral and angular displacement of the cold mass than a single bellow can. These bellows guide also the current leads, instrumentation wiring and safety valve duct. They were PED certified at 27 bars. Nevertheless, mechanical instability (buckling) of all the bellows was observed even at 8.3 bars due to internal pressure during the pressure test (Fig. 4). Because buckling depends on the radius of the bellow and the number of convolutions, the bellow containing the safety duct deformed more than the other bellows with a smaller radius. FEM buckling analysis performed after the failure confirmed the problem (Fig. 4). Commercially available solutions which take more space for an assembly cannot be adopted considering that the turret of the largest multiplets (with 9 magnets) is already crowded with the CLs assemblies and the instrumentation flanges. Instead, a 2 mm thick pipe is now installed inside of the bellows, which can mitigate buckling by increasing lateral stiffness. With this configuration the pressure test was successfully completed during the factory acceptance test. The site acceptance test (SAT) at cold is underway at a dedicated cryogenic magnet test facility at CERN in the framework of GSI/CERN collaboration [8].

SUMMARY

This contribution presents the design and manufacturing status of the FoS multiplet. The challenges of the quadrupole magnetic design and mechanical design concepts are addressed. The construction of the multiplet was completed in Q1, 2019. The factory acceptance test was successfully done. The completion of extensive SAT including a thermal cycle test is scheduled for Q4, 2019.

REFERENCE

[1] P. J. Spiller *et al.*, "Status of the FAIR project", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, May 2018, pp. 63-68. doi:10.18429/JACoW-IPAC2018-MOZGBF2

[2] M. Winkler *et al.*, "The status of the Super-FRS in-flight facility at FAIR", Nucl. Instrum. Meth. B 266, 2008, pp 4183-4187.
doi:10.1016/j.nimb.2008.05.073

[3] H. Muller *et al.*, "Status of the Super-FRS magnet development for FAIR", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Virginia, USA, May 2015, pp. 2792-2794.

[4] A. Perin, R. Jareo and L. Metral, " Study of Materials and adhesives for superconducting cable feedthroughs", CERN, Geneva, Switzerland, Rep. CERN-2001-504, Oct. 2001.

[5] Cobham, Opera magnetic simulation software, http://operafea.com/

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-THPTS015

[6] E. Cho *et al.*," Magnetic Design for the Superferric Multipole Magnets of the Super-FRS ", IEEE Trans. Appl. Supercond., vol. 28, no.4, June 2018, Art. Seq. No., 4101505, doi:10.1109/TASC.2018.2805920.

[7] V. Velonas, I. Pschorn, T. Miertsch, K. Knappmeier and A. Junge," Measurement with laser traker through different media: the MIDAS system", presented *at International Workshop on Accelerator Alignment (IWAA'18)*, Chicago, USA, Oct. 2018.

[8] L. Serio *et al.*, "A New Cryogenic Test Facility for Large and Heavy Superconducting Magnets", IEEE Trans. Appl. [7] Supercond., vol. 27, no. 4, June 2017, Art. Seq. No., 9500105.