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TECHNICAL REPORT

Quadrupole magnet design, manufacturing and the acceptance tests for METU-defocusing beamline

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Abstract: Middle East Technical University Defocusing Beam Line (METU-DBL) performs the Single Event Effects (SEEs) radiation tests with protons in the range of 15 MeV to 30 MeV kinetic energy at Turkish Atomic Energy Authority Proton Accelerator Facility (TENMAK NÜKEN-PAF) for space and nuclear applications. The most critical beam transfer elements in the METU-DBL are three quadrupole magnets, which are used for defocusing the beam like optical lenses. The first two quadrupole magnets were purchased commercially, and the third quadrupole magnet was designed by the METU-DBL project team and manufactured by Sönmez Transformer Inc. in Turkey. Electronic, mechanic and magnetic capability tests of this custom-designed magnet were conducted both at TUBITAK and CERN facilities. After passing the acceptance tests, the magnet was certified by CERN and then installed to METU-DBL as a third quadrupole magnet. In this paper, we present details of the design, production and performed tests of the quadrupole magnet.

Keywords: Accelerator Applications; Accelerator Subsystems and Technologies; Detector alignment and calibration methods (lasers, sources, particle-beams); Detector design and construction technologies and materials

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1 Introduction

Middle East Technical University Defocusing Beam Line (METU-DBL) project is designed to perform the Single Event Effects (SEEs) radiation tests at Turkish Atomic Energy Authority Department of Radiation and Accelerator Technologies Proton Accelerator Facility (TENMAK NÜKEN-PAF) [1]. This beam line uses the proton beam in the range of 15–30 MeV kinetic energy to perform radiation tests in accordance with ESA ESCC No.25100 specification [2]. METU-DBL, which is shown in the figure 1, provides users a wide selectable flux menu (10^5 – 10^{10} p/cm^2/s), over a large test area (15.40 cm x 21.55 cm) enlarged by quadrupole magnets [3].

Magnets play a critical role in particle accelerators. Although, their primary purpose is to accelerate charged particles, they are also used to correct or shape the particle beams. Some of these tasks are also referred to as bending, focusing and defocusing the beam. 3 quadrupole magnets are used in order to have the flexibility of choosing the beam size and flux at METU-DBL. Quadrupole magnets have 4 poles and they apply a force proportional to distance from center.

Two of the quadrupole magnets have been purchased from Scanditronix in the test stages of METU-DBL. The third quadrupole magnet is designed and produced collaboratively by METU-DBL

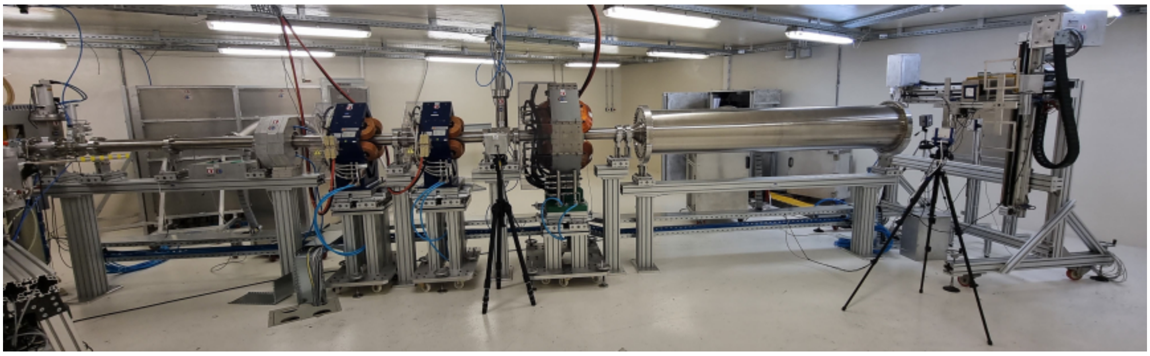

Figure 1. The Final Setup of METU-DBL. The beam enters through the lower left corner and after three quadrupole magnets and a long drift lengths, hits the target area at the end.

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team and Sönmez Transformer Inc. in Turkey. Later, the related magnet tests [4] are performed at TUBITAK, Turkey and CERN, Switzerland. The custom-designed quadrupole magnet passed all tests succesfully and was awarded a CERN certification. This magnet is also the first industrial sized quadrupole magnet which is designed and manufactured in Turkey.

In this paper, we give details of the design and manufacturing process of the quadrupole magnet. We also present details on the tests, that are required to get a certification for quadrupole magnets.

2 Design (magnet parameters and modeling)

The primary requirement of the quadrupole magnet is the magnetic field at the pole to be −6 kG. The 2D magnetic field calculations are made using Opera2D [5]. Then, a 3D CAD model is created by extending the 2D model using SOLIDWORKS. As quadrupole magnets are symmetrical, only 1/8 of the magnet is enough for simulations designed in Opera2D [6]. In figure 2-A, the yoke of the magnet is shown in blue and the coil is in red. The magnetic field map is shown in figure 2-B and −6.0 kG is obtained at the pole.

