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Electron beam final focus system for Thomson scattering at ELBE

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ABSTRACT

The design of an electron beam final focus system (FFS) aiming for high-flux laser-Thomson backscattering X-ray sources at ELBE is presented. A telescope system consisting of four permanent magnet based quadrupoles was found to have significantly less chromatic aberrations than a quadrupole doublet or triplet as commonly used. Focusing properties like the position of the focal plane and the spot size are retained for electron beam energies between 20 and 30 MeV by adjusting the position of the quadrupoles individually on a motorized stage. The desired ultra-short electron bunches require an increased relative energy spread up to a few percent and, thus, second order chromatic effects must be taken into account. We also present the design and test results of the permanent magnet quadrupoles. Adjustable shunts allow for correction of the field strength and compensation of deviations in the permanent magnet material.

For a beam emittance of 13 mm mrad, we predict focal spot sizes of about 40 μm (rms) and divergences of about 10 mrad using the FFS.

1. Introduction

For the development of ultra-fast laser-Thomson backscattering X-ray sources [1] as PHOENIX (PHOton Electron collider for Narrow bandwidth Intense X-rays) at Helmholtz-Zentrum Dresden-Rossendorf (HZDR), high charge densities and high laser intensities are required due to the small Thomson interaction cross-section. Both, the transverse (beam size and divergence) and the longitudinal electron beam parameters (bunch length and energy spread) influence the emission characteristics of the Thomson X-ray pulses, i.e., the spectral shape and bandwidth, the flux and the pulse duration. Hence, it is crucial to control the 6D phase space distribution of the electron bunch, starting from the thermionic injector, during acceleration in the RF cavities, longitudinal bunch compression in the magnetic chicane and focusing onto the interaction point. The goal of this study, focusing on the electron beam final focus system, is the increase of the electron density in the interaction volume with the focused high intensity laser pulse by means of matching beam sizes and reduction of bunch length. Ultimately, this will lead to a higher X-ray flux and peak brilliance of the PHOENIX source. A higher photon flux will also enable the characterization of harmonic features of the emitted radiation in the nonlinear regime at higher laser intensities.

2. Longitudinal bunch compression

The ELBE beamline and the longitudinal bunch compression scheme are illustrated in Fig. 1. A thermionic injector provides bunches with 77 pC charge of 250 keV and two superconducting LINACs accelerate the electron beam to final energies of 20–30 MeV. For longitudinal bunch compression, there are two magnetic chicanes available. The first chicane stretches the bunch from 2–3 ps to about 5 ps to support chirping in the second LINAC. After compression of the chirped beam in the second chicane (momentum compaction factor $R_{56} < 0$), a 40 m long transport line guides the electron beam to the laser interaction chamber. We aim at 1 ps bunch length at the interaction point. In order to obtain realistic input parameters for the design of the final focus system, we have studied the beam transport with start-to-end simulations by use of the tracking codes ASTRA [2] and ELEGANT [3].

3. Final focus system

For optimizing the spatial overlap with the laser spot, we have developed a new electron beam final focus system yielding smaller spot sizes than the ones previously achieved by Jochmann et al. [4] using a triplet system. Due to the longitudinal bunch compression, the transverse beam dynamics are affected by the increased energy spread. This applies especially for the final focusing, where strong quadrupole magnets are needed.

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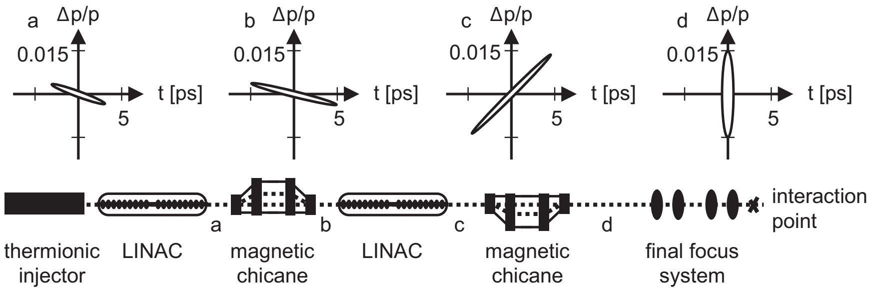

Fig. 1. Sketch of the ELBE accelerator and the longitudinal bunch compression scheme. The longitudinal phase space ellipses show the bunch length reduction and the increase in energy spread due to chirping in the second LINAC. Characteristic positions are (a) after the first LINAC, (b) after stretching in the first chicane, (c) after acceleration and chirping in the second LINAC, (d) after compression in the second chicane.

