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DESIGN, FABRICATION AND MEASUREMENT OF A NORMAL CONDUCTING QUADRUPOLE FOR A LASER-PLASMA ACCELERATOR-BASED BEAM TRANSPORT LINE

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Abstract

For an experimental setup at the laser-plasma accelerator (LPA) at the JETI lasers in Jena, Germany, linear beam transport lines have been studied. The transport line, originally designed to match the LPA beam at 120 MeV and successfully experimentally tested in 2014, will be upgraded to up to 300 MeV by employing stronger focusing quadrupoles. For these high-strength quadrupoles, the magnetic simulation as well as cooling and electrical calculations have been done. To develop fabrication procedures and magnetic measurement techniques, a prototype of the quadrupole magnet has been manufactured and tested at Karlsruhe Institute of Technology (KIT), Germany. This paper is presenting the design, fabrication, and magnetic measurement of the first prototype quadrupole magnet.

INTRODUCTION

The laser-plasma accelerator at the high-power laser JETI operated by the Helmholtz Institute Jena (HI Jena), Germany, accelerates electrons in a plasma wave generated by a high-power laser pulse. The combination of the LPA with a transverse-gradient undulator (TGU) could enable extremely compact free-electron Lasers for EUV- and X-Rays [1], TGU scheme is used to compensate for the relatively large energy spread of the LPA accelerated electron bunches [2]. The transport line matching the LPA beam to the TGU is a key component for realizing this scheme. The HI Jena and the KIT are collaborating on a proof-of-principle experiment and have successfully tested the first version of the transport line at the JETI40 laser in Jena, laid out for a maximum beam energy of 120 MeV [3]. To refurbish the existing transport line for higher energy (300 MeV) and bring the TGU radiation wavelength into a shorter region, a new beam transport line was designed, Fig 1 [4].

According to the beamline design, a quadrupole triplet is used for the optimum collimation in both planes, and three quadrupoles in the dispersive section are located between two pure dipoles which provide the required dispersion and beam optic parameters for the TGU. For the upgrade of this beamline to higher beam energies up to 300 MeV, a new design for the quadrupole magnets has been developed, which is a modification to the existing one [5] by decreasing the gap radius and increasing the current density. These magnets are planned to be installed in vacuum because they must be adjustable to the beam axis, which has some degree of

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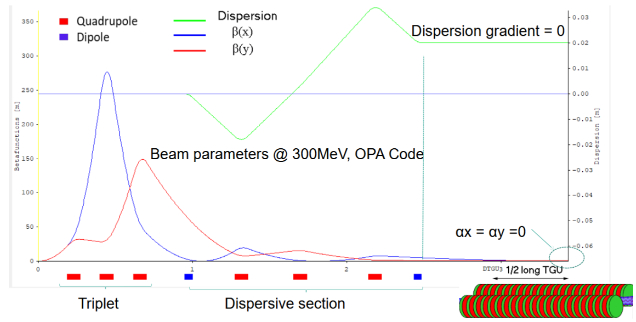

Figure 1: Layout of the lattice and optic parameters at 300 MeV [4] using OPA Code [6]

Table 1: Magnetic and Geometrically Designed Parameters

Parameter	Unit	Value
Magnet dimension	mm^2	218×218
Effective length	mm	86
Gap radius	mm	7
Field gradient	T/m	73
Operating current	A	7.5
Number of turns per coil		412
Current density	A/mm^2	5
Power	W	313.6

variability or uncertainty. The coils are cooled using indirect water cooling. The beam dynamics of the transport line and normal conducting magnet design of the highest strength quadrupoles were presented in [4]. A more compact transport line using superconducting magnets is also presented in [7]. In this contribution, the design, prototype fabrication and powering test of this quadrupole magnet are presented.

DESIGN AND MANUFACTURE

Yoke

The two-dimensional design of the yoke was performed in Poisson-Superfish [8] and the three-dimensional model was simulated in OPERA [9]. Specification and geometrical parameters of the designed quadrupole at full excitation are summarized in Table 1 and the general dimensions are shown in Fig. 2.

