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AN UPGRADE TO THE NORMAL CONDUCTING MINIATURE TRANSPORT LINE FOR LASER PLASMA ACCELERATOR-DRIVEN FELS

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Abstract

In this contribution, we present advancements in upgrading the employed normal-conducting electron beam transport line at the JETI laser facility, University of Jena. To address spectral broadening caused by the large energy spread in laser-plasma accelerators (LPAs), a transverse gradient undulator (TGU) with an energy acceptance of $\Delta E/E_0 = \pm 10\,\%$ has been developed. Efficiently transporting the electron beam from the LPA to the TGU within this acceptance range required an optimized beam transport line as well. Phase-space analysis for single particles across this energy range revealed that earlier transport line designs at KIT exhibited a nonlinear dependence of the transverse beam position x on energy deviation, which led to complications in beam dynamics. By incorporating combined dipole-quadrupole magnets and maintaining a transport line length of approximately 3 m for 300 MeV beams, a linear relationship between the transverse position x and energy deviations was achieved, with minimal variation in the phase x' (less than 2.4×10^{-4}). This redesigned transport line meets the TGU's dispersion requirements, enabling more precise beam alignment and transport.

INTRODUCTION

Laser-plasma accelerators (LPAs) provide a compact and cost-efficient alternative to conventional accelerators, particularly when combined with transverse gradient undulators (TGUs), see [1], for free-electron laser (FEL) applications in the EUV and X-ray range.

To support this, several transport lines have been developed at KIT for varying beam energies and lengths. These include a 3 m normal-conducting line at 120 MeV [2], an upgraded 300 MeV version [3], and shorter high-temperature superconducting (HTS) beamlines at 260 MeV and 700 MeV [4,5]. The 300 MeV design used a quadrupole triplet followed by a dispersive section with two pure dipoles and three quadrupoles to satisfy TGU matching. However, nonlinear dispersion, particularly in the $x(\delta)$ correlation, was observed, reducing beam quality and transport efficiency.

This contribution presents an updated beam dynamics design that mitigates these nonlinearities using a compact magnet layout with combined-function dipole-quadrupole elements. The revised configuration achieves improved energy-position correlation and better satisfies the TGU acceptance conditions.

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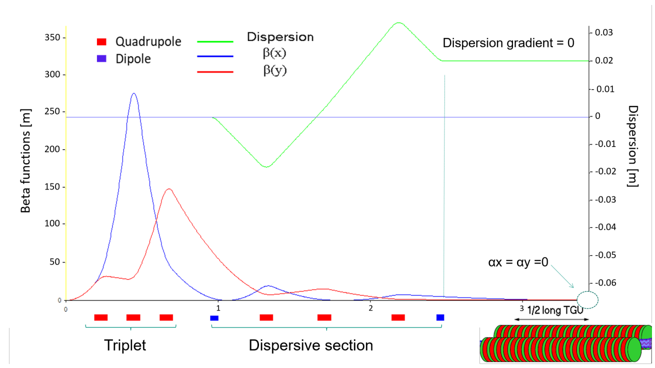

Figure 1: Layout of the lattice and optic parameters at 300 MeV [3].

BEAM TRANSPORT LINE

As shown in Fig. 1, the previous transport line included a quadrupole triplet and a dispersive section composed of two pure dipoles and three quadrupoles. Single-particle tracking simulations using `elegant` [6] across an energy range of 270 MeV to 330 MeV revealed significant nonlinear dispersion $x(\delta)$ and angular deviations x' (up to 5×10^{-3} rad), as illustrated in Fig. 2.

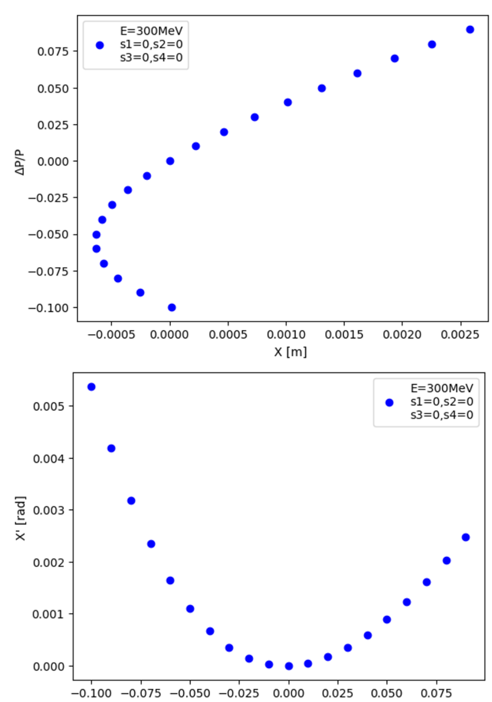

Figure 2: Single-particle tracking results for the previous transport line at 300 MeV.

