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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 triplet. This allows sub-ps electron beam focusing to match the laser spot size at the interaction point. 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. Since the electron beam is chirped for bunch compression upstream, the rms energy spread is increased to one or two percent and second order chromatic effects must be taken into account. For an emittance of 13 π mm mrad, we predict rms spot sizes of about 40 μm and divergences of about 15 mrad.

We also present the design of the permanent magnet quadrupoles to be used for the FFS. Ferromagnetic poles ensure a high field quality and adjustable shunts allow for fine adjustment of the field strength and compensation of deviations in the permanent magnet material.

INTRODUCTION

For the development of laser-Thomson backscattering x-ray sources at HZDR, promising experiments have been performed [1] and important upgrades of the laser system as well as the electron accelerator facility are on the way. In this paper, we concentrate on the FFS as a third important upgrade. Both, the transverse beam parameters (beam size and divergence) and the longitudinal 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 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, compression in the chicane and focusing onto the interaction point.

BUNCH COMPRESSION

The ELBE beamline is illustrated in Fig. 1. The first element is the thermionic injector, providing 77 pC bunches of 250 keV. Two superconducting LINACs accelerate the electron beam to final energies of 20 to 30 MeV. For longitudinal bunch compression, there are two c-chicanes available. The first chicane stretches the bunch to support chirping in the second Linac. After compression in the second chicane, a 40 m long transport line guides the electron beam to the laser interaction chamber. We refer to [2] of this conference for more detailed information on the bunch compression scheme. Some representative longitudinal phase space distributions computed with ELEGANT [3] are plotted in Fig. 1a-e.

FINAL FOCUS SYSTEM

The main drawback of the bunch compression is the increase in energy spread, which is typically between one and two percent and therefore causing chromatic aberration in the FFS. In the following section, we discuss the beam optics of the FFS and the considerations towards chromatic aberrations.

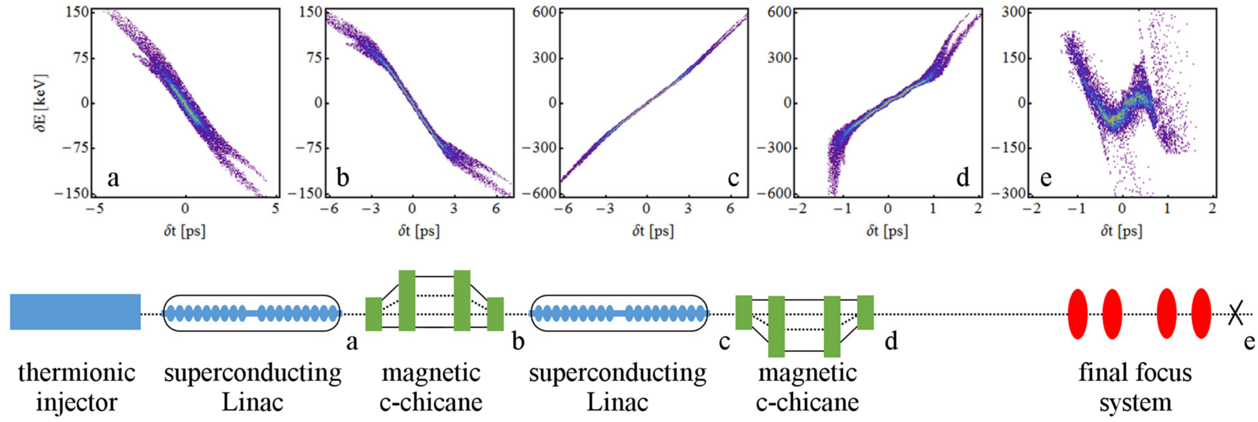

Figure 1: ELBE beamline at HZDR. The longitudinal phase space distributions indicate the functionality of the bunch compression scheme.

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Triplet vs. Telescope System

The simplest focusing system for parallel-to-point-focusing is a quadrupole triplet, which corresponds to a single thin lens in a 2D model. Adding a second thin lens or another quadrupole respectively, leads to a telescope system. Comparison of both systems in a 2D thin lens model shows a significant reduction of chromatic aberrations for the telescope system, which makes it the preferred system over the triplet.

