ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOTK013

COLD TEST RESULTS OF THE FAIR SUPER-FRS FIRST-OF-SERIES MULTIPLETS AND DIPOLE

A. Chiuchiolo, P. Kosek, F. Greiner, A. Beaumont, K. Sugita, E. Cho, H. Mueller, M. Michels, Y. Xiang, F. Wamers, C. Roux, V. Velonas, M. Winkler, H. Simon, GSI, Darmstadt, Germany
H. Allain, A. Madur, V. Kleymenov, CEA-Saclay, Gif-sur-Yvette, France

Abstract

Within the collaboration between GSI and CERN, a dedicated cryogenic test facility has been built at CERN (Geneva, Switzerland) in order to perform the site acceptance tests of the 56 Superconducting FRagment Separator cryomodules before their installation at the Facility for Antiproton and Ion Research (Darmstadt, Germany).

Two of the three benches of the CERN test facility were successfully commissioned with the powering tests of the first-of-series multiplets and dipole. The long multiplet, with a warm bore radius of 192 mm, is composed of nine magnets of different type (quadrupole, sextupole, steering dipole and octupole) assembled with Nb-Ti racetrack and cosine-theta coils, mounted in a cold iron yoke and in a common cryostat.

This work presents the first results of the cold powering tests at 4.5 K during which dedicated measurements have been implemented for the magnetic characterization of the single magnets up to nominal current (300 A for a long quadrupole) and the study of their crosstalk effects.

The results of the acceptance tests will be presented together with the challenges and lessons learnt during the facility commissioning.

INTRODUCTION

For the Superconducting FRagment Separator (Super-FRS) under construction at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, large acceptance superconducting magnets are currently under test at the European Organization for Nuclear Research (CERN) cryogenic test facility for their final validation before installation [1, 2].

In total 199 magnets grouped in 56 cryomodules will be tested: more specifically 32 multiplets and 24 main dipole magnets [3]. The multiplets, of different lengths (from 2.4 to 7 m), are composed of minimum two up to maximum nine magnets of different type (long and short quadrupoles, sextupoles, octupoles, steering dipoles) and positioned at 250 mm distance from each other. The magnets, with the Nb-Ti racetrack and cos-theta coils inside their cold iron yokes, are aligned along the beam pipe within a single common cryostat. Furthermore, the octupoles are nested inside the short quadrupoles.

Since 2019, cold tests started on First of Series short multiplet (FoS SM), First of Series long multiplet (FoS LM) and the FoS bending dipole magnet. The FoS SM is composed by a sextupole (SE) and a short quadrupole (SQ), while the FoS LM is composed by one long quadrupole (LQ), two short quadrupoles (SQ), two octupoles (OCT), three sextupoles and one steering dipole (St.Dip). Figure 1 shows the FoS installation at the CERN test facility on the reception area and on the test benches.

This work presents the FoS testing strategy and the main achievements with a particular attention given to the multiplets results before entering the series testing phase. The results of the FoS dipole magnet, presently under test, will be presented in future works.

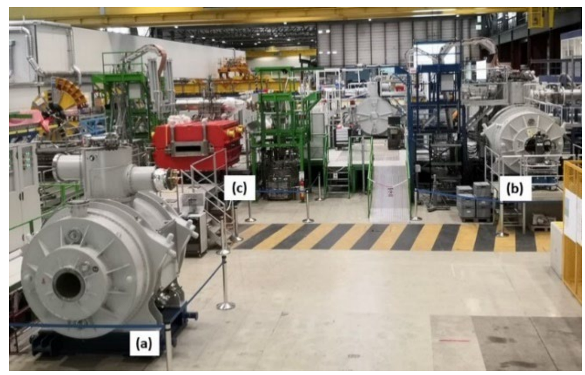

Figure 1: FoS short multiplet (a), the FoS long multiplet (b) and the FoS dipole (c) at the CERN test facility.

FOS TESTING GOAL AND STATUS

The objective of the FoS testing plan is the validation of the magnets design and performances at room and cold temperatures and the reproducibility of the results after thermal cycling.

The qualification of the magnetic field performances, with the required strength and homogeneity, is the most important part of the cold tests. Therefore, extended measurements plan has been followed. Different magnetic measurement methods have been employed and compared in order to optimize the series testing campaign [4].

