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X-FEL quadrupole with gradient of 100 T/m

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Abstract

The paper describes an XFEL quadrupole with a gradient of 100 T/m. The magnets of this quadrupole are designed for installation in the free space between the XFEL undulators to maintain the high quality of the electron beam at an energy of 10 - 20 GeV, which requires high stability of the magnetic axis of the lens. The available size of the aperture of the lens is R = 8 mm. The stability of the quadrupole magnetic axis is better than 5 um for ±10% of the gradient range; the magnetic field quality is good ($\Delta B/B < 10^{-3}$).

Keywords: X-FEL; normalconducting magnet; hight gradient

1. Introduction

The European X-ray free-electron laser (XFEL) is a fourth-generation light source. The facility will produce spatially coherent photon pulses with a duration of less than 80 fs and a peak brilliance of 10^{32}–10^{34} photons/s/mm2/mrad2/0.1% BW in the energy range of 0.26 to 29.2 keV at electron beam energies of 10.5 GeV, 14 GeV, or 17.5 GeV. Three undulator systems are used to produce the photon beams. Each undulator system consists of an array of up to 35 undulator cells (Fig. 1) installed in a row along the electron beam. A single undulator cell consists of a planar undulator, a phase shifter, magnetic field correction coils, and a quadrupole mover. The undulator systems are of central importance for the generation of the X-ray free-electron laser (FEL) radiation. [Massimo et al. (2007)]

Maintainance of high electron beam quality throughout the energy range requires high stability of the magnetic axis of the lens. A special feedback system was designed to ensure stable operation of the accelerator. This system

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enables control of the position of the magnetic axis of the quadrupole lens better than 1um with a special mover system [Altarelli et al. (2007)]. This mover system requires the stability of the magnetic axis of the quadrupole magnet to be better then 5um ± 10% for the gradient range for a current I = 50% Imax. The gradient of the magnetic field quality should be better than $\Delta G/G < 10^{-3}$ at a radius R = 0.3 mm. The maximum value of the magnetic field gradient is to be 100 T/m. This article describes the development and the procedure of magnetic test of the quadrupole magnet XQA.

2. Design of the magnet

2.1. Technical specification

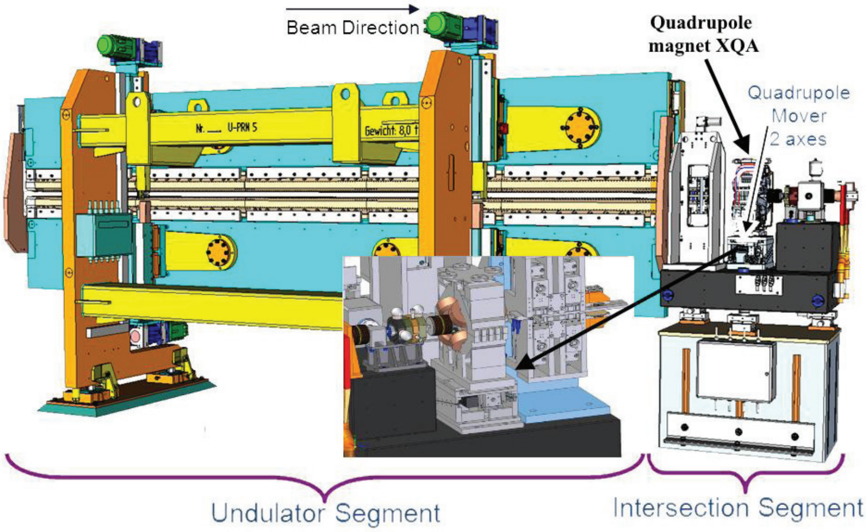


Fig. 1. Position of the XQA quadrupole lens in the XFEL structure [Altarelli et al. (2007)]

Fig. 4 - Fig. 6 show the design of the XQA quadrupole lenses. The main parameter of the quadrupole lenses is the stability of the magnetic axis (Table 1). The next most important parameter is the maximum gradient. It is also necessary to pay attention to the weight limit and the requirement to the magnetic field uniformity. The magnet weight shall not exceed 70 kg. This requirement is due to the limitation of the load on the mover.