The yoke of the first prototype was fabricated in the main workshop (Technik-Haus, TEC) at KIT, Fig.3, using steel S355JR (grade 1.0045 as per EN 10025-2) which was proven to have similar magnetic properties as AISI1010 which was used in the simulations. The transport line magnets will

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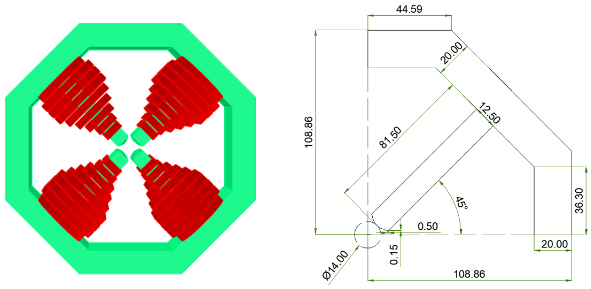

Figure 2: Magnet OPERA 3D model and dimension in mm.

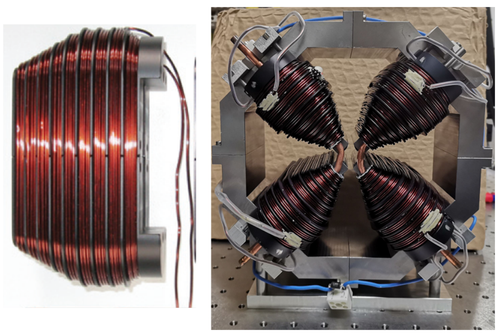

Figure 3: Coil [5] and the first prototype of the quadrupole without cooling system.

be manufactured later using C06 (AISI1006) low-carbon magnetic steel.

A shim with 0.5 mm length and 0.153 mm height was inserted on the edge of the pole and a 30°, 2.77 mm depth cut, so-called chamfer was applied on the pole in the longitudinal direction, in order to improve the integrated field quality in the longitudinal direction in the good field region (GFR) ±5 mm to a tolerable range of a few units of 1×10^{-4}, as shown in Fig.4. Moreover, by designing the shims and the chamfers, the integrated normalized multipole errors, Fig.4, and the relative deviation of effective length within the GFR, Fig.5, are kept below 1×10^{-3} respectively.

Coils and cooling

For the upgraded magnets the existing coils, Fig. 3, are re-used. The coils are wound using copper conductor wires with a cross-section of 1.5 mm^2 [10] on a step-shape coil

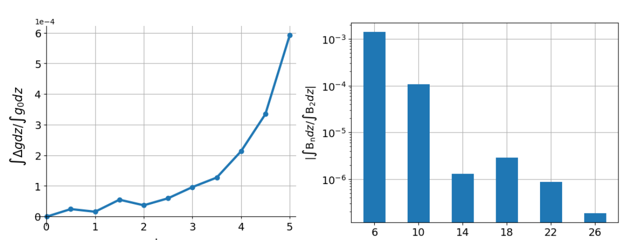

Figure 4: Left: absolute integrated field quality in the longitudinal direction; right: integrated normalized multipole errors of the chamfered model at 5 mm.

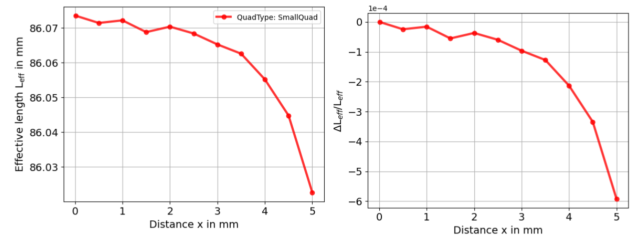

Figure 5: Left: effective length within GFR; right: relative deviation of effective length within GFR.