After achieving the desired −6 kG at the pole, the widths of the conductor and the cooling pipe inside the coil were determined and the values in table 1 were obtained.

The quadrupole magnet was mechanically designed according to the magnetic field simulations made in a quadrant in Opera 2D. The number of coil turns in a quadrant was calculated and the general dimensions of the magnet were obtained as shown in the left of the figure 3. Gray indicates the yoke and the brown parts show the coils. The wide of magnet is 78 cm, and the weight of it is approximately 1010 kg.

3 Manufacturing and acceptance tests

The tender of the quadrupole magnet was awarded to Sönmez Transformator Sanayi in Gebze, Istanbul. The manufacturing process was closely followed by the METU-DBL team and the initial acceptance tests were carried out on site. First magnetic field measurements were performed by TUBITAK National Metrology Institute (TUBITAK UME). TUBITAK UME has an automated scanner hall probe test set up to perform magnetic field tests of the quadrupole magnet. In addition

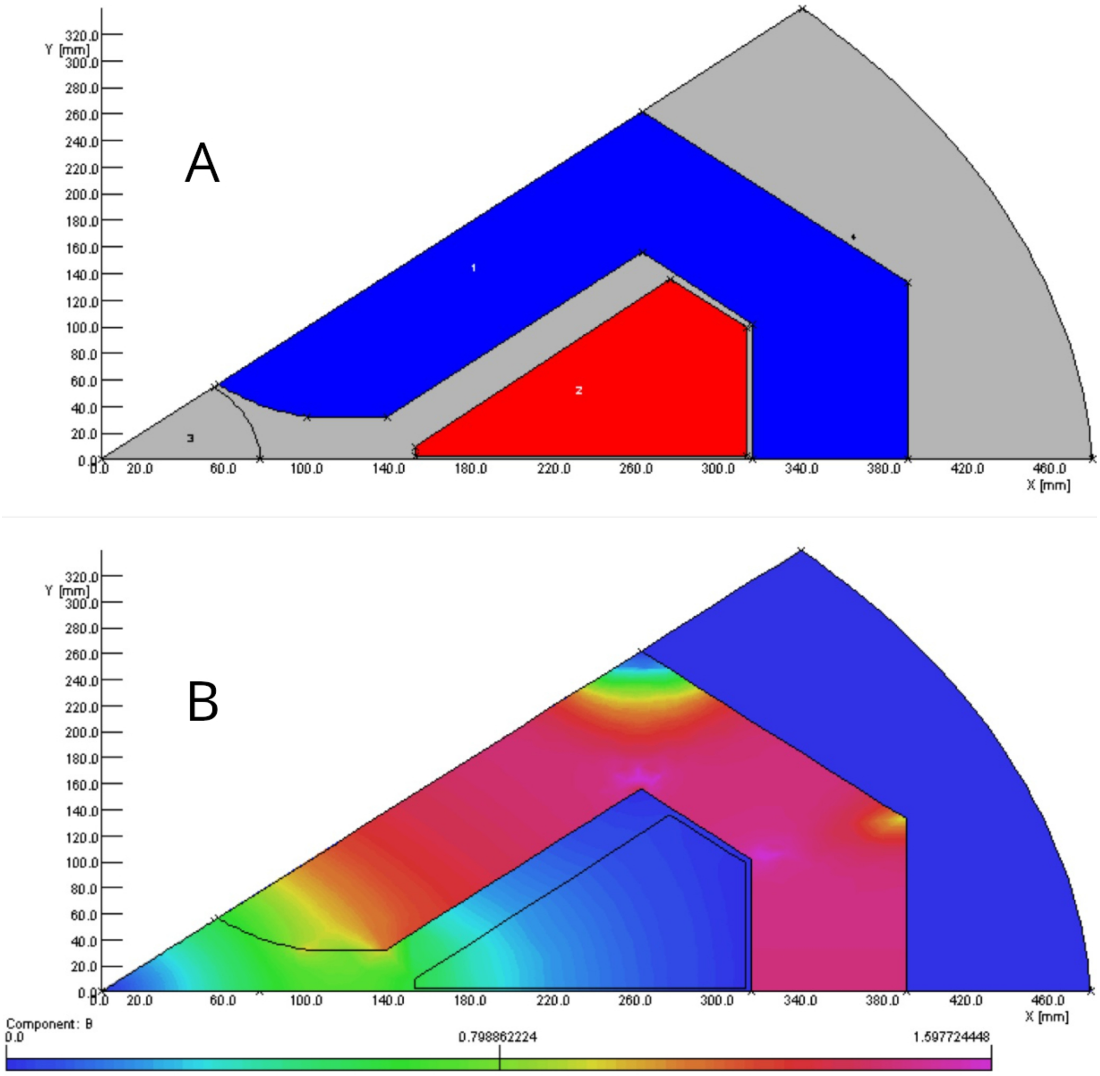

Figure 2. (A) 1/8 of Magnet's Yoke and Coils, (B) and Magnetic Field Distribution.