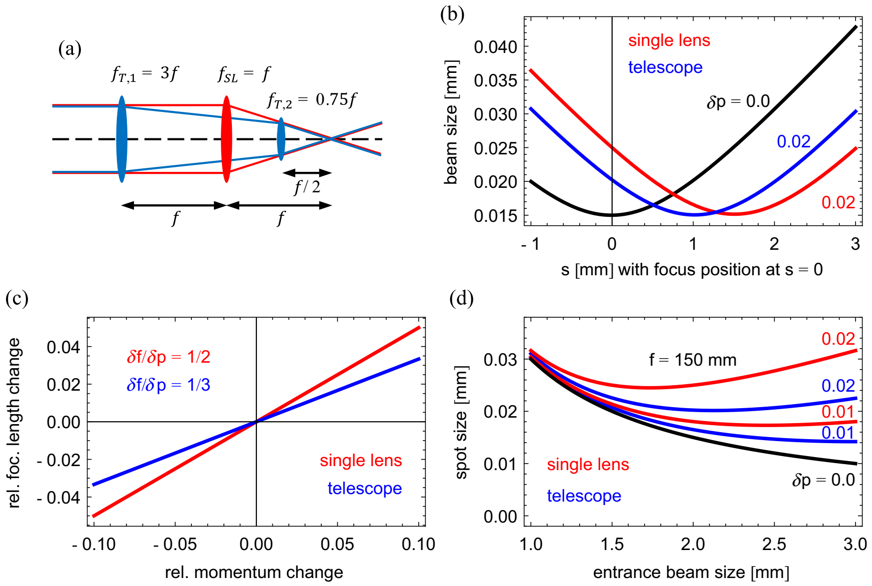

Fig. 2. Comparison of telescope (blue) and single lens (red) in a thin lens model. The telescope has less chromatic aberrations than a single lens. (a) Schematic setup, (b) shift of waist position for off-momentum particles, (c) focal length changes depending on momentum change, (d) spot size on target for different FFS entrance beam sizes and momentum spreads. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

In the following section, we discuss and compare the chromatic aberrations of different electron beam final focus systems. For this comparison, a thin lens model was applied to explain the conceptual design improvements we have implemented. For detailed description of the developed system, full beam transport with a higher order simulation code is performed in a second step.

3.1. Thin lens model including chromatic aberrations

The thin lens model is commonly used in linear beam optics. We extend this model with a momentum dependent term and thereby obtain a simple model including chromatic aberrations. Beam transport matrices in first order (R) are well known, second order terms (T) are listed in the report by Brown [5]. Within the thin lens approximation, all but one term vanish for a focusing quadrupole with focal length f: $T_{216} = 1/2f$. This allows combining first and second order matrices by adding the momentum term $\delta p/2f$ to the first order R_{21} term.

$$\text{Drift section}: \ \mathbf{M_D} = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \text{ and thin lens}$$

$$: \ \mathbf{M_{TL}} = \begin{pmatrix} 1 & l \\ -\frac{1}{f} + \frac{\delta p}{2f} & 1 \end{pmatrix} \qquad (1)$$

For beam transport the beam matrix B with the Twiss parameters α and β and $\gamma = (1+\alpha)/\beta$ is defined as

$$\mathbf{B} = \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \qquad (2)$$

and transformed in the following form:

$$\mathbf{B_1} = \mathbf{M} \cdot \mathbf{B_0} \cdot \mathbf{M^T}. \qquad (3)$$

We assume a parallel input beam ($\alpha = 0$) and take a single lens with the focal length $f = 0.15$ m. Two lenses (telescope) with $f_{T,1} = 3f$ and $f_{T,2} = 0.75f$ in a distance of $1.5f$ from each other yield the same imaging as illustrated in Fig. 2(a). However, they show less chromatic aberrations as shown in the following. We have plotted the beam waists for both systems comparing the beam waist position of an off momentum beam or beam part in Fig. 2(b). For the single lens and a beam with an entrance beam size of 2 mm, a normalized emittance of 10 μm and a relativistic γ of 50, a 2% variation in momentum leads to 1.5 mm shift in focus position. The shift is reduced to 1 mm for the telescope lens system for same parameters. Plotting the relative changes of the focal length over the change in momentum for both systems, one can easily see the reduced slope for the telescope system in Fig. 2(c). This corresponds to reduced chromatic aberrations of the system. A truly second order achromatic system would show a plateau (zero slope) in a certain range of the design energy.

For Thomson scattering applications, it is important to obtain a good spatial overlap of the laser and electron beam. Here, the chromatic aberrations of the final electron beam focusing system

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