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Repeating the simulations for the 120 MeV optics confirmed that these nonlinear effects are intrinsic to the beamline layout. To mitigate this, two sextupole magnets were introduced at locations of minimum and maximum dispersion (Fig. 3). Manual tuning of their strengths ($s_1 = -6500\,\mathrm{m}^{-3}$, $s_2 = 3000\,\mathrm{m}^{-3}$) improved the linearity of the dispersion function, though residual angular deviations persisted (Fig. 4).

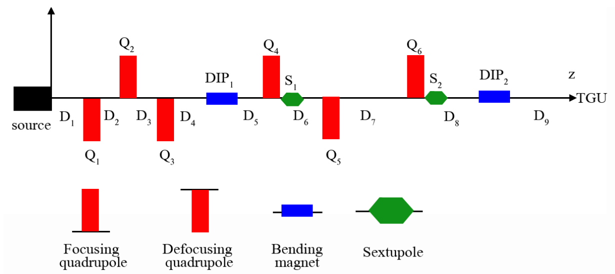

Figure 3: Sketch of two sextupoles S1 and S2 added at the minimum and maximum of the dispersion function.

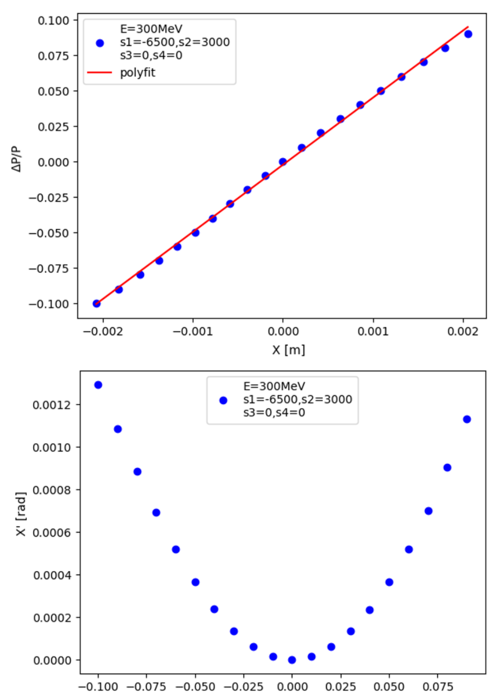

Figure 4: Single-particle tracking results after adding S1 and S2.

As a result, using the OPA software [7], a new beamline design was developed incorporating magnets with combined functions in the dispersive section. The revised layout, shown in Fig. 5, consists of a focus triplet followed by a dispersive section with a central quadrupole positioned between two dipole-quadrupole magnets. This configuration is optimized to meet the TGU matching requirements at 300 MeV.

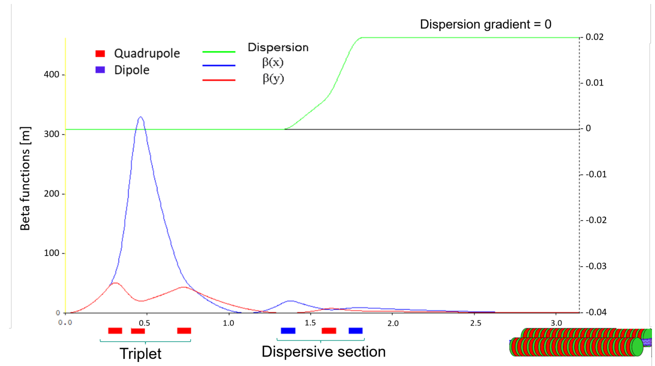

Figure 5: Layout of the newly designed transport line optics at 300 MeV, including combined-function magnets.

The updated transport line exhibits significantly improved performance in a shorter length: the dispersion function is linear and the angular deviations are reduced to below 2.4×10^{-4} rad, as shown in Fig. 6. This value is within the tolerance range of the TGU, i.e., on the order of 10^{-4} rad [8].

