Results of the Magnetic Measurements of the Superconducting Magnets for the European XFEL

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***Abstract*—A new linear accelerator, European XFEL –X-ray Free Electron Laser is under construction at DESY in Hamburg. The construction started in early 2009 and the commissioning is planned for 2016. The design energy of the electron beam is 17.5 GeV (0.05 to 4.7 nm wavelength) and more than 27000 flashes per second are expected. The accelerator contains 102 cryomodules equipped with a string of eight superconducting RF cavities and one superconducting magnet package. Each magnet consists of two cos-θ type correction dipoles, horizontal and vertical deflecting. They are glued onto the surface of the beam pipe and are surrounded by a superferric quadrupole magnet. The package is mounted inside of a compact stainless steel vessel with a length of 30 cm and a diameter of 20 cm. Each package and current lead assembly was tested separately at room temperature and together at 2 K in a dedicated super-fluid helium cryostat at DESY Hamburg. A summary of the results is reported here. During the cold test special emphasis was given to hysteresis and persistent current effects, as the operating current varies from very low currents at the beginning of the accelerator to the full design current 50 A at the end.**

***Index Terms*—Free electron laser, harmonic coils, stretched wire, magnetic measurements, superconducting magnets.**

I. Introduction

The longest part of XFEL is 2.1 km long superconducting linear accelerator. Its main part consists of 102 accelerating cryomodules equipped with a string of eight superconducting Niobium 9-cell RF cavities, one superconducting correction magnet package with current leads, a beam position monitor and cryogenic lines. The magnet package includes three nested magnets enclosed by a stainless steel vessel. They were designed by CIEMAT and manufactured in Spain. A detailed description is given in [1], [2], and [3].

The XFEL magnets (Fig. 1) are powered by conduction cooled current leads manufactured by CECOM in Italy. Their design is based on CERN current leads described in [4], and [5]. To ensure electrical connection of the power supply to the magnet package and minimize the heat loads in the liquid Helium the conductor shape of XFEL current leads was optimized.

Tests of the corresponding prototype components started in 2010 and ended with the tests of all series produced components in autumn 2015. Now they are being assembled into cryomodules and installed in XFEL accelerator tunnel.

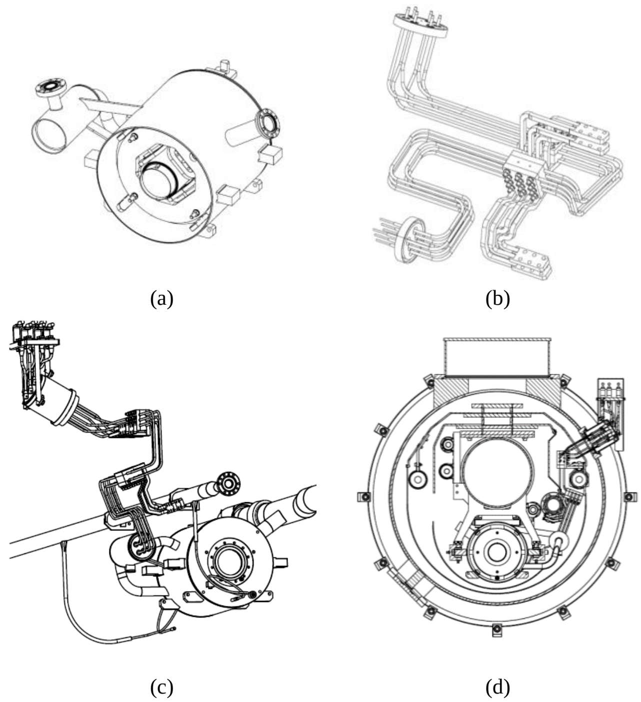

Fig. 1. (a) Magnet package: two dipole coils and one quadrupole enclosed in a stainless steel vessel. (b) Special designed – bended current lead with copper heat sinks. (c) Magnet package assembled together with current leads connected to the helium supply pipes inside the XFEL cryomodule. (d) Cross section of the XFEL cryomodule with a magnet package and a current leads.

II. Testing Procedure

The tests of the superconducting magnet packages and current leads were done in two stages. At first a series of checks at room temperature was performed. In a second step the magnet and the leads were connected and then mounted in the dedicated cryostat (XMTS). Here the magnet was cooled down to 2 K. In order to prove the quality of the magnetic field and its geometry two techniques were used – a rotating coil and a stretched wire system, both at room temperature and at 2 K. All tests were performed by German-Polish collaboration of DESY and IFJ PAN employees at DESY.