The FoS tests had also the goal to commission the CERN test facility, comprising the cryogenic infrastructure and control systems, power converts, energy extraction and quench protection systems, as well as the magnetic measurement devices. For this reason, within the FoS test plan, dedicated powering tests and heat load measurements have been performed [5].

After the commissioning of two of the three test benches, the optimization of the cryomodule interface with the facility, the full characterization of the measurement devices and the successful testing campaign, on February 2022, the FoS SM was delivered to GSI. It will be followed by the FoS LM in July 2022 while the FoS dipole tests are continuing.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOTK013

TEST SETUP AND MEASUREMENTS DEVICES

Within the multiplets each magnet can be individually powered via a pair of current leads integrated in the cryostat and designed for operating in self cooling conditions at constant pressure.

Nine powering circuits can be simultaneously connected to one of the three test benches. Three circuits are equipped with dump resistors which are electrically connected in series with the magnets to extract the stored energy in case a quench is detected. The dump resistors are foreseen only for the multiplets' quadrupoles and the FoS main bending dipole powering circuits. They are used to limit the voltage across the magnet at the quench current and represent an efficient way to lower the energy released in the liquid helium bath. Each dump resistor has a fixed value of R_{dump}= 2.8 Ω, therefore the resulting current extraction time constant is $\tau = L/R_{dump}$ where L indicates the inductance of the magnet at the quench current level.

The signals used for the magnet protection include the voltages across the current leads and the two halves of the magnet. For the quench detection the voltage threshold and the validation time, chosen from the expected quench propagation velocity, are set to 600 mV and 35 ms respectively for the magnet coils. While the current leads are protected with a 120 mV voltage threshold (for the multiplets) and 70 mV (for the dipole) and 6 ms as validation time.

For the extended magnetic measurements program, two measurements devices are used and compared. The rotating-coil magnetometer is used for the field strength (local and integral magnetic flux density) and field quality, while the single-stretched wire (SSW) is used for the integral field strength, the integral field quality and the magnetic axis localization. Due to large required good field region (190 mm radius), these dedicated measurements systems have been designed and constructed at CERN [6] for the Super-FRS magnets and calibrated in situ during the FoS tests.

To protect the cryomodules and the cryogenic installation, interlocks are implemented in the automatised process control system using the UNified Industrial Control System (UNICOS) framework developed at CERN to act on hardware by full or temporary stops [2]. The monitored process parameters comprise the helium vessel pressure, the liquid helium level, and the temperature over the cold mass.

TEST RESULTS

The tests results of the FoS are reported in the following sections with a particular attention given to the cold powering tests and the magnetic measurements of the FoS SM and the FoS LM.

Cool Down and Warm Up Performances

The cool down of the cryomodules is performed in two phases following the cryogenic facility design [7]. The cool down duration for the FoS SM and LM has been 7 and 17 days respectively. During the pre-cooldown phase, from 300 to 80 K, the maximum allowed temperature gradient ΔT over the cold mass was kept below 40 K at 12 bar pressure. The gas helium mass flow rate reached by the SM was about 22 g/s which was increased to 26 g/s on the LM. The cool down from 80 to 4.5 K and the filling were then performed at 1.3 bar pressure which was kept for the whole operation. For the FoS dipole a mass flow rate of 3.5 g/s has been specified and the active cool down duration was about 5 days. Figure 2 shows the temperature difference ΔT over the cold mass along the 7 m LM during the cooldown respect to the coils' average temperature of the first magnet position (SE_A).

The SM and the LM have undergone three and two thermal cycles respectively. The dynamic warmup took 8 days for the SM and 14 days for the LM, without setting the process in standby during the weekends.

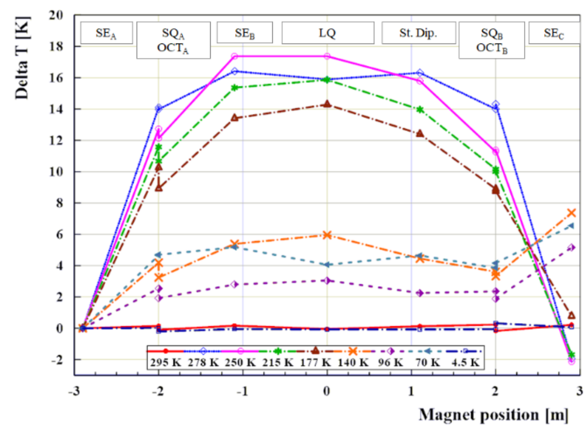

Figure 2: Temperature difference along the FoS long multiplet cold mass during cooldown.