to the magnetic field tests, mechanical and electrical tests of magnet were also carried out within the scope of acceptance tests. Then, the quadrupole magnet was sent to CERN for the certification of the quadrupole magnet. The quadrupole magnet was subjected to mechanical, electrical, and magnetic field tests at CERN. Magnetic field tests were done with a Hall Effect Gaussmeter. The Gaussmeter used had 0.1% (of reading) accuracy, a resolution of $5\frac{3}{4}$ digits, ranged from 300 mG to 300 kG, and was able to measure from 10 Hz to 400 Hz frequency. The hall probe test carried out by TUBITAK UME was also performed by CERN and cross-checked by stretched wire and rotating coil tests.

3.1 Acceptance tests in Turkey

Magnetic field measurements of the quadrupole magnet started on 6 November 2017 at the Sönmez Transformer Company facilities with the participation of a team from TUBITAK UME. The quadrupole magnet was aligned using the lasers according to the earth plane, before starting the mechanical, electrical and magnetic field measurements. The test table on which the hall probe will

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Table 1. Simulated Parameters of Quadrupole Magnet After the Selection of Conductor.

Parameter	Unit	Per Coil
Gradient (G)	$[T/m]$	7.50
Half Aperture (R)	$[mm]$	80
Number of Turn × Current (NI)	$[A]$	19520
Average Turn Length	$[m]$	1.04
Number of Turn (N)	—	122
Current (I)	$[A]$	160
Coil Length (h1)	$[mm]$	8.5
Coil Width (h2)	$[mm]$	8.5
Conductive Cooling Duct Diameter (d)	$[mm]$	5.3
Conductor Area (A)	$[mm^2]$	49
Conductor Length (l_{coil})	$[m]$	126.9
Resistivity (ρ)	$[\Omega m]$	1.8×10^{-8}
Current Density (j)	$[A/mm^2]$	3.2
Power (P)	$[W]$	1173 (Total:4692.0)
Temperature Difference (ΔT)	$[°C]$	20
Flow (Q)	$[L/min]$	0.8 (Total:3.2)
Flow Rate (V)	[m/s]	0.6
Fluid Pressure (Δp)	$[bar]$	2.0
Resistance (R)	$[m\Omega]$	45.75 (Total:183)

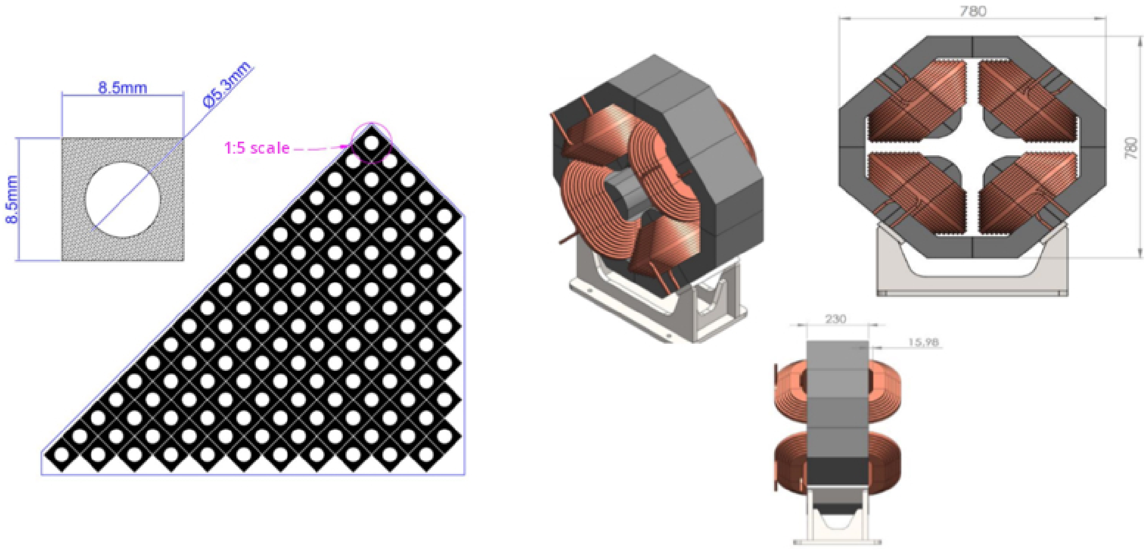

Figure 3. Transition From Coil Design to Quadrupole Magnet Design.

stand was aligned with the quadrupole magnet's coordinate plane. 0.5 mm and 1.0 mm thick epoxy leaves were used to adjust the magnet and hall probe's (Gaussmeter) heights.