First order matrices of drift sections and thin lenses are modified to include the energy spread in a semi second order model. The only second order matrix element of a thin lens is $T_{216} = -1/f$, drift sections do not show any second order terms. This allows combining first and second order matrices by adding the energy spread to the R_{21}- term:

$$M_D = \begin{pmatrix} 1 & l \\ 0 & 1 \end{pmatrix} \text{ and } M_F = \begin{pmatrix} 1 & 0 \\ -\frac{1+\delta E}{f} & 1 \end{pmatrix}. \quad (1)$$

Hence, the beam matrix $B = \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$ transforms like in first order:

$$B_1 = M \cdot B_0 \cdot M^T \quad (2)$$

In this basic model, we exemplarily show the reduction of chromatic aberrations for the two systems in Fig. 2 and $f = 0.15\text{m}$ for different entrance beam sizes and for different energy spreads (see Fig. 3). This comparison also points out the trade-off between first order focusing properties (black curve) and additional chromatic aberrations, which show inverse dependency on the entrance beam size.

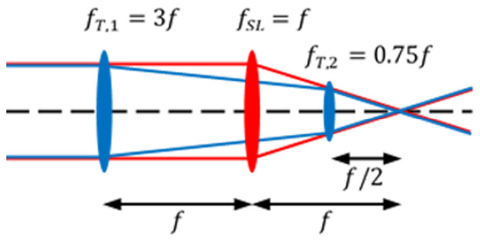

Figure 2: Schematic setup of telescope (blue) and single lens (red).

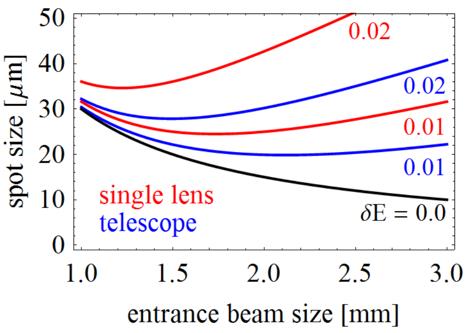

Figure 3: Comparison of single lens and telescope.

Beam Optics of FFS

Obviously, permanent magnet based quadupoles have a fixed field. However, mounting them on a motorized linear stage with individual motors for three out of four quadrupoles (Fig. 4) will enable us to adjust the overall focusing strength for beam energies between 20 and 30 MeV. This energy range is chosen based on the most stable operation of the ELBE linear accelerator.

We have studied the range of movement and effects of fringe fields with TRANSPORT [4]. Due to the compact FFS design, fringe fields are overlapping and have to be superposed. Simultaneously modelling two of the quadrupoles in Opera [5] verifies that this superposition is still in the linear regime. Therefore, it is sufficient to take line scans of the single quadrupoles' gradients and superpose them in a continuous model in TRANSPORT (Fig. 5).

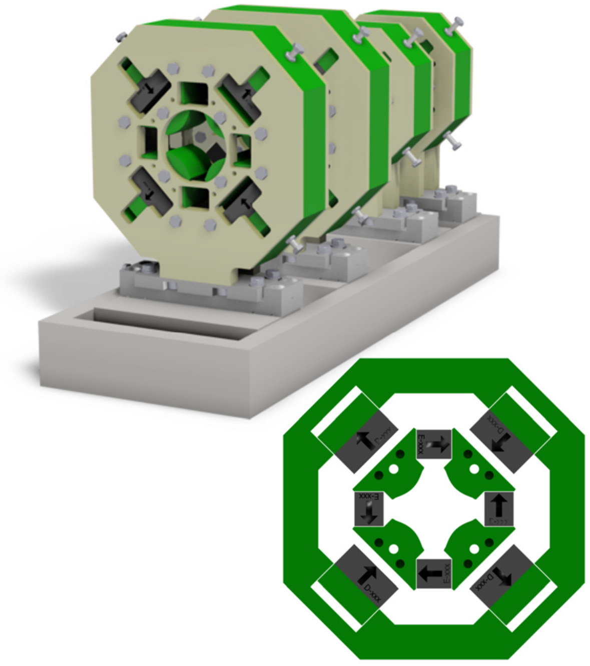

Figure 4: Overall design of telescope FFS.