Table 1 Quadrupole magnet parameters XQA

Name	Value	Unit
Maximum gradient	100 ± 0.3	T/m
Aperture diameter	16 ± 0.02	mm
Magnet yoke length	0.1	m
Magnetic axis stability of ± 10% in the gradient range for current I = 50% Imax	< 5	Um
Magnetic field quality at R = 3 mm	$< 10^{-3}$	$\Delta G/G$
Number of turns per coil	23	
Nominal (maximum) current	120 (140)	A
Resistance at 20 ° C	0.023	Ohm
Voltage at rated current	3.3	V
Power consumption	400	W
Maximum differential pressure	0.4	MPa
Number of water circuits	1	
Maximum temperature drop	< 10	°C

Amount	125+2	
Weight Limit	< 70	kg

2.2. Design features of the magnet

Requirements to the XQA magnet made us use an unusual approach and materials. The residual magnetization of the yoke may considerably modify the topography of the magnetic field [LEP Design report (1984)]. That is why the coercive force of the steel should be as small as possible to meet the requirements to the axis stability. The magnetic permeability of the steel should be large enough for a large gradient and for all the nonlinear effects to be smoothed out. To provide the required parameters we chose the approach that was used in [Pupkov et al. (2011)].

We opted for the anisotropic electrical steel 3408 [Molotilov (1989)] for the production of the magnet. This steel has a minimum coercive force value of about 5 ÷ 10 A/m (0.06 ÷ 0.125 Oe). The dependence of the coercive force on the magnetic field strength is shown in Fig. 2.

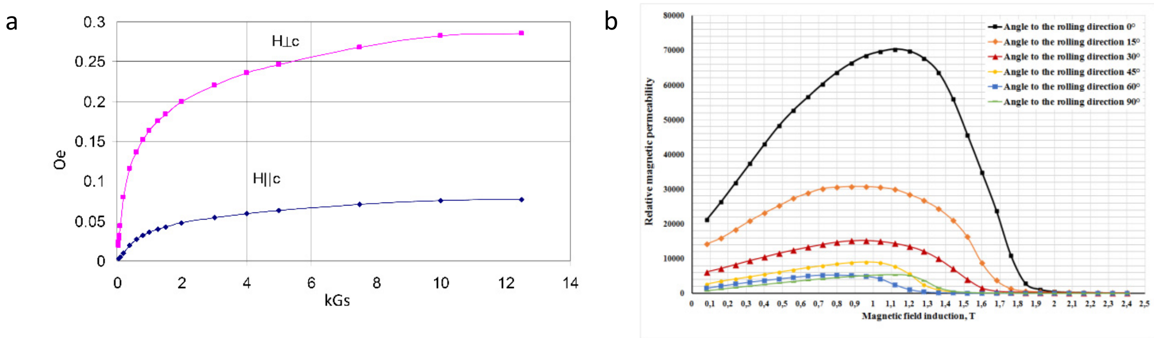


Fig. 2. (a) Coercive force vs. magnetic field strength [Pupkov et al. (2011)]. H||c and H⊥c are coercive forces along and across rolling direction. (b) Relative permeability vs. magnetic field induction for steel 3408.

The anisotropic steel 3408 (GOST 21427.1-83) has the following features:

- a very large $\mu_{||}$ along the direction of the sheet rolling, several tens of thousands [Pupkov et al. (2011), Molotilov (1989)],
- small saturation at high B and low losses in an alternating field,
- the permeability is the smallest at an angle of ~ 55 ° to the rolling direction,
- small values $H_{||c}$ (the coercive force along the rolling direction)
- a sheet thickness of 0.35 mm
- a strong heat-resistant inorganic coating.

The reference data for the magnetic properties of this steel are given for H = 2500 A/m and B ~ 1.5 ÷ 1.9 T depending on the rolling direction. For the calculation one needs to know the magnetic characteristics of the steel up to 2.2 ÷ 2.4 T. Since it was impossible to measure the characteristics of the steel for those values, the author used the methods described in [Pentegov and Krasnozhon (2006), Vonsovskii and Shur (1948)] to interpolate this curves.

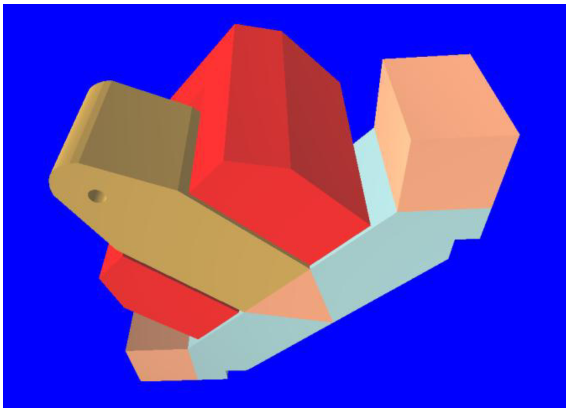
2.3. Calculation of the magnetic lens

A pole of the magnet has a form of hyperbole. The hyperbola is cut off by straight lines parallel to the axes, the so-called shims. The length of the lines is 5 mm. The distance between adjacent pole shims is 5.08 mm. In order to meet the field quality requirements, it is often necessary to change the form of the hyperbole. This technique is not used for the designing of the lens, because the good field region is R = 0.3 mm (37.5% of the aperture) and it is rather simple to provide the required parameters. These straight sections are needed for control of the assembly of the magnetic element and the distance between the poles. The rest of the pole is to host a copper coil.

