MINIATURE, HIGH STRENGTH TRANSPORT LINE DESIGN FOR LASER PLASMA ACCELERATOR-DRIVEN FELs*

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Abstract

Laser-plasma acceleration is an outstanding candidate to drive the next-generation compact light sources and FELs. To compensate large chromatic effects using novel compact beam optic elements in the beam transport line is required. We aim at designing miniature, high strength, normal conducting and superconducting transport line magnets and optics for capturing and matching LPA-generated electron bunches to given applications. Our primary application case is a demonstration experiment for transverse gradient undulator (TGU) FELs, to be performed at the JETI laser facility, Jena, Germany. In this contribution, we present the current design of the beam transport line magnets and the beam optics calculations.

INTRODUCTION

In Laser Plasma accelerators (LPA) electrons are accelerated in the fields of a plasma wave generated by a high-power laser pulse. Electrons are pushed away from the laser propagation axis by the ponderomotive force and oscillate with the plasma frequency in transverse direction. These accelerated electron bunches can gain sufficient energies to generate synchrotron radiation in the X-ray regime within only a few millimeters to centimeters of acceleration length. Owing to these ultra-high accelerating gradients, LPAs are considered as compact sources of energetic beams for light sources [1, 2] and future linear colliders [3]. In 2004, the first production of relatively small divergence, narrow energy spread electron beams at ∼ 100 MeV from mm-scale devices was shown [4] and Subsequently in 2006, using 40 TW lasers interacting in centimeter-scale plasma channels, electron beams up to ∼1 GeV were obtained [5]. In the recent years, with the presence of petawatt-class laser systems, electron beams with multi-GeV energies from a few centimetres long plasma channels has been reported [6, 7].

The main disadvantages of Laser Plasma accelerators compared to conventional ones are the few percent energy spread and mrad divergence of the bunches which makes the bunch shaping and transport difficult. To demonstrate first gain from a laser-plasma driven FEL, one should advance and validate key components for a laser-plasma driven light source i.e. using novel undulators like the transverse gradient undulator (TGU) [8] in one hand and make use of high strength, compact beam optic components [9] on the other hand, Fig. 1.

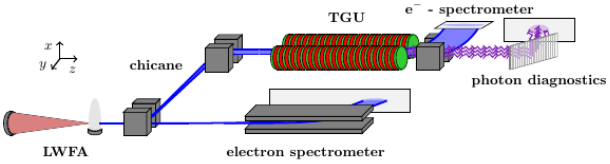

Figure 1: Sketch setup of a LPA [9].

In the transverse Gradient Undulator source, the magnetic field on transverse plane has a gradient and results in a narrow spectrum radiation [8]. In a TGU, the magnetic flux density amplitude B_y and the relativistic factor γ_e of the dispersed electron bunch in the x-z-plane, are functions of x. That leads to a modified undulator equation and matching condition.

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

Besides, to capture divergent, large-energy spread beam, a normal conducting transport line as a modification of the current 3 m set up at Jena, Fig. 2, and also a compact transport line using HTS, compact magnets are proposed.

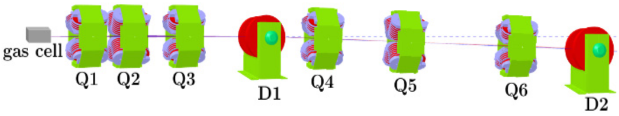

Figure 2: Schematic of the dogleg chicane setup at the LPA in Jena, Germany [9].

In this proceeding paper, the current considered designs of the beam transport line magnets and the beam optics calculations are presented.

BEAM TRANSPORT LINE

In the current design of the normal conducting transfer line, applying high strength magnets, reducing the transport line length and matching the beam dynamics to the TGU input parameters at higher energies is desired.

As it is shown in Fig. 3, the beam from the LWFA is collimated in the triplet and dispersive section with two pure dipoles and three pure quadrupoles to fulfil the TGU input parameters at the energy of 300 MeV.

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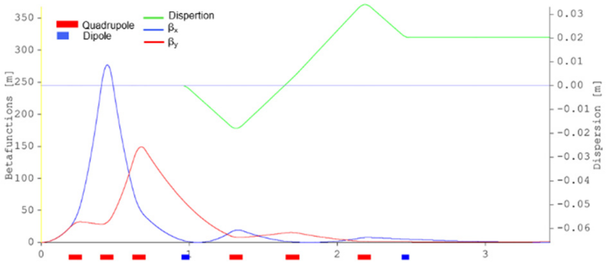

Figure 3: Magnet arrangement and beam optic parameters @300 MeV for the normal conducting transport line.

Using beam dynamic simulation codes OPA [10] and Elegant [11] and assuming a Gaussian beam with initial conditions resembling experimental data, as discussed in [9], the target conditions at the TGU are met [12]. As depicted in Fig. 3, after the second dipole and along the TGU the dispersion gradient would be zero, dispersion value is 20 mm and a beam waist at the center of the TGU is occurred. Also the transport line length is already decreased from 3 m to 2.5 m.