3.1.1 Ball test

All 4 coils should have the same length by design. However, due to manufacturing and other uncontrolled effects they might not have the same length in the final product. Therefore, their length can be checked with the help of a steel ball. A steel ball with 3 mm diameter is used for this test. 5 bar continuous compressed air is used to thrust the ball inside the coil and the time that ball spends inside the coils are recorded. The measurements of the ball test are given in table 2. The test is performed for all coils. Measured times for all coils are close to each other and ball did not stuck inside the coils of magnets. These are the success requirements for ball test.

Table 2. Measurement Results of The Ball Test.

Coil Number	Time (sec)	Status
1	12.00	Passed
2	11.48	Passed
3	12.68	Passed
4	12.69	Passed

3.1.2 Water pressure test

This test aims to test the coils under high pressure against leakage. First, the magnet's water outlet was closed with a blind flange and the coils were filled with tap water until the pressure reaches to 20 bar, which took 30 seconds. Later, the pressure dropped to 18.5 bar and stayed constant due to air trapped in the water which is caused by the pump. The water pressure test resulted with a success because no leakage is observed for 30 minutes.

3.1.3 Thermal switch test

Thermal switches were mounted to each coil during manufacturing as a safety precaution. These switches cuts the power if the temperatures exceed the safety threshold. This test aims to test mentioned safety feature.

The magnet is cooled with tap water while in operation. The cooling water had a flow rate at 3.2 lt/min and around 15–17 °C at 4 bar pressure during the test. The quadrupole magnet was supplied with 160 A current. After some point, cooling water was turned off. This heated the coils and the opening temperatures of thermal switch were recorded. Then, the coils started to cool off and the temperature at which the switches turn off were recorded. The opening and closing temperatures are within the desired limits, so test was successful. The temperatures can be seen in table 3. The opening and closing temperature of each coils are slightly different due to different epoxy coating of coils and positions of the thermal switches.

Table 3. Results of The Thermal Switch Test.

Coil Number	Opening Temperature (°C)	Closing Temperature (°C)
1	78.8	57.8
2	81	53
3	81	67
4	71	58

3.2 Acceptance test at CERN

After the acceptance test performed in Turkey by TUBITAK UME and METU-DBL team, the magnet was sent to CERN for certification tests. The serial number, PXMQNOONWP-S3000001, was given to magnet by CERN.

3.2.1 Visual inspections

CERN requires IP2 protection standards in quadrupole magnet covers which prevents direct access to the coils. Visual inspections were performed to check IP2 standards. The quadrupole magnet cover can be seen in figure 4. Cover in figure 4A is the old one. This cover is changed to new one. This new cover complies with the IP2 standards.

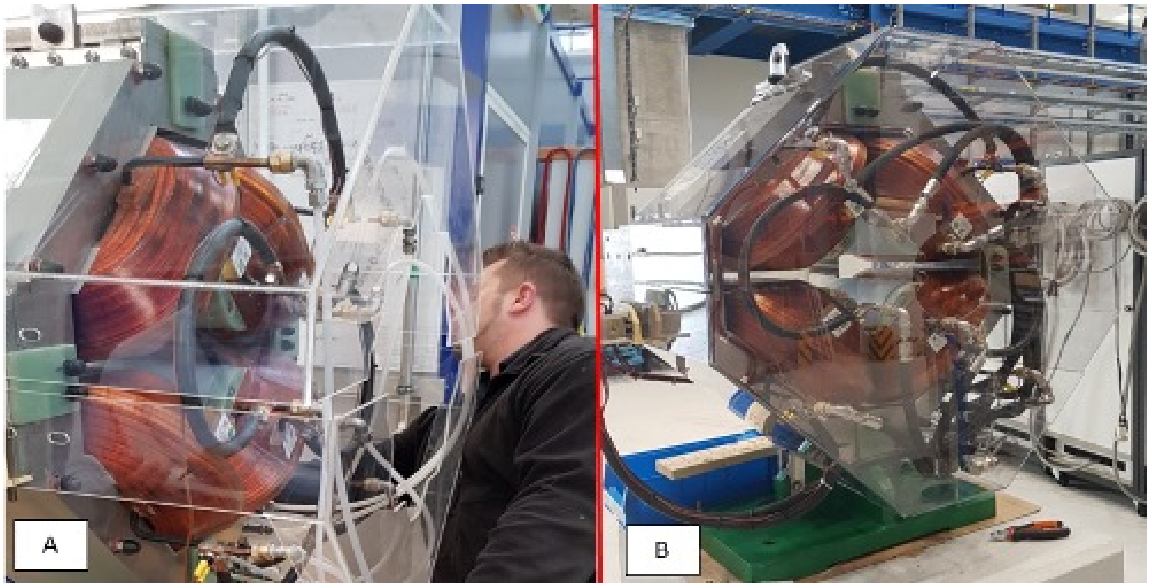

Figure 4. The cover of quadrupole magnet of METU-DBL.

