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A SHORT-LENGTH TRANSPORT LINE FOR LASER-PLASMA ACCELERATORS USING HTS PERIODIC MAGNETS*

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Abstract

In laser-plasma accelerators (LPA), due to extremely high accelerating gradients, electron bunches are accelerated to high energies in only a few millimeters to centimeters of acceleration length. To efficiently capture and transport the LPA-generated bunches in a compact transport line, beam line designs employing high-strength combined-function magnets based on high-temperature superconductor technology have been studied. Moreover, to overcome coil winding challenges in fabricating miniature HTS magnets, novel periodic magnets have been designed, which can collimate and guide the electron beams in a well-controlled short-length transport line. In this contribution, we present the beam dynamics calculations as well as the magnet designs for a 1.4 m transport line matching the LPA-generated electron beams to a transverse-gradient undulator.

INTRODUCTION

Laser plasma acceleration (LPA) is one of the novel accelerating methods; in which the ionized plasma medium generates and handles electric field gradients up to 100 GeV m^{-1}. In fact, in these small but efficient accelerators, the electromagnetic field of a high-power Terawatt (TW) laser pulse separates the plasma charges and generates a strong longitudinal electric field where the trapped electrons are accelerated to very high energies of the order of GeV in cm scales, Fig. 1.

Moreover, by generating ultra-short electron bunches with micrometer bunch lengths, LPAs are attractive to be used as drivers for a compact radiation source or even free-electron lasers (FELs) [1]. However, one of the major disadvantages of the LPA technology compared to the conventional accelerators is the percent-level energy spread and milliradians divergence which makes bunch shaping and transport difficult. To overcome these difficulties and capture divergent, large-energy spread beams efficiently an effective beam transport line is required which in combination with a transverse gradient undulator (TGU) as the radiation source can generate narrow bandwidth radiation. The TGU is designed such that the dispersed electron beam entering the undulator meets a magnetic field with a gradient in the transverse direction which obeys Eq. (1).

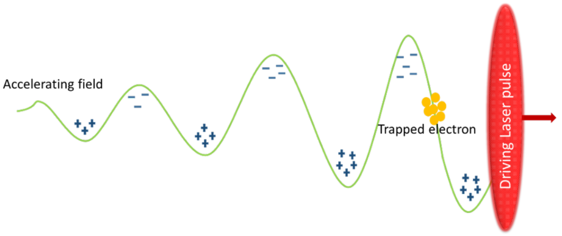

Figure 1: Schematic sketch of an LPA acceleration process.

$$\lambda = \frac{\lambda_u}{2\gamma^2(x)}\left(1 + \frac{K_u^2(x)}{2}\right), \; K_u(x) = \frac{-eB_0(x)}{m_0 c}\frac{\lambda_u}{2} \tag{1}$$

Electrons with different energies travel through the TGU and encounter different field amplitudes leading to monochromatic radiation, [2] and [3]. By inserting the parameters of the existing superconducting TGU [4], i.e. λ =10.5 mm and B_0 = 1 T, in Eq. (1) it can be seen that electrons with 440 MeV can generate extreme ultraviolet radiation and in order to have x-ray radiation electrons of GeV energy should be guided through the TGU.

Thus, aiming at developing reliable lab-scaled transport lines at relevant high energy levels for LPAs and assuming the TGU as the radiation source, different transport lines with different lengths at different energies have so far been designed and developed at KIT: a 2.5-meter normal conducting transport line at an energy of 120 MeV [5] as well as an upgrade to this transport line which has the same 3 m length but works at 300 MeV [6], and 1.6 m length transport lines at 700 MeV which employ high-temperature superconducting (HTS) cos-theta magnets [7]. In this contribution, the magnet design and beam optics calculations for a 1.4 m transport line using HTS periodic iron-core magnets are presented.

HTS IRON-CORE TRANSPORT LINE

The majority of high-temperature superconductors (HTS) are ceramic materials that are usually applied in form of flat tapes consisting of a substrate, a thin, epitaxially grown HTS, e.g. Rare-earth Barium Cuprate (ReBCO) layer and covering Copper layers for stabilization. Due to the anisotropy of mechanical as well as superconducting properties, HTS are usually in form of tapes and cannot be wound in the same way as low-temperature superconducting strands. On the other hand, cos-theta air-core magnets are the most common type of superconducting magnets which by generating high-strength magnetic fields can guide and control the particle beam at high energies. But due to the complicated coil geometries of these magnets and the limiting mechanical properties of the ReBCO tapes, it is difficult to wind such coils using HTS tapes. Therefore to proceed with developing HTS ultra-short transport lines and facilitate the winding difficulties of the cos-theta magnets a short transport line using novel periodic iron-core magnets with simple pancake-shaped coils was designed and developed for a design energy

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of 260 MeV. This transport line consists of a focusing and a dispersive section and by assuming a Gaussian beam with initial conditions discussed in [5], it matches the optical functions to the dynamic acceptance of the TGU [8] at the end.