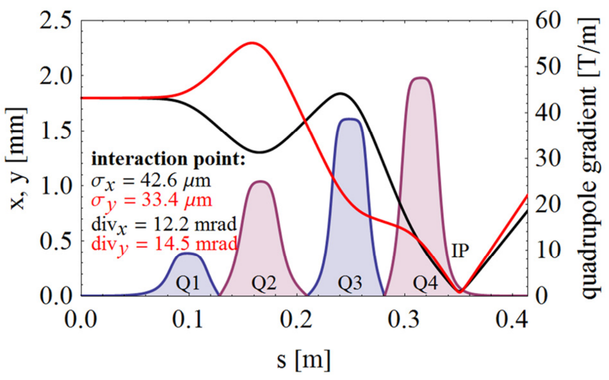

Figure 5: Final focus system with continuous gradients from 3D models, emittance= 13π mm mrad, $\delta E = 0.01$.

MAGNET DESIGN

In the following, we present the main features and design considerations of the permanent magnet quadrupoles.

Ferromagnetic poles are assembled to the yoke with two aluminium end plates. The yoke is machined in one piece and the poles are wire-cut after assembly. Openings in the end plates allow for inserting the permanent magnet material, the ferromagnetic shunt and shim foils for tuning. Additional permanent magnet blocks are placed between the poles to further increase the quadrupole gradient. We have chosen Sm2Co17 as the permanent magnet material due to its radiation hardness.

The ferromagnetic poles ensure low harmonic content and little sensitivity to deviations of the magnetization angle (Fig. 7). Variations of remanence, magnetization angle, dimension and relative permeability of the magnet blocks result in deviations of the quadrupole gradient and the position of the magnetic center. Both can be corrected by adjusting the shunt in the conservatively chosen range of ±5 % of the quadrupole gradient.

The poles are chamfered to reduce the integrated dodecapole (3D effect). The chamfer depth is 17% of the aperture radius at an angle of 45° and the resulting integrated dodecapole is 0.5 units (parts in 10^{-4} of the field gradient).

The magnets have been design in 2D and 3D with the simulation software Opera. Harmonic content is obtained by Fourier analysis of the radial field component on a circle in 2D and on the surface of a cylinder in 3D respectively.

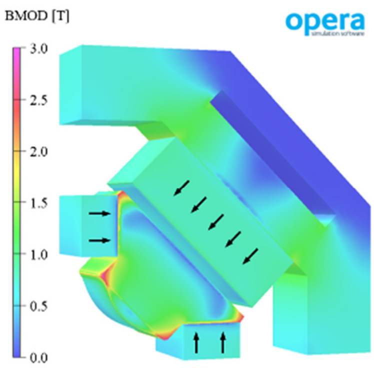

Figure 6: 3D field map of the magnet surface.

Table 1: Quadrupole Specifications

Name		Q1 / Q2 / Q3 / Q4
Mechanical pole length	mm	30
Aperture diameter	mm	30 / 30 / 20 / 20
Integrated gradient	T	0.420 / -1.094 / 1.539 / -1.881
Good field radius	mm	9 / 9 / 6 / 6

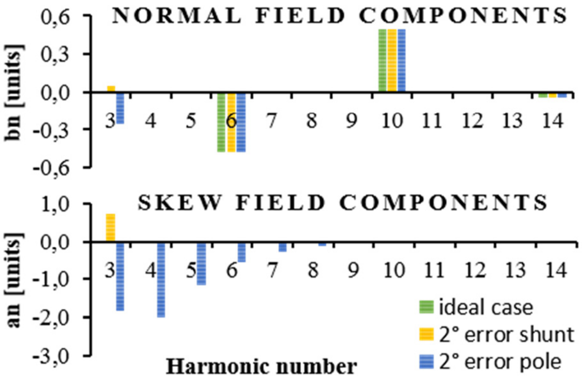

Figure 7: Higher harmonics computed in 2D for ideal case and for errors of 2° in the magnetization angle in units.

There have also been alternative solutions for permanent magnet quadrupoles in the laser plasma community [6], mainly based on the Halbach design. However, the presented design exceeds in field control, easy adjustability and potentially improved radiation hardness due to the higher work point of the permanent magnet material.

CONCLUSION

We have presented a compact final focus system for low energy electron beams, which is optimized for reduction of chromatic aberrations. The permanent magnet based quadrupoles convince with their low harmonic content and adjustability in strength. We will manufacture and test the system at Danfysik and commissioned it at HZDR within the next year.

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