Magnets Cold Powering Tests

After cooldown, each magnet insulation integrity was tested before any powering tests. The multiplets quadrupoles and the FoS dipole passed the high voltage tests at 1.5 kV (coil-to-ground) and the steering dipole, the sextupoles and the octupoles passed the 200 V tests. On the SM a breakdown voltage of 1 kV was reported limiting the ultimate current of the quadrupole to 310 A instead of 330 A. After the individual magnets' powering tests, the combined tests up to nine circuits together successfully followed.

Table 1 reports the nominal and ultimate current levels (I_{nom}, I_{ult}), the nominal ramp rates (dI/dt) and the measured inductance at I_{nom} for each magnet of the LM.

Table 1: Multiplet's Magnets Parameters

Magnet	I_{nom} [A]	I_{ult} [A]	dI/dt [A/s]	L [H]	Bdl [Tm/m^{n-1}]	n
LQ	300	330	2.5	17	12.3	2
SQ	300	330	2.5	12	8.40	2
SE	291	320	2.5	0.76	20.3	3
St.Dip	280	308	2.3	0.05	0.1001	1
OCT	160	176	1.3	0.11	85	4

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOTK013

Figure 3 shows the inductances measurements at nominal current levels for the SM and the LM short and long quadrupoles magnets, validating the magnets production.

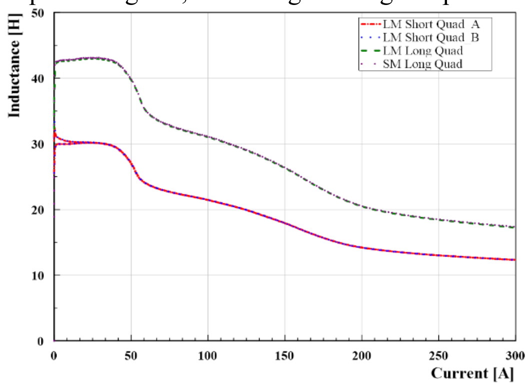

Figure 3: Inductance measurements comparison of the short and long quadrupoles of the FoS multiplets.

Magnetic Measurements

The number of magnets inside the multiplets, their large size (476 mm pole tips distance) and the high saturation (up to 40% that creates extended fringe field) imply significant challenges for the magnetic measurements. The dedicated rotating shaft used for the multiplets has a 167 mm radius and it is composed by two segments of 1300 mm length radial printed circuit board (PCB) search coils for integral field measurement and a 100 mm length PCB search coil for local field measurement. The shaft design allows longitudinal translation into the multiplet warm bore for integral or local field measurements of individual magnets. Figure 4 shows the magnetic flux density profiles of the nine magnets in the LM over the 7 m length. Data points were acquired every 100 mm. Magnets were powered individually at nominal currents. The measured magnetic flux density is scaled in percent normalized to their respective maximum field value. As expected, the magnets of the highest order are characterized by the less extended fringe field towards the neighbouring magnets.

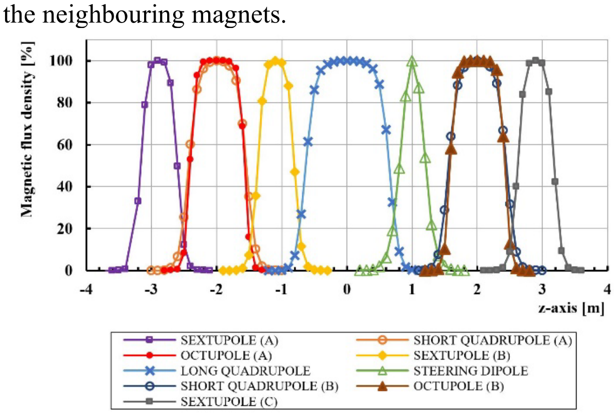

Figure 4: Magnetic flux density over the length of the long multiplet.