A. General Checks

The tests at room temperature started with the incoming and visual inspections. Next the tightness check was done by a

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helium leak detector (Pfeifer HLT550) to ensure tightness of welds and flanges (Fig. 2a,b). The electrical insulation was checked (by a Gossen Metrawat HV insulation meter Metriso C) at 1 kV for current leads and 500 V for the combined magnet with current leads (Fig. 2c). The current lead was also tested in respect of resistivity by Agilent Technology: N5741A, 6 V/100 A/600 W power supply at a nominal current of 50 A with varying ramping rates. At the end of warm checks an alignment of the magnet was done by FARO arm system on a special support in order to allow a transfer of the magnetic field axis and the field angles to fiducial marks on the vessel (Fig. 2d). Later those data combined with a magnetic field geometry measurements were used to align a magnet in a cryomodule with the cavity string axis.

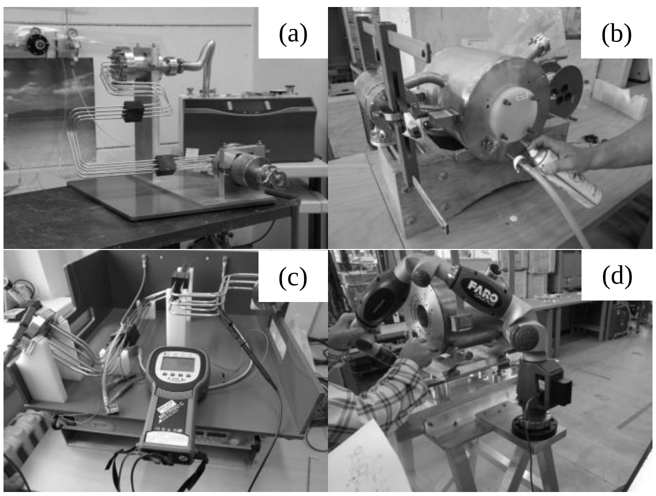

Fig. 2. Tightness check by helium leak detector Pfeifer HLT550 current lead (a), magnet (b). (c) Electrical insulation test, (d) alignment by FARO arm system.

After the tests of the magnet and the current leads at room temperature a magnet and a current lead were assembled together to a unit which then was inserted into the XMTS cryostat. A controlled cool-down in several steps to superfluid helium temperature at 2 K and 30 mbar was performed. The cold checks were first focused on the thermal stability of the current leads at nominal current. Normally a voltage drop of about 55 mV per lead is reached after 2-3 hours of operating and the measurement of the heat loads. The procedure was to monitor possible temperature rises and voltage drops of the six individual leads during the 12 hours measurement. Using calibrated gas flow sensors heat loads could be calculated.

B. Magnetic Field Properties Measurements

To prove the field quality of the XFEL magnets and to determine the magnetic axis and the field angles, two common techniques were used at room temperature and at 2 K – harmonic coil and stretched wire system.

Warm and cold test stands were set up for both techniques with similar configurations. The XMTS cryostat was equipped with anti-cryostat tube running through the magnet allowing access to the cold field region from the outside at room temperature.

The stretched wire measurement was done with a single CuBe wire with a diameter of 125 μm stretched through the magnet. It was moved by Newport precision stages installed on both sides of the tested unit. The magnetic flux was measured by Voltage-Frequency converters.

The rotating coil measurements used two radial coil systems for different temperature conditions moved by stepping or servo motors:

- detector for warm tests with a length of 0.5 m and a pick-up radius of 30 mm;
- detector for cold tests with a length of 0.5 m and a pick-up radius of 28 mm.

The detailed description of the test stand set ups with photos and measurements procedures is given in [3]. Specification of a data acquisition, database and a test follow-up system can also be found there.

III. Final Results

A. Current Leads

The currents leads were produced and delivered by only one manufacturer. The critical parameters for this component were resistivity and heat transportation. During at least two years of tests minor changes in resistivity were observed. They could be explained by seasonal temperature changes in the testing hall. However in a few cases slight variations appeared (Fig. 3). It turned out that some production parameters have changed, for example, change of the batch of materials used in the lead production or variations in the copper coating procedure. An average lead resistance was 0.0037 ± 0.00013 Ω and all of them met the acceptance criteria.

