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DEVELOPMENT AND LABORATORY VALIDATION OF A PRECISE ALIGNMENT SETUP FOR ELECTRON BEAM-BASED THZ RADIATION GENERATION AT EUROPEAN XFEL

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Abstract

We present the development and laboratory testing of an alignment setup for the STERN experiment at the European XFEL, aimed at exploring beam-based THz radiation generation methods using Cherenkov waveguides. The setup employs an alignment laser to simulate the electron beam trajectory, enabling the accurate positioning of critical components, such as a copper block housing dielectric waveguides. The alignment process involves scintillator screens placed before and after the vacuum chamber to measure the electron beam trajectory, with the alignment laser subsequently adjusted to replicate this path. The experimental validation focused on the reproducibility of alignment under simulated operational conditions, testing the positioning and movement of mirrors, and ensuring the stability of the alignment system for the critical components.

INTRODUCTION

Users at the European XFEL have requested a THz pump source capable of operating at the X-ray repetition rate, specifically in 10 Hz burst mode. The experiment titled superradiant THz radiation generation (STERN) is exploring to meet this demand by developing a novel THz source for pump-probe applications in the range of 0.1-30 THz. As part of the EuXFEL R&D program, STERN explores beam-based radiation generation techniques using two approaches, diffraction radiation and Cherenkov waveguides. The latter involves passing the electron beam through a wakefield structure with a small inner diameter, lined internally with a dielectric layer, thereby producing narrowband THz pulses [1–3].

A proper alignment of the electron beam with respect to the waveguide structure is critical to avoid beam losses which would limit user operation and lead to additional unwanted effects e.g. activation, particles in vacuum, heating etc. An alignment setup has been developed for the STERN experimental area. It uses a visible alignment laser to replicate the electron beam trajectory, allowing accurate positioning of key components, including a copper block housing waveguides. Scintillator screens placed upstream and downstream of the waveguide section enable the marking of the alignment laser with the electron beam.

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STERN EXPERIMENTAL AREA

The STERN experimental vacuum area is designed to generate THz pulses using two complementary approaches: diffraction radiation (DR) and dielectric-lined waveguides (DLWs), the layout of the experimental chamber can be seen in Fig. 1. The first method utilizes diffraction radiation, generated when the electron beam passes through a small aperture in a metallic sheet [4, 5]. This diffraction radiation sheet is mounted on a 3D actuator providing micrometer-level control positioning. When inserted, the electron beam traverses the small-diameter hole, stripping off part of its electromagnetic field to generate broadband THz radiation. The radiation is then collected using a system of two parabolic mirrors and one flat mirror, ensuring efficient capture and focusing. The captured THz beam is then transported out of the chamber via a dedicated THz beamline.

The second method focuses on the production of narrowband THz pulses using dielectric-lined waveguides (DLWs). When the electron beam passes through these waveguides, the TM_{01} mode is excited, see [3] for details. Various types of waveguides are planned for testing, including coated, tapered, and corrugated structures to optimize performance across different frequency ranges. Like the DR, the THz radiation generated from the waveguides is collected by parabolic mirrors and directed into the transport beamline where it is transported into a laboratory area designated for diagnostics experiments. The DLWs are mounted inside a cooled copper block with 5 degrees of freedom; the longitudinal (z) axis provides a rail system for 80 cm of travel. All motors are stepper-based with precision to the micrometer level to avoid common radiation damage associated with piezo motors.

The initial alignment procedure of STERN will rely on first aligning DR, waveguides, and holey outcoupling mirrors with the alignment laser. Subsequently the transport line to the diagnostic laboratory will be aligned. Two scintillating screens place up- and down-stream of the chamber will be used to mark the position of the alignment laser. With support from the DESY alignment group, we anticipate alignment precision to the beam axis of ~10 µm. The electron beam will then be aligned to the marked scintillating screens without other components present. We note the screen stations at this location have a resolution of ~10 µm. Next, the outcoupling mirrors will be introduced, as well as large-aperture waveguides to facilitate the alignment procedures. Smaller apertures will subsequently be inserted to determine the smallest possible apertures at this location

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with acceptable beam-losses with regards to the machine protection system.

A mini-beta lattice has been implemented to provide STERN with a minimum symmetric beta function of β^*=1 m, corresponding to an rms beam size of σ ~3 µm. We are especially concerned about the beam halo which we have modeled as a homogenous distribution of 10^{-6} of the beam charge over 30σ. Measurements at other locations in the machine have suggested we could potentially use apertures of less than 300 µm diameters by scaling the beta function, however this must carefully developed. The STERN experimental area will be installed in the second half of 2025.