Focusing Section - Periodic Quadrupole

The periodic quadrupole consists of several HTS pancake coils in which the neighboring coils have opposite current directions making a periodic structure with period length λ. The coils are located on a cylindrical iron yoke and the quadrupolar field shape is created by an optimized hyperbolic iron pole. Figure 2 depicts a draft design of this magnet.

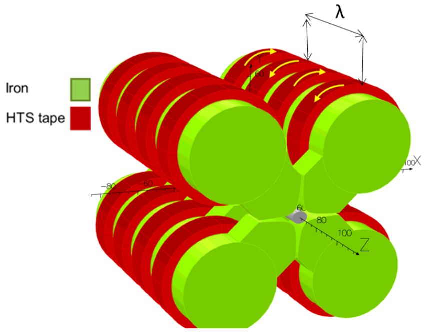

Figure 2: Periodic quadrupole; draft design with the periodic length λ.

Applying the B - H curve of the soft ferromagnetic material XC-06 [9], a broad pole profile was designed using the code Poisson [10], and the magnetic field quality parameter $\Delta g/g_0$ is obtained to be less than 0.01% in the good field region of ±5 mm, as shown in Fig. 3. Here, g_0 is the nominal field gradient and $\Delta g = g(x) - g_0$ is the local deviation.

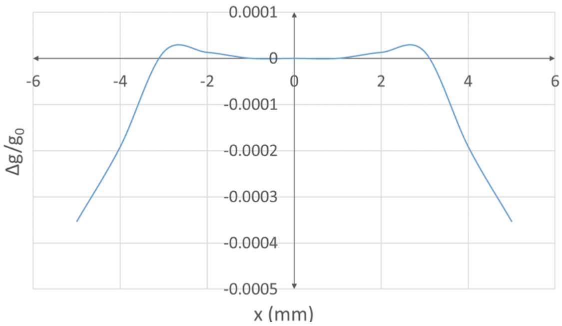

Figure 3: Magnetic field quality versus horizontal direction x at $y, z = 0$.

Using the CST and Opera software [11, 12], the 3D design of the magnet was explored to determine the number of periods and the periodic length required for the beam capture. The magnet design was done in parallel to the beam dynamics simulation with the code ASTRA [13], in order to ensure an efficient capture and transportation of the LPA-generated bunches in this periodic magnet structure. After many iterations, it was deduced that the 3-period model with λ = 11.9 cm can provide a good focusing of the electron beams in both transverse planes. Figure 4 depicts the optimized magnet structure in which the coils are considered to be wound with 12 mm wide SCS12030-AP ReBCO tape from Superpower Inc. [14]. There are 72 turns of tape per coil and at 4.2 K, by applying 1.3 kA current, a maximum field gradient of 170 T m^{-1} can be created. The obtained magnetic field gradient in the longitudinal direction z is illustrated in Fig. 5 and the magnet parameters at 4.2 K are summed up in Table. 1.

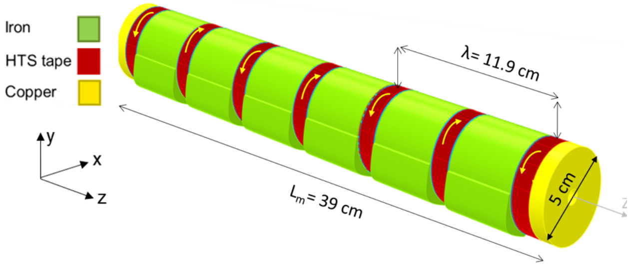

Figure 4: One-fourth of the optimized periodic quadrupole.

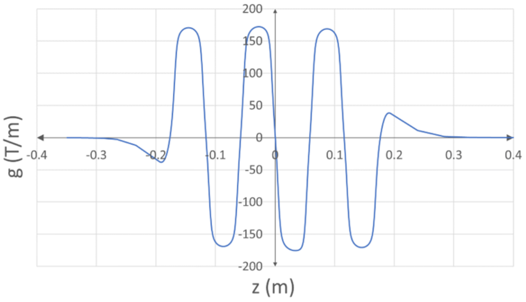

Figure 5: Field gradient g versus longitudinal direction z.

Table 1: Magnet Parameters for the Periodic Quadrupole at 4.2 K

Parameter	**Unit**	**Value**
Magnet Length	cm	39.00
Periodic length	cm	11.90
No. periods	-	3.00
Aperture radius	cm	0.70
Magnetic field gradient	T m^{-1}	170
Coils current density	A mm^{-2}	2000

Tracking the LPA electron bunches through the obtained field maps with ASTRA yields the beta functions as shown in Fig. 6.