Each quadrupole magnet has 4 coils made of solid hollow conductor. The coils have 23 turns: 7 turns on the first and second layers, and 4 and 5 turns on the third and fourth layers, respectively. The coils are formed in a solid, mechanically rigid body. The conductor is to be made of oxygen-free electrolytic copper (OF-Cu according to DIN 1787) with a specific resistance of 1.72 x 10^{-8} Ω m or less at 20 °C. The conductor dimensions are to be 6x6 mm2 with a centered bore of 3 mm in diameter. The shape of the lamina and results of the measurement of the lamina reference surfaces are shown in Fig. 4. Fig. 3 and Fig. 5 show a 3D model of the magnet. The lamina has an asymmetrical form, and thus a groove can be made for tightening bolts. It also enables the revolution of the package while the yoke is made. This procedure allows one to get rid of problems beause of different thicknesses of the rolled steel.

Magnetic field calculations were performed using the finite element method by the computer program MERMADE developed at the BINP. A feature of this simulation is the steel 3408. This steel significantly changes its characteristics depending on the angle to the rolling direction. A model of the quadrupole yoke was split into sections with different dependences B(H). Fig. 3 shows the uniformity of the magnetic field gradient, and Fig. 7 presents the integral and normalized gradient depending on the current.

a



b

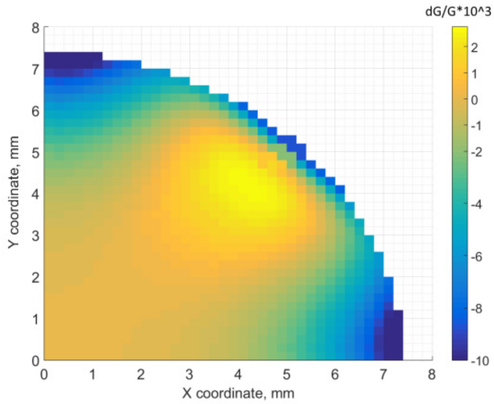


Fig. 3. (a) Computer model of quadrupole lenses. Different colors designate steel with different rolling directions. (b) Magnetic field gradient uniformity

Restrictions on the weight of the magnet lead to a limitation on the amount of steel in the yoke and coil. The magnet yoke is designed meeting this requirement. It is possible to improve the magnetic characteristics of the lens without this restriction. The quadrupole magnet yoke consists of laminated iron quadrants produced from sheets 0.35 mm thick of cold-rolled anisotropic electrical steel 3408 GOST 21427.1-83. The magnet is easily separable for subsequent installation of the vacuum chamber. The coils sit symmetrically on an iron quadrant with respect to the axis and all the four coils are electrically connected in series.

As mentioned previously, this steel has no adhesive coating. In order to form a yoke we use the side and end stainless steel plates. The plates are welded together in a special stock. In order to fasten the yoke we have to make a hole Ø6 mm in the lamella (Fig. 3 and Fig. 4). The quadrupole yoke consists of four yoke parts. The procedure of the yoke manufacturing is follows:

- the special stainless steel end plates are installed in the stock (Fig. 4),
- between this stainless steel plates we install packages ~ 12.6 mm long (including the thickness of the protective coating) collected of the laminas; the total length of the yoke part is 100 mm ± 0.3 mm,
- the packages are installed in the stock so as to form grooves for tightening bolts,
- the side stainless steel plate and a pin are installed on the yoke part,
- the yoke part with the plates is clamped in the stock,
- the side and end stainless steel plates and a pin are welded together and secured by spot welding to the yoke part (Fig. 4),
- the four yoke parts assembled together are subjected to annealing,
- the yoke is assembled completely, inspected on the coordinate measuring machine (CMM) and sent to the painting.

