MEASUREMENTS OF HIGH-ORDER MAGNETIC FIELD COMPONENTS OF PERMANENT QUADRUPOLE MAGNETS FOR A LASER-PLASMA-DRIVEN UNDULATOR X-RAY SOURCE

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Abstract

Laser wake-field accelerators as a novel sources of high-energy electron beam are prominent candidates to drive a next generation of compact light sources. However, to preserve the unique properties of laser-plasma driven electron beams, it is crucial to capture the beam directly after the target using quadrupole magnets with extremely high field gradient. We designed and manufactured compact permanent quadrupole magnets based on a Halbach design using 12 NdFeB wedges with 1.02 T remanent field which provide field gradients up to ~500 T/m at an aperture radius of only of a few mm. We measured the magnetic field of the permanent magnet quadrupoles using both the pulsed-wire and rotating-coil technique. Here, we present a first analysis of the magnetic field quality, the integrated field gradient and high-order field components. We briefly discuss the influence of field imperfections on the electron beam quality and its consequences for application in the transport line of a laser-plasma-driven undulator X-ray source.

INTRODUCTION

Laser wake-field accelerators (LWFA) already demonstrated GeV level beam energies over centimetre distances [1]. Laser accelerated electron beams are typically characterized by extremely small transverse beam sizes of only a few micrometer, together with kA-level peak currents and ultra-short bunch lengths of only a few femtoseconds [2], which enable applications such as compact light sources [3, 4]. For such applications, a dedicated electron transport beam line together with a stable laser plasma accelerator, are crucial elements [5]. More specifically, the electron beams from the laser-plasma target, which typically show a comparatively large divergence on a mrad scale and a few percent-level energy spread, have to be captured quickly after the plasma and then transported to the final application without degradation of their unique properties. Consequently, is necessary to install focusing elements as close to the source as possible.

Following a Halbach type design [6], high-gradient permanent magnet quadrupoles (PQMs) have demonstrated field gradients on the order of ~500 T/m. Such high gradient can capture the electron beam within only a few centimetres from the source to minimize chromatic emittance growth in the subsequent drift. Previously, we have presented a detailed concept for a transport beam optic, which is solely based on PMQs and preserves the unique properties of plasma-generated beams for application in a compact undulator [7]. Here, we present manufactured PMQs as required by the design in [7] and briefly characterize their field quality using the pulsed-wire and rotating-coil techniques. Finally, we discuss the effect of magnet field imperfections on the electron beam transport.

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PERMANENT MAGNET QUADRUPOLES

Using CST Studio [8] we design Halbach type PQMs following a design based on 12 $Nd_2Fe_{14}B$ reaching field gradients of order ~500 T/m. The quadrupoles have to provide a clear aperture sufficiently large to prevent clipping of the main driver laser. This sets an additional requirement on the inner radius of the quadrupole design. Main parameters of the permanent quadrupole magnets are shown in Table 1.

Table 1: Design Parameters of Quadrupole Magnets

		PQM1	PQM2
Core length	mm	60	50
Inner diameter	mm	6	11
Outer diameter	mm	20	42
Central gradient	T/m	520	283
Good field region	mm	± 1.5	± 3.0

In the simulation, we assume a remanent field of 1.0236T and include the effect of a 5% random error in magnetization for each wedge, which results in a degradation of the maximum field gradient of up to 1%.

FIELD MEASUREMENTS

Permanent magnets quadrupoles have been build based on magnets from Vacuumschmelze [9] and characterized for field quality using the pulsed wire (PW) and rotating coil (RC) technique:

Pulsed Wire

The pulsed wire technique measures the longitudinal resolved first and second field integral of a magnetic structure. In this setup, a thin tungsten wire is mounted through the magnetic field and connected to a function generator, which provides a square wave current pulse. Behind the magnetic structure a laser is focused onto the wire and then hits a photo diode. The transverse deflection of the wire is proportional to the transmitted laser light on the photodiode. When a current pulse is applied

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to the wire, it is locally deflected by the magnetic field in the same way an electron beam would be deflected. A mechanical wave is excited, which travels along the wire. The photodiode signal then represents the longitudinal resolved field integral of the magnetic device. We used such a setup to measure field gradients for PQM1 of 482T/m and 492T/m in the horizontal and vertical plane, respectively. For PQM2, the measured field gradients are 282T/m and 255 T/m in the horizontal and vertical plane, respectively. The estimated error of the measured field gradient is about ±10% and mainly determined by the calibration. We aim to minimize those systematic errors in a future measurement campaign.

Rotating Coil

In addition to the field gradient, the magnetic field quality, described by the high-order field components (HOFC), is an important characteristic of the assembled quadrupoles. The HOFCs serve as an important input to more detailed simulation of the electron beam transport We characterized both permanent magnet quadrupoles, PQM1 and PQM2, with a rotating coil setup. We inserted a rotating double coil into the PQM aperture and retrieved the higher order field components by Fourier analyzing the voltage induced by the azimuthal field of the magnet. The results were cross calibrated to a Hall probe. The measurements of the Hall probe and the rotating coil show similar gradients compared to the PW measurement. However, more investigation is required to calibrate and cross-reference all three measurement techniques.

From the rotating coil measurement, we find, that the high-order multipole fields have a contribution of less than 1% of the total field.

ANALYSIS OF THE FIELD

We used the 3D field maps from CST to study the electron beam propagation with GPT [10]. We expect that small corrections to the position of the permanent quadrupole magnets will be necessary when considering measured fields. We find, that the high-order field components of the PQMs do not lead to significant increase the normalized beam emittance. This can be explained by the comparably small transverse size of the electron beam.

We used the measured PQM fields to simulate the transport of a 400 MeV beam with 1% rms energy spread. Using a doublet of 450 T/m and 270 T/m quadrupoles we can capture and collimate the beam within 20 cm after the target. The emittance mainly increases within the short drift after the plasma and before the first quadrupole, but is conserved within a factor of 2 for the whole duplet. This is already sufficient to transport the beam to an undulator for first applications.

CONCLUSION

The field quality of Halbach type permanent magnets quadrupoles is comparable to the field quality of the state-of-art electro-quadrupole magnets. Contributions of the high-order multipoles to the main field are less than a fraction of 1%, which is much smaller than effect of the significant energy spread of the LWFA electrons.

The extremely short focal lengths of the PQMs result in a compact 'doublet' focusing structure which allows to keep the transverse size of the initially divergent beams at a minimum. Simulations show that the normalized emittance of a 400 MeV LWFA electron beam can be conserved within a factor of 2, which is already sufficient for transport and to enable first applications.

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