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FIRST TESTS OF A BEAM TRANSPORT SYSTEM FROM A LASER WAKEFIELD ACCELERATOR TO A TRANSVERSE GRADIENT UNDULATOR*

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Abstract

An experimental setup for the generation of monochromatic undulator radiation at the laser wakefield accelerator (LWFA) in Jena using a transverse gradient undulator (TGU) is planned. Proper matching of the betatron functions and the dispersion of the electron beam to the undulator is essential. Therefor a beam transport system with strong focusing magnets and chromatic correction of the magnets is required.

As a first step, a linear beam transport system without chromatic correction was assembled at the LWFA. With this setup the electron beam's dispersion and the beta function of one selected energy are matched to the required parameters at the TGU. This contribution presents the experimental results of these measurements.

INTRODUCTION

A challenging but essential part of any experimental setup at a laser wakefield accelerator (LWFA) is the beam transport system. One has to match the electrons of the LWFA to the parameters required by the experiment. Due to the relative energy spread of the LWFA-generated bunches of some percent a chromatic correction is necessary. At the same time the large initial divergence of some milli-radian required strong focusing with compact magnets.

For the generation of monochromatic undulator radiation at the LWFA using a transverse gradient undulator (TGU) a dogleg chicane is required for matching the beam parameters and the dispersion. In the chicane the electron bunch is dispersed in the deflection plane of the undulator, i.e. the x-z-plane, and the resulting lateral distribution of the electron energy is matched to the flux density amplitude $B_y(x)$ of the undulator with a transverse gradient dB_y/dx. So a broadening of the radiation spectra is prevented such that electrons of different energies emit radiation at the same wavelength [1, 2].

Several studies were performed to optimize the layout of a beam transport system to the TGU [3, 4]. In this measurement campaign such a beam transport system was set up to demonstrate that it is possible to transport a LWFA-generated bunch with a complex transport system and to match the beam parameters required for the undulator. As a first step a linear system was assembled consisting of six quadrupoles to focus the beam and two dipoles for generating the dispersion. The transverse beam profiles were measured with scintillating screens. For measuring the spectra an electron spectrometer was integrated in the setup.

In this contribution the results of a first experiment are presented. The parameters of the LWFA and of the magnets and the alignment procedure is described in the next section. Thereafter some magnet configurations and the measured beam profiles are presented and compared to simulations performed with *elegant* [5] and MADX [6].

EXPERIMENTAL SETUP

The experiment was performed at the JETI-40 laser system in Jena. The laser pulse with an energy of 700 mJ and a pulse duration of 27 fs was focused by a f/12 off-axis parabolic mirror to a spot size of 12 μm^2 (FWHM). This results in a peak intensity of $I_L = 9.1 \cdot 10^{18}$ W/cm^2. The target was a gas cell of 3.0 mm length. A gas mixture of 95% helium and 5% nitrogen was used.

The beam transport system consisted of six in-house built quadrupoles [7] installed inside the vacuum chamber and two commercially available dipole magnets [8], which were inside an air-box as they are not designed for in-vacuum use. A sketch of the setup is shown in Fig. 1. The yoke length of the quadrupoles is 80 mm and the gradient at the maximum current of 5 A is 35 T/m for the quadrupoles with the slightly larger size (Q2 and Q5) and 29 T/m for the quadrupoles with the more compact design (Q1, Q3, Q4 and Q6). The dipoles with rectangular pole shape and a pole length of 50 mm have a maximum field of 460 mT.

All quadrupoles are mounted on motorized vertical translation stages for alignment in x, the deflection plane. The four compact quadrupoles have an additional horizontal translation stage for alignment in y. Quadrupole four to six are inclined by the deflection angle of 24.5 mrad. The dipoles are mounted at a fixed height without inclination.

For measuring the electron beam profile a scintillating screen, which was placed under an angle of 45° to the beam axis, could be placed at three different positions along the beam line at 0.7 m, 1.8 m and 2.9 m distance from the electron source (marked as screen 1 to 3 in Fig. 1).

The electron spectrometer consists of a permanent dipole magnet, which deflects the electrons to a scintillating screen. The range corresponding to an electron energy of 3 MeV to

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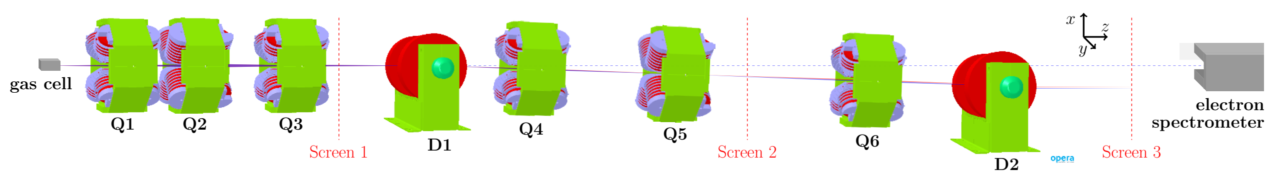
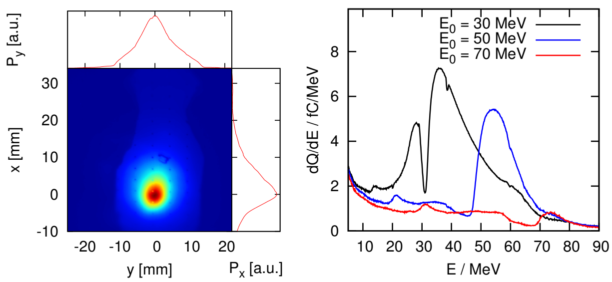


Figure 1: Sketch of the setup with six quadrupoles and two dipoles. The beam profile was measured with scintillating screen 1 to 3, the energy distribution with the electron spectrometer.