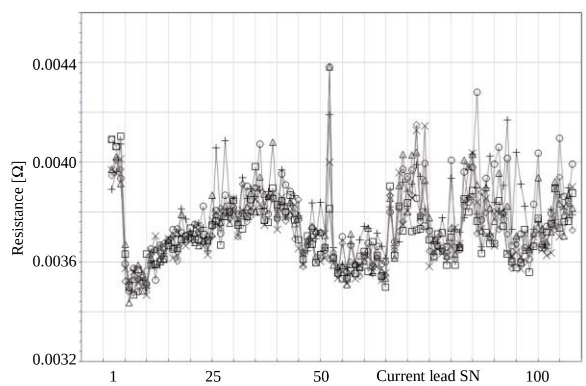

Fig. 3. Resistance of current leads, prototypes and series units.

B. Magnet Coils

The production of coils for only 103 relatively small magnets packages only needs a small amount of superconducting wire. Thus only a limited number of possible superconducting wires were available for the quadrupole and dipole coils production and the optimal could not be ordered. To determine the homogeneity of the series the resistance of the three different magnets was measured. All were in tolerances with an average coil resistance for the quadrupole 95.94 ± 1.23 Ω, for dipole 1 2.32 ± 0.4 Ω and for dipole 2 2.43 ± 0.4 Ω (Fig. 4).

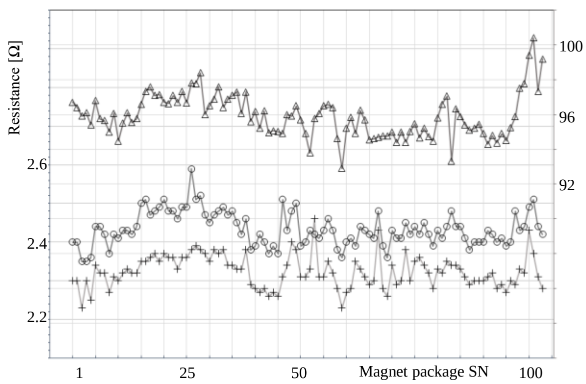

Fig. 4. Resistance of the dipole and quadrupole coils versus serial number (Q – triangle, D1 – plus, D2 – circle).

C. Warm Measurements

The alignment procedure described in [3] worked very well. An average quadrupole offset for x was 0.043 ± 0.036 mm and for y 0.109 ± 0.046 mm. Slightly larger y values were caused by a shrinking effect during a welding procedure (Fig 5). For more than 100 magnet packages no major deviations from correctness of assembling the coils were observed except one serial number 83. The deviation was traced back to a winding short in one of the quadrupole coils. The magnet was not accepted and is being repaired by the manufacturer.

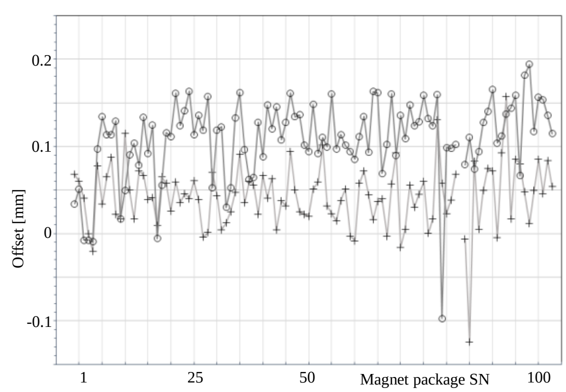

Fig. 5. Quadrupole offset from a mechanical geometric center of the magnet package (x – plus, y – circle). SN 83 removed due to a large deviation.

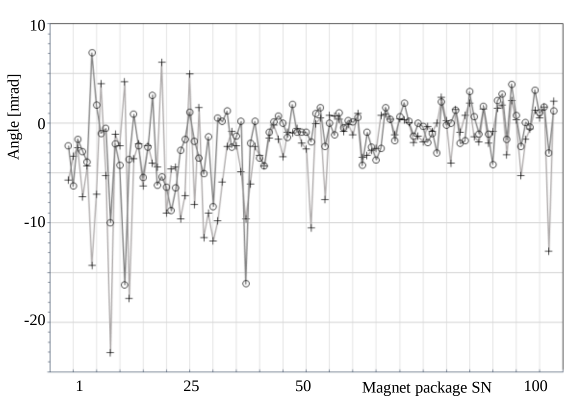

Fig. 6. A relative angles of the dipoles with respect to the quadrupole (D1 – plus, D2 – circle).