Dispersive Section - Combined Dipoles

After exploring the periodic quadrupole's effect on the electron beam, the resulting Twiss parameters at the end

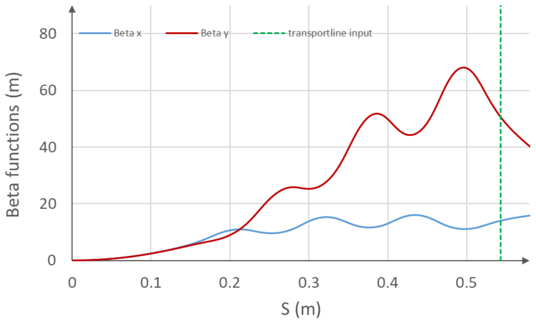

Figure 6: Beta functions β_x and β_y along beam trajectory for the optimized periodic quadrupole, [13].

of this magnet were extracted and inserted as starting parameters into the OPA software [15] to investigate the beam dynamics in the whole transport line at the design energy of 260 MeV. Using the built-in matching algorithm of OPA to fulfill the TGU input parameters, a 0.9 m long dispersive section was successfully designed for the periodic quadrupole. Adding this length to the 0.54 m long focusing section (from the LPA to the end of the periodic quadrupole), the whole transport line has a length of 1.44 m at the end of the second dipole. Figure 7 shows the magnet layout and optical functions of the whole transport line. As can be seen in Fig. 7,

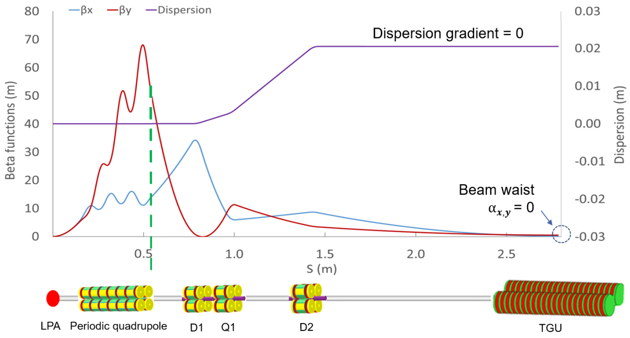

Figure 7: Magnet layout and beam optic parameters along beam trajectory at 260 MeV.

after capturing and collimating the beam with the periodic quadrupole, the electron beam goes through two combined function dipoles (dipole-quadrupole) and a pure quadrupole. The magnet specifications for the designed dispersive section are summarized in Table 2. The combined dipoles,

Table 2: Magnet Specifications at 260 MeV

Magnet	**D1**	**Q1**	**D2**
Aperture radius (cm)	0.7	0.7	0.7
Magnetic field (T)	0.27	0	-0.27
Field gradient (T m^{-1})	84.48	-136.72	19.86
Current density (A mm^{-2})	500	1000	180

especially D$_1$, with low-field and high-gradient components, can not profit from the common method of superimposing the required gradient in the pole shape. Therefore an offset quadrupole design is used in which the magnet center is moved by 3 mm with respect to the beam center and generates the required dipole field at the center as a feed-down component of the quadrupole field. To benefit from the simple coil shape of the periodic quadrupole, half a period of the periodic quadrupole was used. Also by applying magnetic shielding tubes, the unwanted magnetic fields at the two ends can be shielded. Figure 8 shows the combined dipole magnet with magnetic shielding tubes and in Fig. 9 its magnetic field profile in the longitudinal direction z is shown.

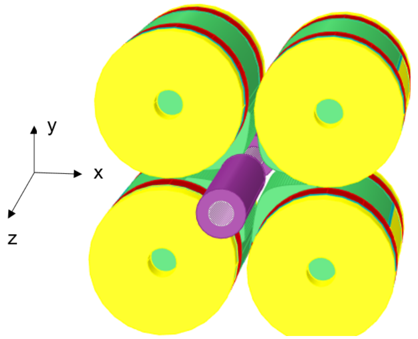

Figure 8: Combined dipole magnet model with magnetic shielding tubes around the beam chamber, colored in violet.

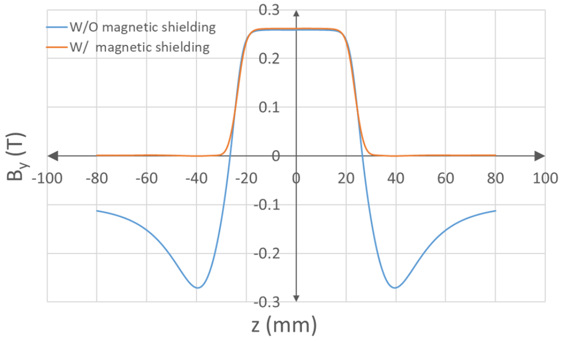

Figure 9: Magnetic field profile in the longitudinal direction at $x, y = 0$, with and without magnetic shielding

CONCLUSION

A novel periodic iron-core quadrupole magnet with simple pancake-shaped HTS coils was designed and successfully applied to the specific use case of a transport line from LPA to the TGU. The periodic quadrupole can well collimate the LPA electron beams to a designed dispersive section while the whole transport line fulfills the TGU beam optic requirements at 260 MeV. The magnet design for the dispersive section magnets was also done using half a period of the periodic quadrupole and applying magnetic shielding tubes at the magnets' ends. Moreover, to prove the concept, manufacturing a prototype and measurements at liquid helium temperature $T = 4.2$ K are underway.

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