(a) beam profile (b) energy distribution

Figure 2: (a) Beam profile of the unfocused beam measured on screen 1 with the projection P on both axes. (b) Spectra of the electrons for three different configurations of Q1 to Q3 focusing a certain energy range to the spectrometer.

150 MeV was covered with two 12-bit CCD cameras with partly overlapping field view. The entrance of the spectrometer magnet is at 3.3 m distance from the source and has an aperture of 20 mm in x and 10 mm in y.

Alignment of the Quadrupoles

For the beam based alignment of Q1 and Q2 the electron beam was focused by the quadrupole to be aligned in each transverse plane, so a line focus was observed on screen 1. The quadrupole position was corrected until the line focus matched the position of the beam axis. This procedure was repeated for the other polarity of the quadrupole.

For aligning Q3 to Q6 it was necessary to focus the beam on either screen 2 or 3 with the first doublet to get a measurable signal. Again the quadrupole was shifted in x- and y-direction until the line focus matched the beam axis.

RESULTS OF THE MEASUREMENTS

The parameters of the unfocused electron bunches emitted by the LWFA were determined at the position of the first screen (see Fig. 1). The average of 202 single bunches is taken, where 21 images are neglected due to low bunch charge or a diffuse beam profile. The averaged beam profile is shown in Fig. 2a. The divergence of the averaged profile in x is 10.6 mrad (FWHM) and in y 9.6 mrad (FWHM). Considering single bunches the divergence is significantly lower with 4.9 mrad in x and 6.9 mrad in y. The reason for this difference is the pointing of the single bunches which varies with 4.2 mrad in x and 2.4 mrad (rms) in y. In contrast the averaged beam profiles changed little during the measurement so only they were considered for the evaluation.

For measuring the energy distribution of the electron bunches the triplet of Q1 to Q3 was used to focus certain energies to the screen of the spectrometer. The averaged distributions of 60 images for three different magnet configurations are shown in Fig. 2b. According to the spectra measured for the three different cases, the bunches had a broad energy distribution with a maximum in the range of 25 MeV to 45 MeV or even below.

Focusing of the Electrons

In Fig. 3 the averaged beam profiles for three different magnet configurations are shown: Fig. 3a shows the beam profile near a focus for an energy of 60 MeV on the second screen. In Fig. 3b the beam is deflected by the two oppositely poled dipoles with a deflection angle of 24.5 mrad and the optics focus a central energy of 40 MeV on the third screen. In Fig. 3c the beam profile for the optics, which match the required conditions at the entrance of the undulator for 40 MeV, is shown. For each beam profile the projection P on both axes and a cut C through the maximum is shown. The position and strength of the magnets and the beta functions are indicated in the plots above the beam profile. For the calculation of the beta functions initial values of $\beta_{x,y} = 0.005$ m and $\alpha_{x,y} = 0$ are assumed.

None of the beam profiles shows a perfect focus as expected at least in Fig. 3a and Fig. 3b. In contrast, all of the profiles show noticeable lines in horizontal or vertical direction. The maximum itself has a slight diamond shape. All of this might be caused by the relatively large divergence of the source, which was underestimated in the design of the transport system, the energy spread of the bunches or a misalignment of the magnets. To analyze the profiles, tracking simulations with a variation of the source parameters and the energy spread of the bunches were performed with *elegant*.

The influence of the source parameters on the setup of Fig. 3a is shown in Fig. 4 a-c. The profile in a shows a beam with the source divergence of 1 mrad (rms), the value initially assumed when designing the transport line. However, the divergence of the unfocused beam during the measurements was $\sigma_{y'} = 3.4$ mrad in the horizontal and $\sigma_{x'} = 3.8$ mrad in the vertical plane. Profile b is simulated with the measured source divergence. An increase of the beam size along both axes is observed. As the unfocused beam profile is not

