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COMPACT IN-VACUUM QUADRUPOLES FOR A BEAM TRANSPORT SYSTEM AT A LASER WAKEFIELD ACCELERATOR*

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Abstract

For the transport and matching of electrons generated by a Laser Wakefield Accelerator (LWFA) a beam transport system with strong focusing magnets and a compact design is required. For the realization of such a beam transport system at the LWFA in Jena, Germany, two small series of inexpensive, modular quadrupoles were designed and built. The quadrupoles are iron-dominated electromagnets in order to keep the transport system adaptable to different energies and target parameters. To achieve the required field strength it was necessary to choose a small magnetic aperture. Therefore the magnets were designed for in-vacuum use with water-cooled coils. In this contribution the design, the realization and first field measurements of these quadrupoles are presented.

INTRODUCTION

Capturing, transporting and matching electron beams generated by Laser Wakefield Accelerators (LWFA) is a major challenge due to their significant energy spread, intrinsic divergence and pointing variance. To approach this problem experimentally one would certainly like to proceed step by step, each step involving a limited number of focusing and correcting magnets adapted to the respective experimental strategy. Such an approach, different from the situation at classical accelerators, calls for inexpensive, easy to build and easy to modify magnets providing maximal experimental flexibility.

Since the magnets, as explicated in more detail in the following section, have to be strong, compact, and adjustable to a not exactly predictable beam axis, the conventional concept of feeding a vacuum-beam pipe through the magnet gaps is discarded. Instead, the magnets should be capable of being operated in vacuum (10^{-5} mbar). At the same time it should be possible to tune the magnets on-line or to switch them off completely. Accordingly, in-vacuum electromagnets are the technology of choice.

Following these lines we designed, built and tested a set of electromagnetic in-vacuum quadrupoles and employed them in our first experimental step realizing a linear beam optics at the LWFA in Jena [1]. The basic design strategies applied can easily be transferred to higher-order multipole magnets for further experimental steps.

DESIGN REQUIREMENTS

Two small series of in-vacuum quadrupoles were realized. The magnetic and geometric design parameters for the two series are summarized in Table 1. The values for series *QG* result from an optimization with respect to the following geometric requirements and restrictions: On the one hand the large initial divergence of the beam in both transverse planes requires that the first magnets (either a doublet or a triplet) are placed as close as possible to the source and to each other. As a first approximation the focal length $f = (kl)^{-1}$ should be of the same order as the distance from the source. Here, $k = \frac{e}{p} g$ is the focusing strength, l the yoke length, g the field gradient and $\frac{e}{p}$ the beam stiffness, which is for our design beam energy of $E_0 = 120\,\mathrm{MeV}$ $\frac{e}{p} = 2.4\,\mathrm{T}^{-1}\,\mathrm{m}^{-1}$. At the same time the source-to-magnet center distance and the center-to-center distance between neighbouring magnets sets an upper limit to the full magnet length (including coils). To accommodate, on the other hand, a spectrally dispersed beam with a total dispersive beam splitting of ~ 4 mm, we chose an inscribed gap radius of 11 mm. Given this gap radius, the first estimations yielded 125 mm for the focal and 140 mm for the overall magnet length and 60 mm to 100 mm magnetic length as reasonable values. We note that for these parameters the thin lens approximation our estimation started off, is only valid in a heuristic sense.

The same basic consideration also applies to the series *QK*, however, these magnets are foreseen to be replaced by combined function quadrupole-sextupole magnets in a later experimental step. Consequently, following our design strategy of inexpensive and easy to modify magnets, the coils for series *QK* have already been designed and built for these magnets and therefore feature a sextupole geometry and a lower number of turns per coil.

Correspondingly the magnet coils for both series are laid out for being operated with standard laboratory power supplies and wound with a standard copper wire without internal cooling channel.

Table 1: Design Parameters for Two Small Series of Quadrupoles

Series	**QG**	**QK**
yoke diameter [mm]	210	203
magn. length [mm]	80	80
gap radius [mm]	11	11
turns/coil	465	412
max. operation current [A]	6	6
max. design field gradient [T/m]	39	30

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To enable the in-vacuum operation of the coils and the required modularity we developed water-cooled coil formers serving as heat sinks for the winding packages and forming coil modules mountable to the yokes. Figure 1 shows the geometry of these coil formers, the yoke modules and the complete magnet assembly.