The second part of the measurement campaign was dedicated to the SSW measurements. The two stages were positioned on each end of the multiplet aperture spanning the wire at 8.07 m distance. The integral field of each magnet was measured in terms of gradient (except for the steering dipole). The manufacturing repeatability of the same magnet types was established in long and short multiplets: 0.04% for the 2 short quadrupoles, 0.06% for the 2 long quadrupoles, 0.12% for the 4 sextupoles, 0.2% for 2 octupoles. The average integral field values are presented in Table 1. Figure 5 shows the transfer function of 5 different magnets from the LM measured with the SSW. The quadrupoles magnets saturate very strongly starting at 50 A generating around 40% less magnetic field per ampere/unit of current at their nominal level with respect to the minimum current level. These results confirm the design expectations and the agreement with the FoS SM quadrupole and sextupole measurements presented in previous work [4].

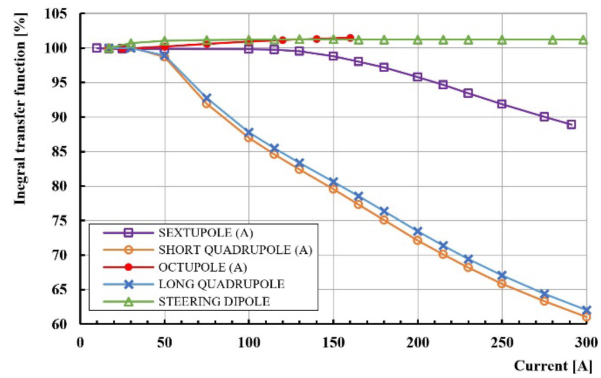

Figure 5. Integral transfer functions of magnets in the long multiplet.

To determine the multiplet magnetic axis, the position of the magnetic centre of the quadrupoles has been measured as well as the angles with SSW. The long distance between the stages presents a challenge due to the significant wire sagitta that affects the measurement of the vertical magnetic centre and also the angle of the short quadrupoles. The SSW system was also used for the integral field quality measurements in terms of multipole field components. The SSW results are in agreement with the rotating coil measurements within 0.01 ± 0.003% (computed on a reference radius of 190 mm up to 15th order component) for quadrupole magnets. For sextupoles and octupoles the centre has been determined by feed-down from the homogeneity measurements.

CONCLUSIONS

Cold powering tests have been successfully performed on the Super-FRS FoS multiplets at the CERN test facility. Extended magnetic measurements results show the fulfilment of the beam optics requirements and the reliability of the measurements device to be used for the series testing.

The validation of the magnets design and manufacturing, together with the commissioning of the test facility, set the beginning of the multiplet series testing.

ACKNOWLEDGEMENTS

The authors would like to thank the members of the CERN TE, EN, SY and BE departments for their support in the commissioning of the FAIR test facility and FoS test campaign.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOTK013

REFERENCES

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

[2] L. Serio *et al.*, “A new cryogenic test facility for large and heavy superconducting magnets”, *IEEE Trans. Appl. Supercond.*, vol. 27, no. 4, pp. 1-5, 2017. doi: 10.1109/TASC.2016.2626270

[3] H. Muller *et al.*, “Design, production, and testing of superconducting magnets for the super-FRS”, *in Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 4128-4131. doi:10.18429/JACoW-IPAC2019-THPTS011

[4] E. Cho *et al.*, “Preliminary Test Results of the First of Series Multiplet for the Super-FRS at FAIR”, *IEEE Trans. Appl. Supercond.*, vol. 30, no. 4, pp. 1-4, June 2020. doi:10.1109/TASC.2020.2981302

[5] IIF International Institute of Refrigeration, https://iifiir.org/.

[6] G. Golluccio *et al.*, “Instruments and Methods for the Magnetic Measurement of the Super-FRS Magnets”, in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 1183-1185. doi:10.18429/JACoW-IPAC2016-TUPMB037

[7] A. Perin *et al.*, “A new cryogenic test facility for large superconducting devices at CERN”, *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 101, no. 1, p. 012185, 2015. doi:10.1088/1757-899X/101/1/012185