During visual inspections, it was observed that the placement of thermal switches is not very convenient and it should be closer to the coil or at the hottest point of the magnet. Therefore, thermal switches are replaced with ones that are used on CERN magnets which has normally close contacts that opens at 65°C. Electrically insulating holders were glued with Araldite 2022 epoxy on the coils. During the assembling of new thermal switches, it was noticed that there should be a shim between coil and yoke. In the absence of the shims, epoxy may crack in the long term and move on the coil pole. Therefore, shims with 1 mm thickness were mounted between coils and yoke.

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3.2.2 Water pressure test setup

Water pressure tests that were performed in Turkey were repeated by CERN. Blind flanges were assembled to the water inlet and outlet of the quadrupole magnet. The test was carried out at 20 bar pressure for 2 hours with tap water at a temperature of 15–20 °C. The setup can be seen in figure 5. A leakage on the 1$^{\mathrm{st}}$ coil was observed and the fitting, connection point, was changed. Then, the test restarted and no other leakage was observed for 2 hours.

Figure 5. Water Pressure Test.

3.2.3 Thermal switch test

Thermocouples were placed near the old and new thermal switches in order to test thermal switches. The test was performed with 180 A current supply and 2 bar pressure of 2.8 lt/min water. After the temperatures reached to an equilibrium, the flow rate was started to decrease to 1.3 lt/min, 0.8 lt/min, and 1.0 lt/min, respectively. When the coils warmed to 83 °C, all thermal switches opened, as shown in table 4.

3.2.4 Insulation between yoke and soil

The insulation test of the core concerning the soil with the insulation test device was carried out for 1 minute at 500 V DC and 1 minute at 5 kV DC. Insulation resistance was measured to be 780 GΩ. The highest leakage current that may occur in the magnet was calculated as 0.57 pA with the highest operating voltage of magnet, 45 V, even if there is a high conductivity coolant in it. The insulation test of the core for the soil with the insulation test device was carried out for 1 minute at 5 kV and insulation resistance was measured to be 43.6 GΩ.

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Table 4. Opening Temperatures of The Thermal Switch.

Thermal Switch Number	Opening Temperature (°C)
1	83.00
2	80.68
3	80.70
4	80.19
5	81.38
6	78.93
7	76.63
8	75.72

3.2.5 Capacitive discharge test

In that test, characteristic curve of coils was obtained via DC disharge on coils and whole magnet for comparison of the results. The results of the characteristics curves for each coil and magnets should be same for successful test. Coils were tested by applying 1.25 kV to test individually. After that, 5 kV was applied to whole magnet with capacitive discharge immediately. When the capacitive discharge test result curves of the coils individually and the entire magnet superimpose. It is indicated that the coils have the same properties with the other coils in the magnet since the curves are same.

3.2.6 Inductance test

This test was applied to measure the inductance of the coils. Various frequencies were imposed to coils to observe the response of the coils. The tests, results are seen in table 5, were performed at 1 Hz, 20 Hz, 100 Hz, and 1 kHz frequencies, respectively. As a result, it was observed that the inductance decreased and the inductive reactance increased with the increasing frequency which is the acceptance requirement of the inductance test. Therefore, the coils were found suitable.

Table 5. Measurement Results of The Inductance Test.

Frequency (Hz)	Inductance Lp (mH)	Inductive Reactance Rp (Ω)
1	190.19	0.17
20	181.64	0.54
100	177.53	5.85
1000	147.72	159.00

3.2.7 Resistance of coils

The resistance of the coils was measured by the four-wire method [7]; the voltage was limited to 0.24 V and measured using 1 A constant DC current. Then, the voltage drops on the coils are measured with a voltmeter. The voltage measurement is divided to 1 A (supplied current) to obtain the resistance values. The resistance was measured to be 178.4 $m\Omega$. A more standardized resistance was generally used because the resistance depends on temperature. This is referred to as R_{20} and it is the resistance at 20 °C degrees and can be calculated easily using eq. (3.1).

$$R_{20} = \frac{R}{1 + \alpha(T - T_{20})} \tag{3.1}$$

When we insert the measurements and the temperature coefficient of the coils (0.004041), the R_{20} value was obtained as $177.8\,m\Omega$. This result is compatible with the designed value ($183\,m\Omega$). Therefore, this result is acceptable.

3.2.8 Pulsed-current test

The magnet was subjected to the impact current test to check the compatibility of the filling parts placed between the coils and the electrical sheets. In this test, 160 A current was supplied to the magnet instantly, and it was followed whether the coils were moving or not. It was noticed that the coil numbered 12643-3 was moving, and the amount of motion was measured as 160 μm using the dial indicator placed on the coil. Then, a comparator was placed on the other side of the coil 12463-3, and the pulse current test was repeated. The amount of movement was observed as 350 μm. This measured movement can be prevent by using the shims, so these values are acceptable.