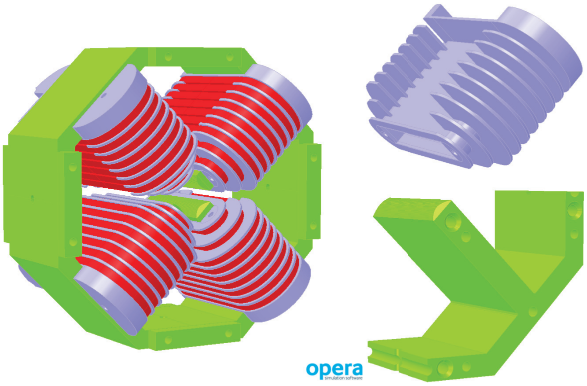

Figure 1: Basic layout of the in-vacuum quadrupoles (left). Water-cooled coil former (top right) and yoke module (bottom right).

DESIGN AND MANUFACTURE

The magnetic and thermal design of the magnets was based on three-dimensional finite element calculations performed with the Vectorfields-OPERA solvers TOSCA and TEMPO. The optimization of the magnet's geometry was done by varying the free parameters of a parameterized model within the boundaries explained in the previous section.

Yoke Modules

For optimizing the iron yoke geometry an ideal hyperbolic pole shape was assumed and the gap radius, the overall magnet length and the yoke diameter were fixed. The magnetic length, the pole width and accordingly the coil geometry were varied, keeping the engineering current density constant at $J_{\mathrm{eng}} = 2.5\,\mathrm{A\,mm^{-2}}$ and maximizing the field gradient under the condition that the harmonic distortion factor is kept in the range of a few 10^{-4} [2, p. 242]. The spurious relative field harmonics were summed up to ninth order.

As a general result, both the field gradient maximization and the harmonic distortion factor minimization favour an as large as possible pole width. Increasing the magnetic length is only possible at the expense of reducing the number of Ampère-turns due to the fixed overall magnet length. The maximum field gradient is achieved at a magnetic length of 60 mm, however, in order to accomplish the required focal length, i.e. the required integrated focusing strength, we chose a magnetic length of 80 mm providing a $\sim$ 10% lower field gradient as compared to the optimum, but meeting the requirement on integrated focusing strength.

The manufacture of the yokes was done in-house at the KIT. The quadrupole yokes are composed of four modules aligned through aligning pins and clamped together by means of ISO-K clamps. Each yoke module consists of a stack of laser-cut electric steel sheets pinned and bolted together. The complete stack was subsequently chamfered at the pole ends by electrical discharge machining in order to reduce spurious multipole components in the edge field region.

Coil Modules

The FEM-based design optimization of the magnet yields the total number of Ampère-turns in the coil volume and in turn the engineering current density. Following our design philosophy of inexpensive solutions we aim at an operation current range $I \lesssim 10\,\mathrm{A}$, well accessible with standard laboratory power supplies. This choice in turn calls for a conductor with a relatively small cross-section in the order of 1.5 mm^2. We chose an enamelled copper wire with circular cross section and a diameter of 1.4 mm bare/1.468 mm insulated. The dissipated power per coil at maximum operation current is 54 W for series *QG* and 47 W for series *QK*, respectively.

For extracting this power we employ specially designed and manufactured water-cooled coil formers shown in Fig. 1. These formers were machined in two parts from solid Aluminum and anodized. They feature two cooling water channels each and equally spaced cooling fins extracting the heat from the upper layers of the coils. The coils are wound as packages in between the cooling fins with four and three turns per layer, respectively, in sphere packing topology. Figure 2 shows photos of the coil former parts and the completed coils which were manufactured and wound at the University of Jena.

The heat transport inside these coil assemblies was simulated with the OPERA-3D TEMPO-solver. For this simulation we assumed the external surfaces of the coil modules to be thermally insulated with the exception of the surface of the cooling channels for which a fixed temperature of 293 K was assumed. The coil packs were modelled as volumes with

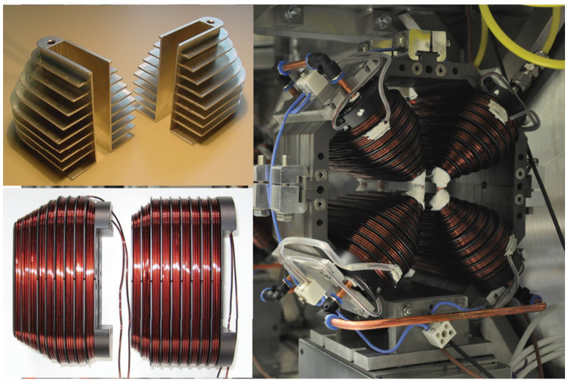

Figure 2: Coil former parts (top left, courtesy B. Klumbies), completed coil modules for both magnet series (bottom left, courtesy A. Rose) and a complete magnet of type *QK* readily installed in the vacuum chamber at the LWFA.