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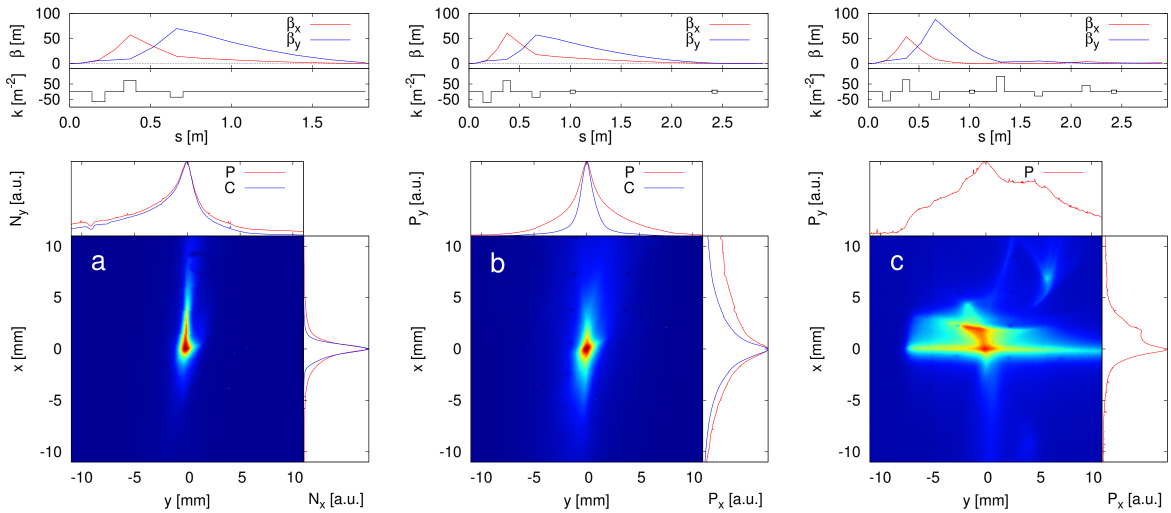

Figure 3: Measured beam profiles with a projection P on and a cut C along each axis. The quadrupole strength k the position of the dipoles and the betafuncions are depicted for each setup with $\beta_0 = 0.005$ m and $\alpha_0 = 0$. (a) Focus of 60 MeV on the second screen; (b) focus of 40 MeV on the third screen with deflection by the dipoles; (c) parameters necessary for the operation of the undulator at 40 MeV.

symmetrical along the x-axis (see. Fig. 2a) this asymmetry seems to influence all observed profiles of Fig. 3.

Increasing the energy spread from $\sigma_E = 0.1\%$ to 3%, the simulated profile in Fig 4c shows the same characteristics as the measured profile: the vertical line, the diamond shaped maximum and the horizontally slightly stretched center. The discrepancy might still be caused by misaligned magnets, but also the asymmetric beam profile of the source.

The simulated profile in Fig. 4d for the second setup (see Fig. 3b) again shows the same characteristic as the measured profile apart from the weaker smearing along the vertical axis to higher values. For negative values of x the smearing is

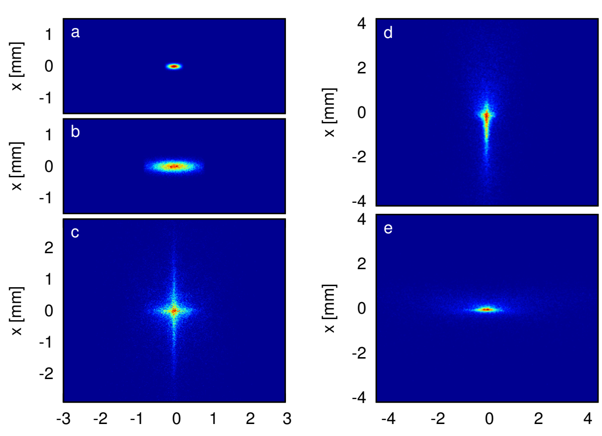

Figure 4: left: Simulated beam profiles at the position of screen 2 with (a) $\sigma_{x',y'} = 1$ mrad, (b) the measured source divergence and (c) additionally an energy spread of $\sigma_E = 5\%$; right: simulated beam profiles on screen 3 with the measured divergence and 5% energy spread with (d) setup of Fig. 3b and (e) setup of Fig 3c.

caused by the deflection of the electrons in the energy range below the central energy by the oppositely poled dipoles.

The last profile in Fig. 3c now shows a stronger discrepancy from the simulated profile in Fig. 4e. A horizontal line with a slight maximum in the center would be expected, but there is a second maximum above the beam axis, which is probably caused by alignment errors.

The measurements have shown that in general it is possible to transport and shape the beam originating from a LWFA. However, the divergence of some milliradiant and the significant energy spread deteriorate the profile considerably. To improve the beam transport system a more accurate alignment procedure, an aperture to reduce the source divergence and an energetic filter should be included in the setup.

SUMMARY AND OUTLOOK

In this contribution first tests of the linear beam transport system at the LWFA in Jena were presented. The size of the foci and the shape of the beam profile did not match the expected values, as the parameters assumed for the design of the transport system were different from the source parameters measured. With an adaption of these parameters in the simulations the measured beam profiles can be reproduced. Apart from that it can be concluded that the alignment procedure has to be improved. The test of the different components, especially the magnets, was successful and it was shown that in general beam based alignment of the quadrupoles is possible.

For subsequent measurements it is planned to improve the LWFA in terms of stability from bunch to bunch and higher electron energies. Furthermore, an aperture to limit the divergence and an energy filter to narrow the energy range could be applied.

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