The relative angels between the quadrupole and both dipoles were for dipole 1 −2.71 ± 4.62 mrad and for dipole 2 −1.36 ± 3.43 mrad. Only 4 magnets were slightly out of the tolerances of ± 15 mrad (Fig. 6).

D. Cold Measurements

The harmonic tests at 2 K were focused on precise multipoles measurement at 3 fixed currents followed by hysteresis measurements for each individual magnet package. The magnets were powered from -50 A to 50 A with different ramping rates. Several fast ramping current pre−cycles (0A→50A→-50A→0A) were necessary to predefine the persistent current effects in the superconducting wire.

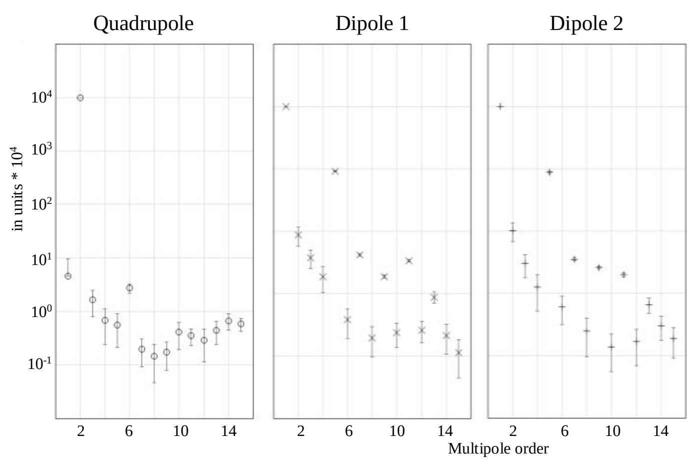

Fig. 7. Multipoles at 50 A for the three magnets at 30 mm reference radius.

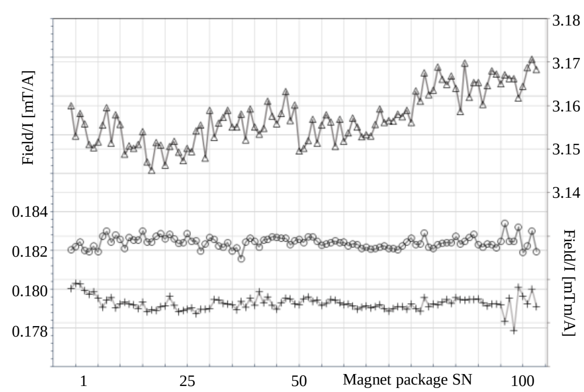

Fig. 8. Average field at 30 mm normalized by current (50 A) for the three magnets (Q – triangle, D1 – plus, D2 – circle).

Fig. 7 shows the multipoles of the three different nested magnets. The multipoles of the superferric quadrupole are essentially determined by the pole contours. The single layer cos-θ type correction dipoles show much larger odd multipoles, only the sextupole could be minimized here by the design. This compromise was accepted after the prototype tests because they are operated in a linear accelerator, where the beam passes only once.

The magnetic field at the maximum design current of 50 A normalized by current for quadrupole was about 3.157 ± 0.006 mT/A, 0.179 ± 0.0004 mTm/A for dipole 1 and 0.182 ±

0.0003 mTm/A for dipole 2 (Fig. 8). They compare very well to the model predictions.