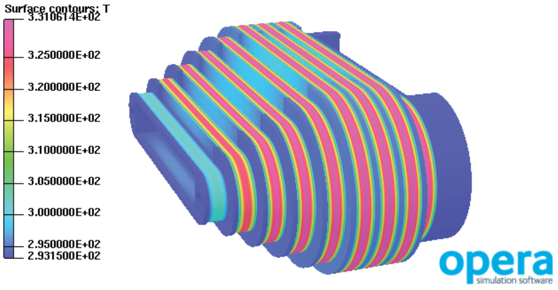

Figure 3: Temperature map of water-cooled *QK*-coil operated in vacuum at maximum operation current (OPERA-3D/TEMPO simulation).

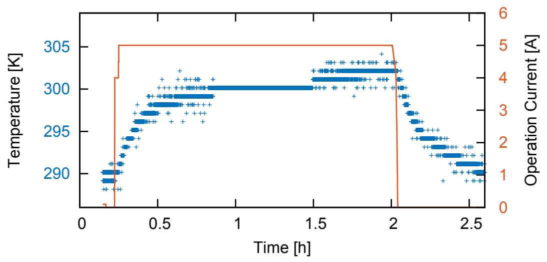

Figure 4: Measured coil temperature during in-vacuum operation test at maximum operation current.

a constant dissipated power density and with an anisotropic heat conductivity: in the direction of current flow the heat conductivity of copper was assumed, the transverse heat conductivity was conservatively estimated from the heat resistance of the contact surfaces between adjacent turns of the wire or between the wire and the coil former. Figure 3 shows the resulting temperature map at the coil module surface for the coils of series *QK*. The temperature does not exceed 335 K which is well within the tolerable range (< 378 K).

PERFORMANCE

Two magnets of type *QG* and four magnets of type *QK* were tested and preliminarily characterized at the start of the first experimental campaign at the LWFA. The magnets were operated in high vacuum at up to 5 A of operation current. The coil temperature was measured with silicon diode temperature sensors (one for each magnet) glued to one coil at a position identified as hot spot in the thermal FEM simulation. Figure 4 shows the measured temperature as a function of time after switching on and turning off the current, respectively. The temperature difference between cooling water and hot spot stays below 16 K, which is significantly less than suggested by the conservative FEM calculation and shows that the magnet can safely be operated in vacuum.

To preliminarily characterize the magnets a basic Hall-probe scanning setup was realized, which allowed to measure the B_y component as a function of x in the center of the magnet ($y, z = 0$ with z the magnet's symmetry axis and x-z its median plane). Figure 5 shows a sample measurement of magnet *QK3* and a linear fit to the measured data. In the

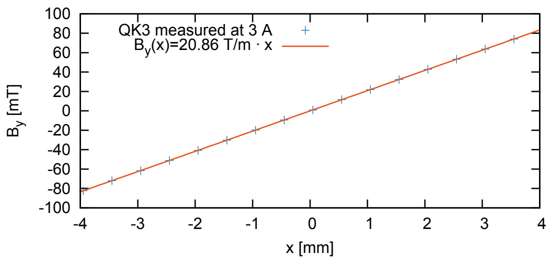

Figure 5: Magnetic flux density as a function of transverse position in the median plane of magnet *QK3*

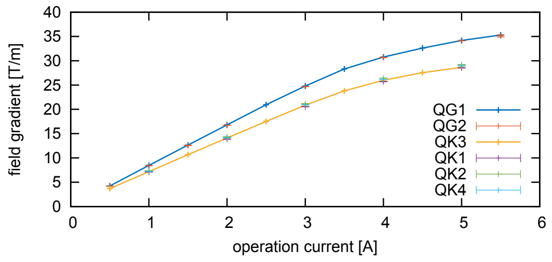

Figure 6: Field gradient as a function of operation current for all magnets, determined from linear fit to the flux density measurements.

measured range $\pm 0.48 r_0$ the flux density depends linearly on the transverse position in very good approximation. The field gradients resulting from the linear fits to the data measured for different currents are plotted for all magnets in Fig. 6. While the magnets of series *QK* virtually reach the design values the magnets of series *QG* achieve field gradients about 10% lower than expected on the basis of the FEM calculations, yet still sufficient with regard to the beam optics requirement.

A more comprehensive magnetic characterization of the quadrupoles at the magnet measurement setup, currently being commissioned at KIT [3], is planned.

SUMMARY AND OUTLOOK

We have designed, built, successfully tested and employed compact, strong and inexpensive focusing electro-magnets for in-vacuum operation, providing a high degree of experimental flexibility as desirable for building up a challenging beam transport system at a laser wakefield accelerator in a gradual manner. In particular our conception of the water-cooled coil modules turned out to be viable. In the next step combined-function quadrupole-sextupole magnets will be realized along the lines of the same design philosophy.

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