Triplet Quadrupoles

A triplet magnet is used for the optimum collimation in both planes. The first quadrupole is located close to the source to keep the β-functions small. The focusing strength of this quadrupole should be moderate to avoid a large defocusing effect. For keeping the beam small in the second plane the second quadrupole is placed as close as possible to the first quadrupole and the third quadrupole completes the focusing of the beam in the first plane.

Using Steel M270-50A for the yoke material, decreasing the gap radius from the previous designed 11 mm [13] to 7 mm and keeping the current density in the optimum range of 3 A/mm^2 $<j_{opt}<$ 5 A/mm^2, the maximum field gradient of these triplet quadrupole is 68 T/m, magnetic length is 80 mm and all the magnets have the same cross sections of 22 cm×22 cm. Using two and three dimensional codes POISSON [11] and Opera [14] a pole and yoke geometry was developed for these magnets and a field homogeneity of under 0.1% over a bore radius region of ±5 mm is achieved. Main parameters for the triplet quadrupoles are given in the Table 1.

Table 1: Triplet Quadrupole Parameters

Parameter	Unit	Value
Aperture radius	mm	7
Pole tip Field	T	0.476
Field gradient	T/m	68
Magnetic length	mm	80
Good field region	mm	±5
No. of turns per coil	-	412
Copper cross section	mm^2	1.5
Current	A	5.39
Current density	A/mm^2	3.6
Resistance of magnet	mΩ	138
Power consumption	W	161

Figure 4 depicts General layout and dimensions of the triplet quadrupoles, field quality and absolute multipoles' error at the radius of 5 mm are shown in Figs. 5 and 6 respectively.

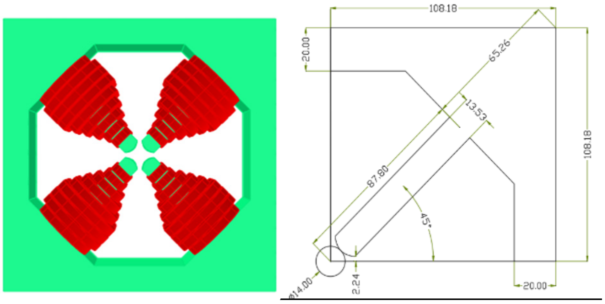

Figure 4: Magnet 3D-model and dimensions of the triplet quadrupole in mm.

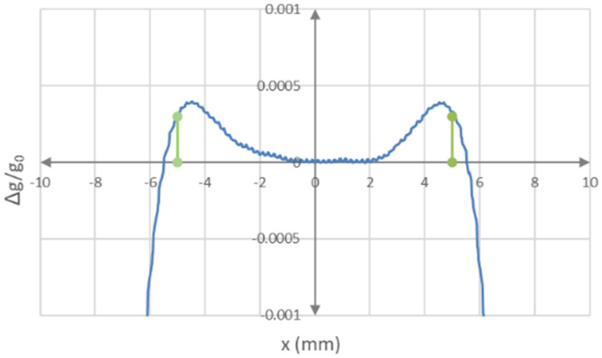

Figure 5: Field tolerance of the triplet quadrupole magnet boundaries of the good field region (±5 mm) are shown in green.

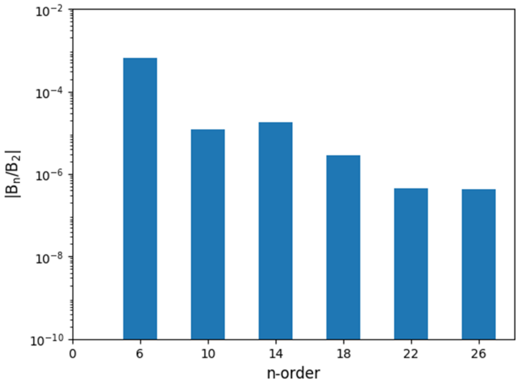

Figure 6: Absolut normalized multipoles' error at radius of 5 mm.

It is planned to make use of the available coils which were used for the Jeti small quadrupole magnets installed in the JETI laser facility, Jena, Germany. The magnets are placed in vacuum and the coils are contact-cooled by a water-cooled winding body. These coils are wound of a solid conductor copper mounted on a coil former. As it is shown in Fig. 7, the temperatures at the design current do not exceed 299 K, which is well within the margins of the safe operation.

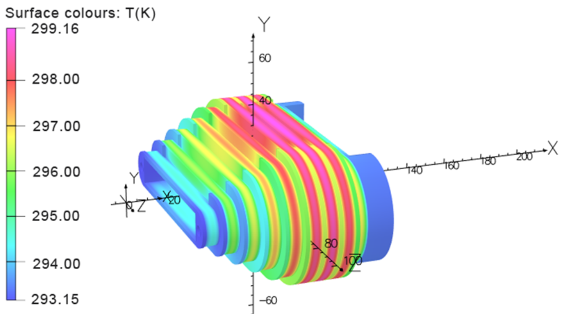

Figure 7: Heat analysis of the quadrupole coil, temperature in each part is shown in kelvin.