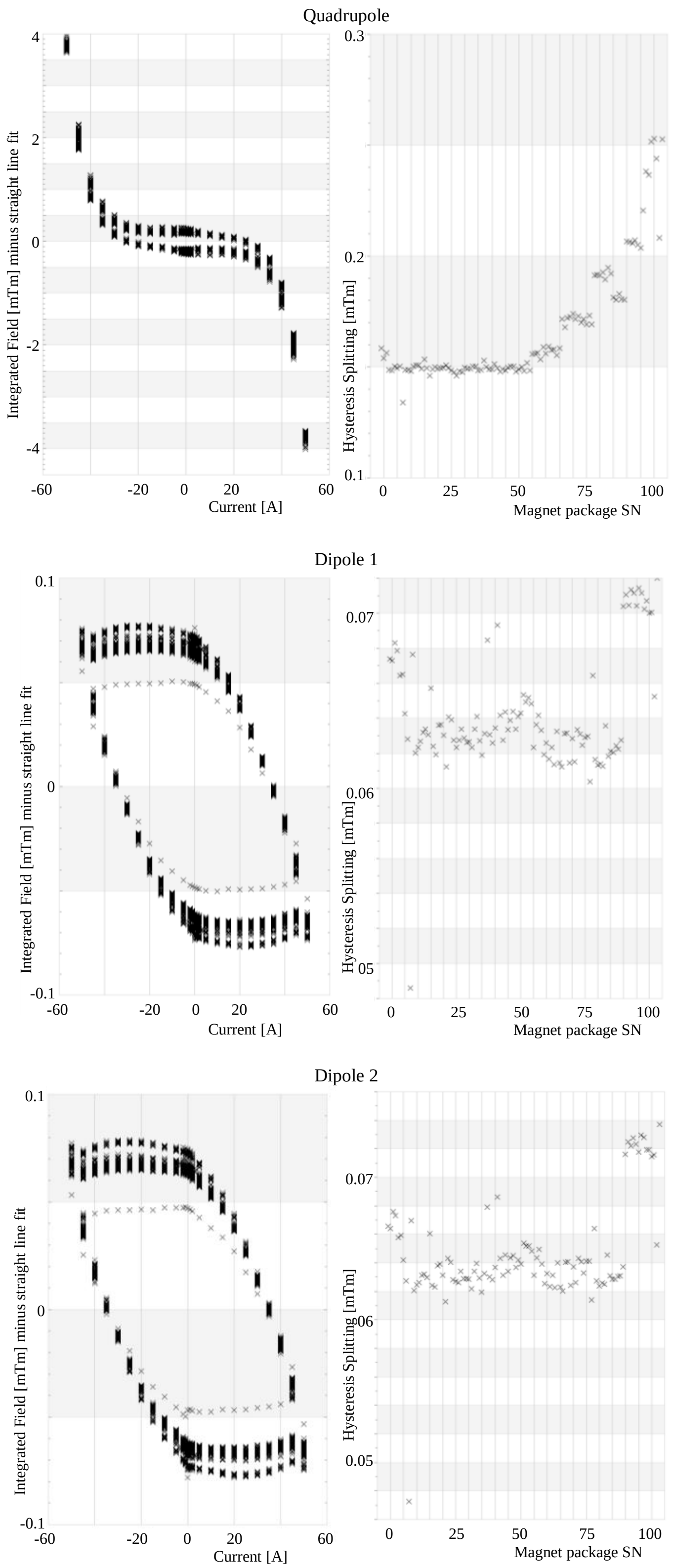

Fig. 9. Left: Hysteresis extracted from linear fit for operating currents ±50 A for three coils. Right: Extracted hysteresis splitting showing significant changes in production of magnet package series. One curve for both dipoles differs significantly because thicker iron laminations were used in one magnet package.

The hysteresis splitting measures the difference between up and down ramps at zero current (Fig. 9). The splitting for the quadrupoles is nearly constant (about 150 μTm) until the serial number 55. From there on the splitting increases in groups of 5 to 10 magnets up to 250 μTm. For the dipoles the change in the splitting is much smaller, but also shows systematic effects.

It can be partially explained by the use of different spools of wire during the coil production and by the manufacturing of the iron yoke sheet. Investigations carried out by the manufacturer of the magnet packages did not fully resolve this effect. Scanning electron microscope photos of some superconducting wires were taken, but did not show any significant deviations. Magnets packages from serial number 90 onwards were produced by using a second batch of iron. This can explain the variation for the dipoles of the last 10 magnet packages, but not of the quadrupoles from 55 to 100.

IV. Conclusion

The warm and cold testing of the magnet package and the current leads phase took more than two years. An average testing time for one magnet and one current lead was five working days, including cool-down and warm-up. During the tests no major problems showed up and there was no delay in the production. Only one current lead was rejected because of heat load problems and merely two magnets must be repaired by the manufacturer due to a short circuit of coils. All magnets reached the design current without quenching and there was no thermal run away of the current leads. The magnetic properties were as expected confirming the mechanical and electrical design. The magnetization and persistent currents in the superconductor leading to the hysteresis splitting were rather large due to superconducting wire properties. But the variation between the magnets was small and the effect can be handled during accelerator operation.

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