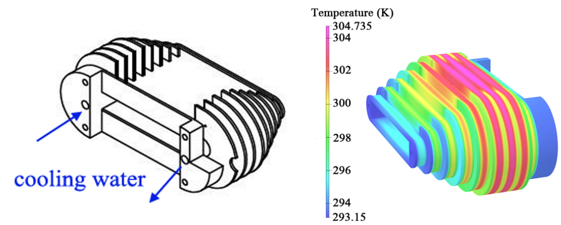

Figure 6: Left: the design of the coil former with built-in cooling channels [10]; right: heat analysis model of the coil in OPERA in full excitation.

former with two built-in cooling channels (Fig.6). To simulate the heat transfer inside the coils, the coils were modeled in OPERA with a constant dissipated power density in the coil volume and with an anisotropic heat conductivity accounting for the largely different effective heat conductivities in transverse and longitudinal (i.e. current flow) direction. The cooling channel surface temperature was set constant (T = 293.15 K), and all outer surfaces were assumed to be thermally insulated. The temperature distribution at full excitation of the coil, corresponding to a dissipated power of 313.6 W, is shown in Fig.6. The maximum temperature rise in these conditions is 11.6 °C.

Measurement and results

The powering test and magnetic measurement of the first prototype were done in the magnetic measurement lab of the Laboratory for Applications of Synchrotron Radiation (LAS) at KIT, the experimental set-up is shown in Fig.7. It uses a standard Gauss meter HIRST GM07 with the transverse Hall probe being fixed on the three-dimensional adjustable stage, in order to measure the magnetic field at different positions in and outside the quadrupole. Figure 8 shows the simulated and measured field gradients while ramping the current up to 4.5 A. Comparing these results it can be seen that the properties of steel S335JR and steel C10 (AISI1010, used in the simulation) are quite the same. Since the cooling system was not installed for the first prototype, the magnetic measurement was done up to 1 A. Figure 9 presents the measured field gradients in transverse and longitudinal planes, which agree well with the simulation.

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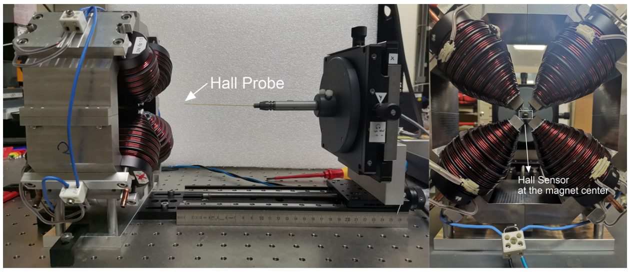

Figure 7: Left: experiment setup for the magnetic measurement of the first prototype; right: the measuring point at the center of the magnet

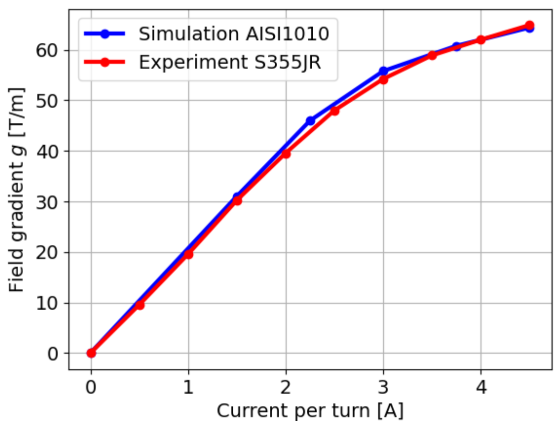

Figure 8: Field gradients as a function of operating currents comparison of materials AISI1010 (simulation) and S355JR (experiment).

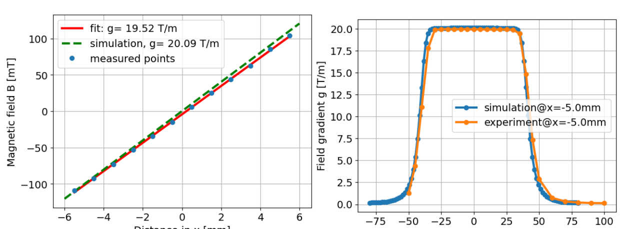

Figure 9: Transverse and longitudinal magnetic measurement results at operating current of 1 A.

CONCLUSION AND OUTLOOK

For the designed 300 MeV LPA-based beam transport line, the highest strength quadrupole was designed, and a prototype was fabricated and successfully tested at KIT. The measurement results were compared to the OPERA 3D simulation at 1 A operating current which showed very good consistency. The in-vacuum measurement for the first prototype after attaching the cooling channels is planned and the fabrication of the transport line's quadrupoles is foreseen. By installing the newly designed magnets, the experiments with the TGU at an energy of 300 MeV will be prepared.

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