3.2.9 Magnetic tests

Magnetic tests were performed using a rotating coil which was inserted to center of the quadrupole magnet. The quadrupole magnet was mounted to a test table, and cooling and electrical connections were assembled. Before the magnetic tests, measurement systems were aligned according to the quadrupole magnet using the X and Y stages shown in figure 6. Tubing was placed on X-Y drivers located on either side of the magnet to facilitate alignment.

Figure 6. Alignment of Test Setup.

The rotating coil system was integrated into the X-Y stages by the help of the tubing between the stages. After completing the alignment, tubing was removed from the aperture of the magnet, as shown in figure 7.

Rotational speed of rotating coil was chosen as 1 Hz to provide the optimum signal-to-noise ratio for the system. The software called The Flexible Framework for Magnetic Measurements (FFMM) was used for data acquisition.

Demagnetization was performed to remove residual magnetic fields in the magnet, before starting the test. Magnet demagnetization was performed with a maximum of +240 A and a minimum −240 A, the current was decreased by $\frac{1}{3}$ of previous amplitude at each step. This process was repeated for five steps so that residual magnetic fields on the magnet were cleansed.

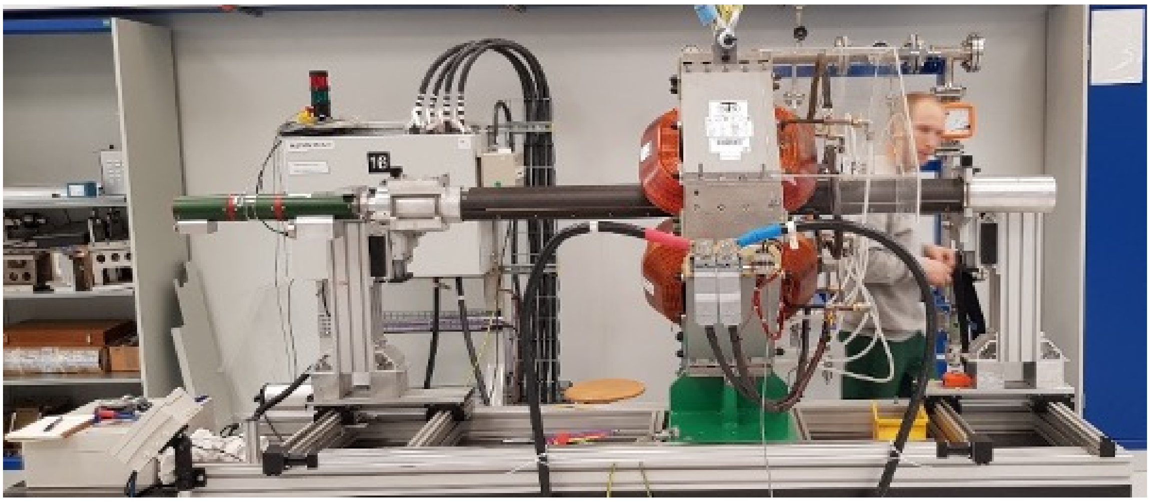

Figure 7. Integration of Rotating Coil.

Field harmonics test. Multipole field components (field harmonics) and multipole coefficients were measured at a reference radius of 50 mm using the rotating coil method in order to observe the shape, asymmetry, and homogeneity of the magnet's field. The field harmonics coefficients are expressed in "units" that have the value of 10^{-4} of the main field [8]. Field harmonics measurement precision is found 1 unit at one sigma, calculated over several measurement repetitions. The field harmonics test requirement for each multipole component corresponding unit value must be less than 100 unit. Both regular and skew multipole field components were measured with a current interval of 20 A between −240 A and 240 A, as shown in figure 8. It can be seen that each multipole field component of the magnet is measured to be less than 20 unit. Measurement results showed that the requirement for the field harmonics test is satisfied.

Integral field test. This test aims to obtain the integral transfer function and compare it against the simulations. The integral magnetic function is the magnetic field divided by supplied current. In figure 9, the horizontal axis shows the current supplied to the magnet, and the vertical axis shows the integral transfer function. Blue lines indicate the measured integral transfer function from −240 A to 240 A at 20 A intervals, while red lines indicate simulated integral transfer function obtained using the Opera3D software.

The magnetic field of magnets increase linearly with increasing current, until the magnetic saturation begins. Therefore, the integral transfer function is expected to be constant until the saturation point. Although the integral transfer function fluctuates slightly between 120 A and −120 A, it is almost constant in this range. Outside of this range, the integral transfer function decreases. Therefore, 120 A is the point where the magnet saturation begins. Above 120 A, the integral transfer function decreases with increasing current and magnet can be operate up to 277.5 A. It can also be seen that simulation and measurement results are consistent with each other.