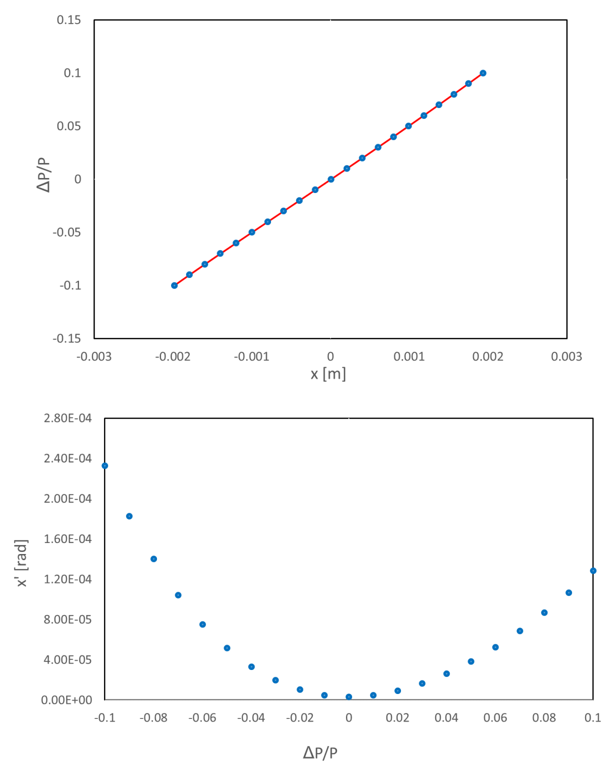

Figure 6: Single-particle tracking results for the updated transport line.

MAGNETS

As shown in Fig. 5, the transport line collides with the LPA beam using a quadrupole triplet. The first magnet Q_1 provides horizontal defocusing and vertical focusing, which is compensated by the nearby focusing quadrupole Q_2. The

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Table 1: Magnet Specifications for the Transport Line at 300 MeV

Magnet	Length (m)	Deflection Angle (°)	k (m^{-2})
Q_1	0.086	–	-83.958
Q_2	0.086	–	85.2458
Q_3	0.086	–	-35.767
D_1	0.086	1.8	78.574
Q_4	0.086	–	-77.154
D_2	0.086	-1.8	30.000

third quadrupole Q_3 completes the focusing system to create a beam waist at the position of the first dipole. The dispersion of the energy that matches the TGU is generated by two combined function dipoles, D_1 and D_2, which have opposite bending directions and embedded quadrupole components. The bending angles are adjusted to provide a dispersion of 20 mm at the entrance of the TGU. All magnets are 86 mm long, with the strongest focusing field in Q_2 at 85.24 m^{-2}, corresponding to a gradient of 85.24 T m^{-1} at 300 MeV. The full list of magnet parameters is provided in Table 1.

The quadrupoles Q_1–Q_4 in the beamline are pure magnets and can be reused from existing magnets already fabricated at KIT [9]. For dipole-quadrupole magnets (D_1, D_2) in the dispersive section, the required magnetic field values at a beam energy of 300 MeV result in a dipolar field of 0.36 T and field gradients of 78.6 T m^{-1} for D_1 and 30.0 T m^{-1} for D_2.

Magnet Design

Conventional combined-function dipole magnets typically employ a non-uniform pole gap to introduce a weak quadrupole component. However, the designed beamline requires a combination of low dipolar fields and relatively high quadrupole gradients, which cannot be achieved using traditional methods. Therefore, a novel geometry based on an offset quadrupole approach with an auxiliary pole, similar to those implemented in the ESRF-EBS and Diamond Light Source upgrades, was considered. A preliminary magnet design was performed using the CST software [10], utilizing the existing quadrupole magnets available at KIT, which feature a narrow pole profile, see Fig. 7. Although the desired dipolar field and field gradient can be achieved with this configuration, the asymmetric geometry inherently introduces an undesired sextupole component. In particular, the limited pole width of the main quadrupole section makes it challenging to meet the magnetic field quality requirements within the shifted good-field region. As a result, further modifications to the combined-function dipole design are currently in progress to improve field homogeneity and suppress higher-order multipole errors.

CONCLUSION

A compact beam transport line has been designed to deliver LPA-generated electron beams to a transverse gradient undulator at 300 MeV. Initial designs showed significant non-linear dispersion and angular deviations, which could not be adequately corrected by using sextupole elements. To address this, a new beamline configuration was developed using combined-function dipole-quadrupole magnets in the dispersive section. The final layout achieves linear dispersion and reduces angle deviations to below 2.4×10^{-4} rad, meeting the acceptance criteria of the TGU.

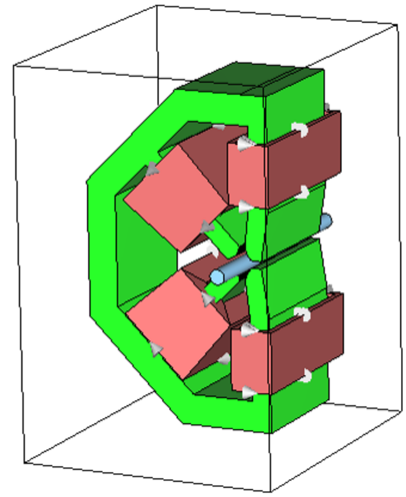

Figure 7: A primary design of the dipole-quadrupoles [10].

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