The annealing mode is as follows:

- heating from 20°C to 800°C ÷810°C with a rate of ≈100°C per hour;
- exposure for 2.0 hours;

- cooling together with the furnace to a temperature of 40°C

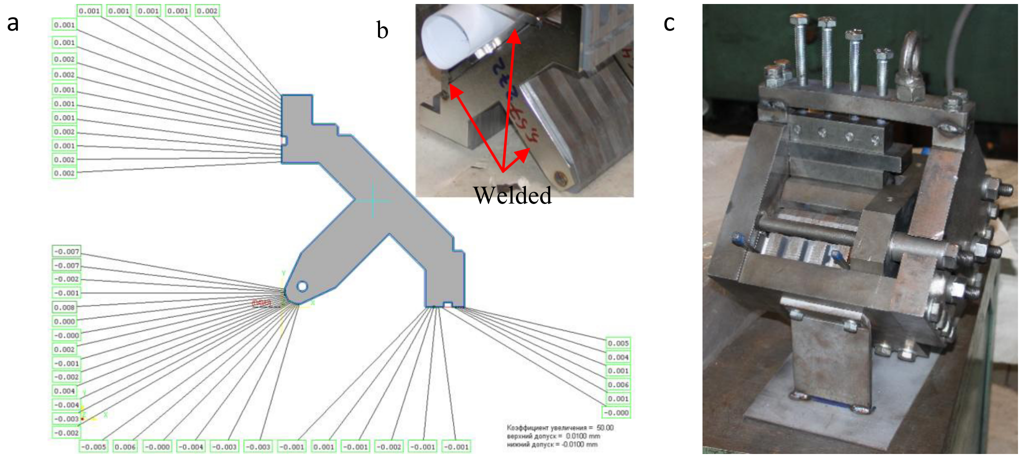


Fig. 4. (a) Plate of the XQA quadrupole lens; values in green squares given in mm.
(b) Quadrupole yoke part
(c) Stock with yoke part

The final assembly of the quadrupole magnet occurs after all the tests according to the specifications. The main mechanical requirements to the magnet assembly relate to the gaps between shims (Fig. 5). The fully assembled magnet passes tests on hydraulic, electric and magnetic stands.

The described magnet is a complex electromagnetic device. In addition to the mechanical and electrical requirements, it is subject to requirements to the positioning and relation of the magnetic axis to fiducials placed on a special stand. Primary alignment and linking with the fiducials were done in BINP using the CMM. Swedish experts performed a more precise coonexion under the contract with XFEL [European XFEL Annual Report (2012)].

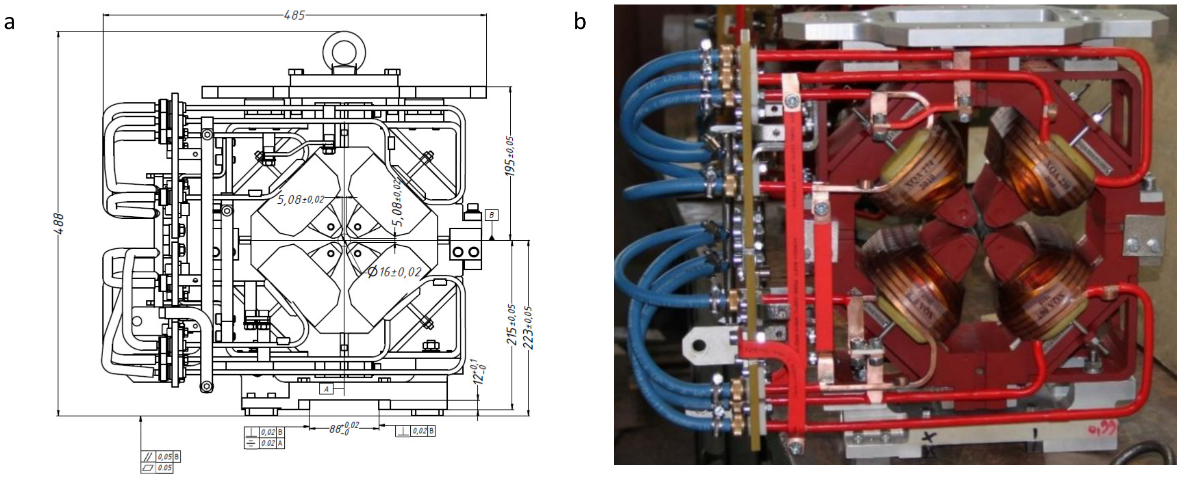


Fig. 5. Quadrupole lenses XQA. (a) model draft. (b) real magnet.

3. Magnetic measurements of lens prototype

The magnetic measurements were carried out using the equipment described in [Okunev et al. (2016)]. A setup with a ceramic shaft was fabricated for the measurement of the quadrupole magnetic axis to within better than 5 microns. The choice of the material was defined by the shaft deflection under its own weight. To reduce the shaft beat and vibration we established a special assembly containing two precise bearings on the ends of the shaft. The rotating coils are 15 mm in diameter and 325 mm in length.