Other tests. ESA ESCC No.25100 specification had been followed during the design consideration of the magnet for the Single Event Effect radiation tests. According to this specification, the radiation area at the target point must be at least 21.55 cm × 15.40 cm. Simulations of beam optics studies

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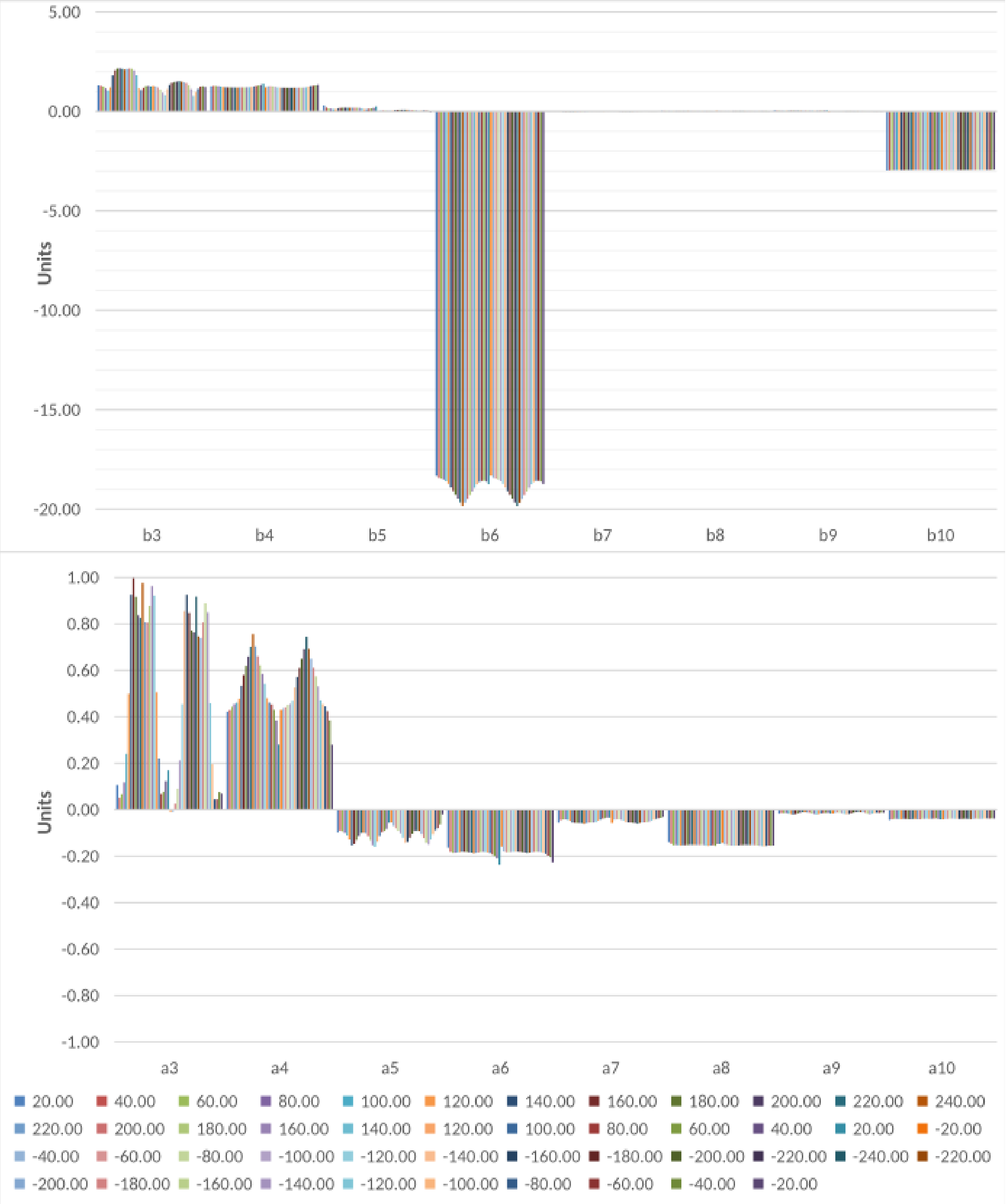

Figure 8. Measurement Results of the Normal (top graph) and Skew (bottom graph) Multipole Field Components of the Magnet.

showed that to satisfy the minimum beam area requirement in the ESA ESCC No.25100 specification, the magnet needs to be operated at 6.0 kG.