HTS BEAM TRANSPORT LINE

In order to have compact transport line at higher energies and reaching to the new technological approaches for using LPAs, compact, high temperature superconducting (HTS) magnets using ReBCO tapes are planned to be used in the transport line. The beam from the LPA is collimated in the triplet and then a dispersive section, two combined dipoles and a pure high strength quadrupole, fulfils the TGU input parameters at the energy of 700 MeV.

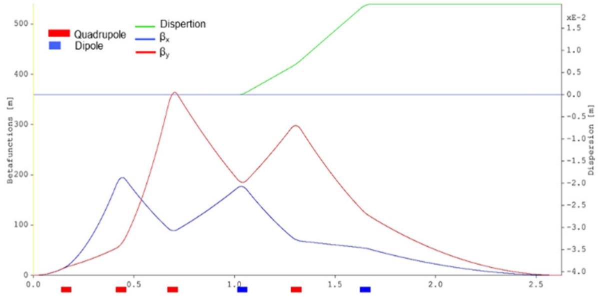

Figure 8: Magnet arrangement and beam optic parameters @700 MeV for the HTS transport line.

Applying the same initial conditions as for the normal conducting case, after the second dipole and along the TGU the dispersion gradient would be zero and a beam waist at the center of the TGU is considered, Fig. 8. Also using high strength HTS combined compact magnets leads to a decrease in transfer line length from 3 m to 1.6 m.

It should be noted that the reported results are linear beam optics calculations and the aim of the next phase of the project will be to develop beamline and magnet design strategies for handling the energy spread in these transport lines.

Triplet Quadrupoles

Having high strength super conducting triplet magnets leads to capture the divergent, large-energy spread beam in a relatively short distance. Two different choices for the high temperature super conductors were considered, BSCCO and ReBCO coated tapes. Application of ReBCO coated conductors is more widely spread as it has a higher engineering current density than BSCCO, it does not require any heat treatment and is more resistant to mechanical stress and thermal cycling [15]. In the ReBCO tapes, critical current depends on three variables Jc (B, T, α), where α is the magnetic field angle with respect to the face-normal of the crystallographic planes. Using ReBCO tape, SuperOx # 337-R type, a current density of 2000 A/mm2 at the magnetic field of 5T and temperature of 4.5 K is easily achieved. Different geometries for the HTS triplet magnets have been investigated and a 60 mm coil-based geometry which creates a field gradient up to 600 T/m has been chosen and simulated.

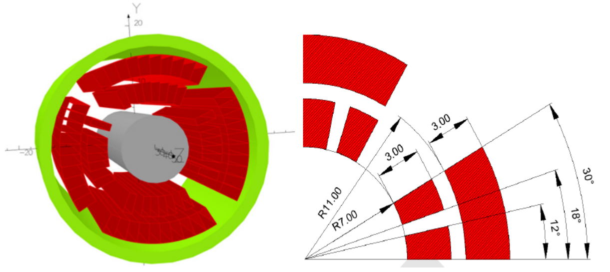

Figure 9: Magnet 3D-model and configuration of coil sectors.

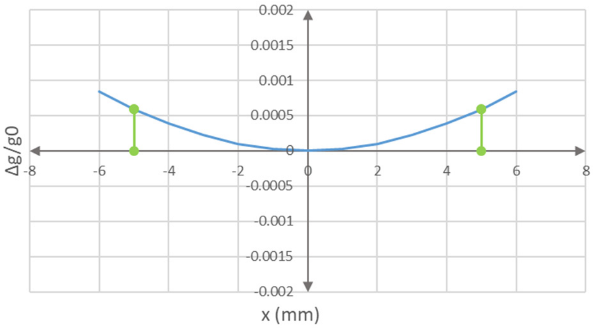

Figure 10: Field tolerances of the HTS triplet quadrupole. Magnet boundaries of the good field region (±5mm) are shown in green.

As depicted in Figs. 9 and 10, with a sector coil configuration of 12°-18°-30° in an inner bore radius of 7 mm, a field quality of less than 0.1% is achieved.

CONCLUSION

We have designed a 2.5 meter compact normal conducting transport line for energies up to 300 MeV as a modification of the current 3 m set up at JETI laser facility which is working at 120 MeV. Triplet magnets with a small gap radius of 7 mm and field gradient of 68 T/m are simulated and fabrication of these magnets has been recently started.

Also beam dynamics calculations and triplet magnets simulations for a compact HTS transport line is done. Applying small, high strength magnets, we could reduce the transport line length to 1.6 m for energies up to 700 MeV which is a good step forward for future applications. Further investigations to develop beamline and magnet design strategies for handling the energy spread would be a future task.

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