To improve the measurement accuracy of the setup, we fixed the shaft with the bearings units on the setup. To install the magnet on the setup we split quadrupole into the lower and upper halves and put the magnet on the ceramic shaft.

The magnetic measurement procedure is as follows:

- the normalization cycle 0A - 140A - 0A, 3 times,
- the temperature normalization cycle at a current of 70A for 30 minutes,
- adjustment of the quadrupole magnetic axis along the shaft axis with an accuracy better than 30 um,
- magnetic measurements of the quadrupole from 0A up to 140A with a step of 10A, 10 measurements per point.

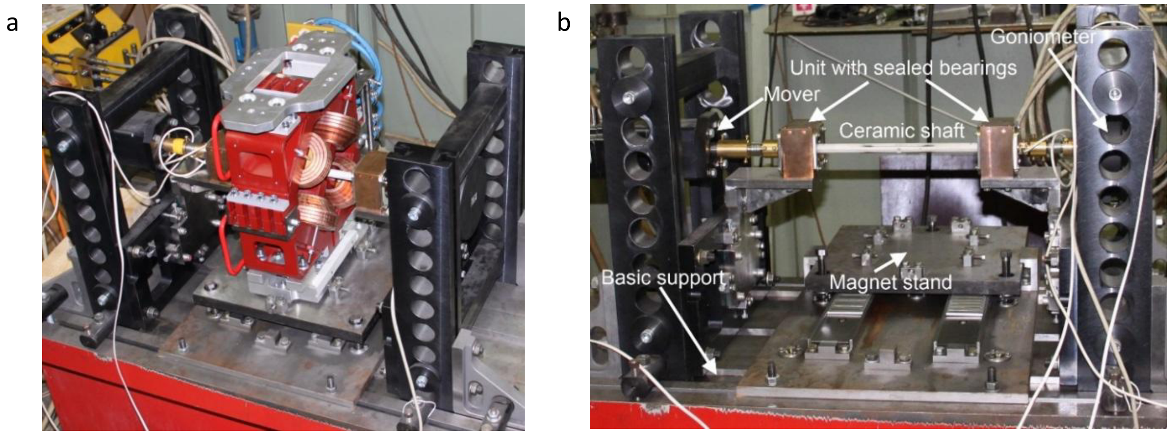


Fig. 6 (a) Quadrupole on measurement stand. (b) Magnetic measurement setup [Okunev et al. (2016)].

The DC power supply provided a maximum current of 300A and a voltage of 12 V. The computer-controlled power supply provided a relative accuracy of about 2×10^{-4} and a stability of 5×10^{-5}.

The measurement results are shown in Fig. 7.

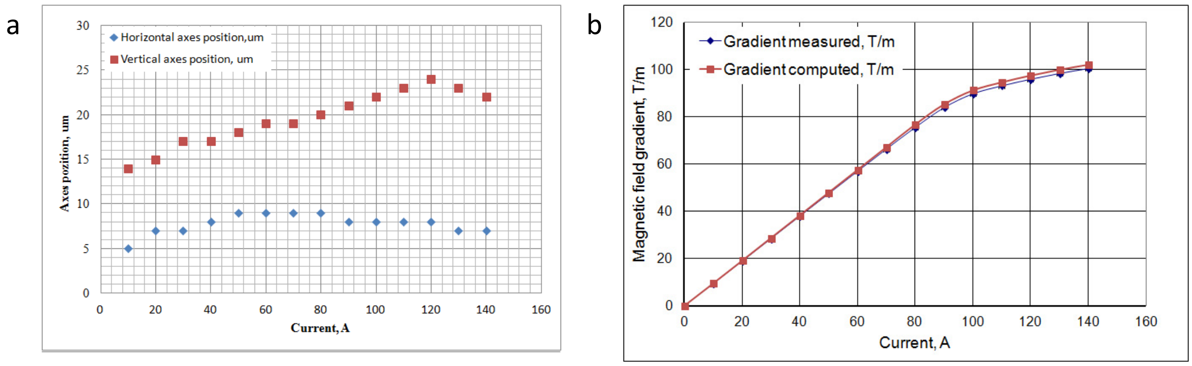


Fig. 7. Axis position vs. magnetic current. Magnetic field gradient vs. current

4. Conclusion

Requirements to magnetic lenses in modern SR sources are becoming more stringent [Baranov et al. (2015)]. Not only the aperture·gradient value grows, but the requirements to the stability of the magnetic axis also increase. The approach used in the design of these magnets can be applied to development of a warm magnetic lens with a large aperture or a gradient. The advantages of this magnet is the price of its operation and production, as well as the ability to work in a wide gradient range.

Acknowledgements

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