The magnetic field at the pole tip of the magnet was measured with a hall probe in order to see whether the magnet's saturation around 120 A will prevent reaching 6.0 kG. In table 6, first column

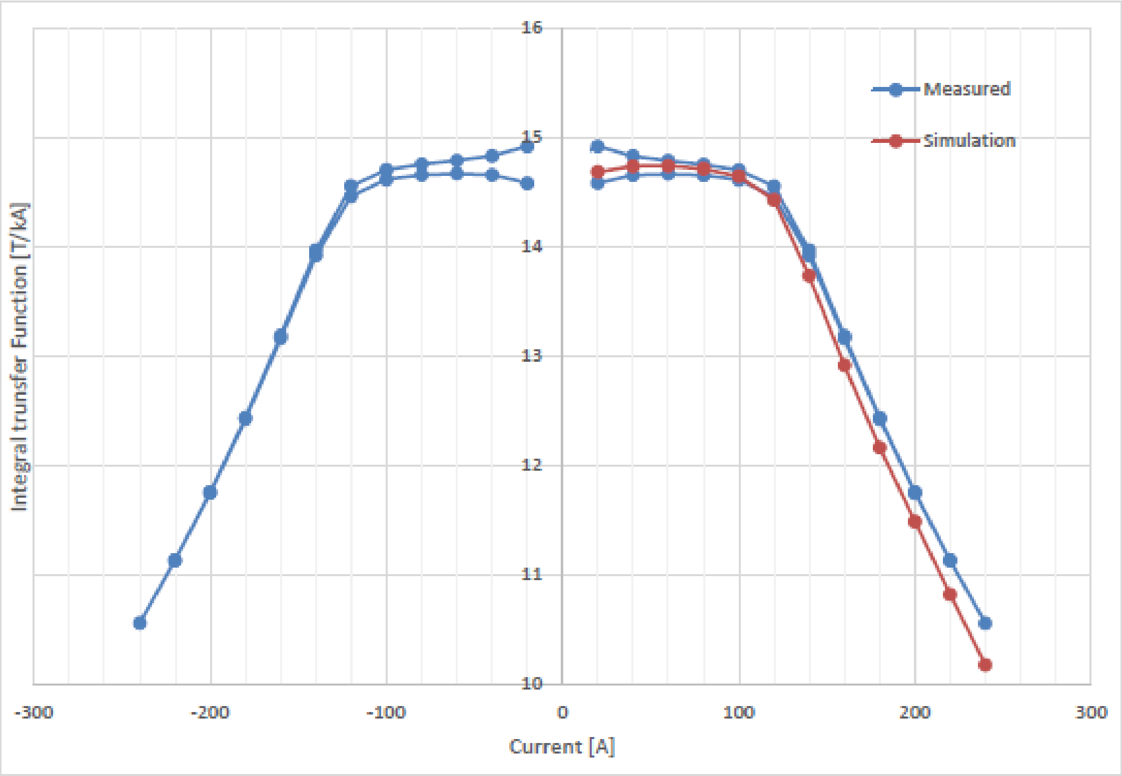

Figure 9. Integral Transfer Function Corresponding to Different Current Values From −240 A to 240 A at 20 A Intervals.

for each pole is measurement taken at the operation position on the beamline room, second column for each pole is measurement taken during testing at CERN and last column is linear extrapolation according to linear relation between magnetic field strength and current. 6.0 kG magnetic field at the pole tip was measured, when 200 A current was supplied to the magnet. Although, this value is above the saturation limit, the power system allows the quadrupole magnet to be operated up to 277.5 A. Therefore, the magnet can be used to constantly obtain 6.0 kG at the pole tip. To sum up, although OPERA 2D simulations and linear extrapolation indicates that 160 A operating current is enough to achieve the target 6.0 kG magnetic field strength at the pole tip, it was achieved at 200 A during testing. This also shows that 120 A limit at the central magnetic field strength measurement did not effect the magnetic field strength at the pole tip required for its operation.

4 Conclusion

Electronic, mechanic and magnetic capability tests of this custom-designed magnet were conducted. After successfully passing these acceptance tests, the magnet was certified by CERN.

The production of the quadrupole magnet took six months between May and October 2017 [9]. This custom-design quadrupole magnet passed mechanical, electronic tests and CERN certified magnetic tests at the production site at CERN between November 2017 and January 2018. The custom-design quadrupole magnet was integrated into METU-DBL on 22 May 2019. It was used in

Table 6. Measurements of Magnetic Field at Each Pole Tip of the Magnet (kG).

Current (A)	Pole-1		Pole-2		Pole-3		Pole-4		Linear Extrapolation
40	1.447	1.500	1.446	1.500	1.446	1.500	1.445	1.490	1.504
80	2.894	3.030	2.896	3.000	2.893	2.950	2.898	3.050	3.008
120	4.305	4.470	4.307	4.400	4.322	4.460	4.316	4.390	4.512
160	5.250	5.400	5.254	5.420	5.263	5.420	5.250	5.400	6.016
200	5.883	6.030	5.890	6.040	5.929	6.010	5.881	6.080	7.520
240	—	6.530	—	6.630	—	6.510	—	6.500	9.024

proton irradiation tests in the range of 15–30 MeV kinetic energy for electronic cards, solar cells, and coating materials, which are developed for space applications by different users such as TUBITAK, Gazi University, METU, Sabancı University [10]. Further information about proton irradiation tests can be at https://ivmer.metu.edu.tr/.

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Acknowledgments

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