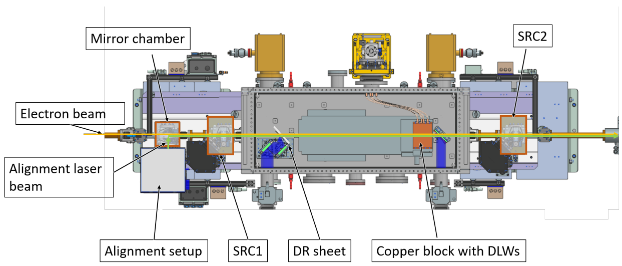

Figure 1: Layout of the STERN experimental chamber showing the positions of the diffraction radiation (DR) target, dielectric-lined waveguides (DLWs), and associated THz collection optics. The setup enables switching between DR and DLW-based THz generation.

Alignment Setup

The alignment laser is injected into the beamline via a mirror chamber located directly upstream of the experimental vacuum chamber. A breadboard is attached to the chamber and allows for an optical setup to control the beam position and size through the main chamber. The setup incorporates five dielectric mirrors, including two motorized mirrors (MM1 and MM2) for remote adjustment of beam angle and position. A lens (f = 2000 mm) is used to focus the laser such that its waist coincides with the position of the dielectric-lined waveguides (DLWs) in the experimental chamber, replicating the spatial conditions experienced by the electron beam.

The alignment setup shown in Fig. 2 was tested in the lab, incorporating a telescope setup to reduce the beam diameter at the pinhole, allowing more optical power to pass through and producing a more strongly diverging beam behind the pinhole.

During lab testing, a 4D precision mount is used to hold the DLWs and emulate positioning and angular control provided by the in-vacuum mover system.

RESULTS

The coupling efficiency was measured for different pinhole diameters using the alignment setup without the two telescope lenses (f_{T1} and f_{T2}), as shown in Table 1. The

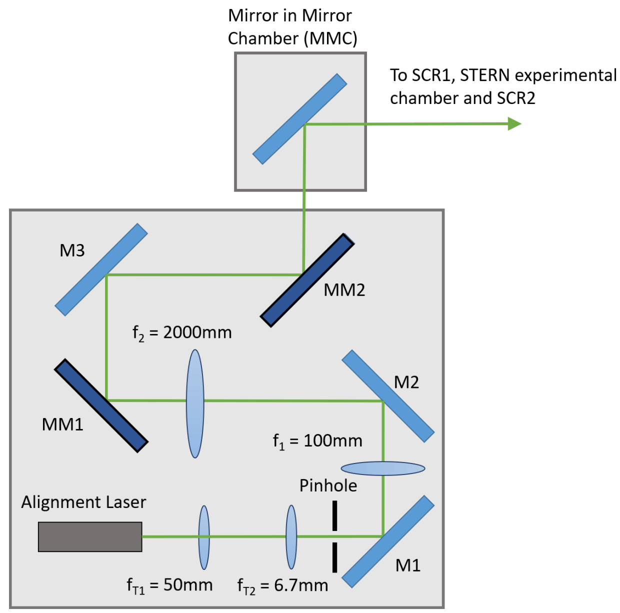

Figure 2: Schematic of the alignment setup: beam path with telescope for reduced beam diameter at the pinhole.

results show a significant decrease in coupling efficiency with increasing pinhole diameter, indicating that smaller pinholes are more favorable. A pinhole diameter of 40 µm was selected for subsequent measurements, as it provided a coupling efficiency of 61.5 %. When using the setup with telescope lenses, the coupling efficiency was slightly lower, at 58.9 %.

The main advantage of the telescope lies in the significantly higher optical power delivered to the tube entrance. This is due to the reduced beam diameter of the alignment laser in this configuration. The setup without a telescope delivers only 0.62 µW of optical power at the tube entrance, the configuration in Fig. 2 achieves a substantially higher value of 4.45 µW.

Table 1: Coupling Efficiency for Different Pinhole Sizes Without a Telescope

Pinhole Size [µm]	max. Coupling Efficiency [%]
40	61.5 %
100	14.0 %
400	1.0 %
1000	–

To characterize the alignment tolerances of the optical tube system, measurements were taken for four degrees of freedom: axial displacement ΔZ, lateral displacement ΔY, and angular misalignments θ_z and θ_y. For each axis, transmission efficiency was recorded as a function of misalignment. The results are shown in Fig. 3

Quantitative analysis was performed by extracting the Full Width at Half Maximum (FWHM) and the range over which

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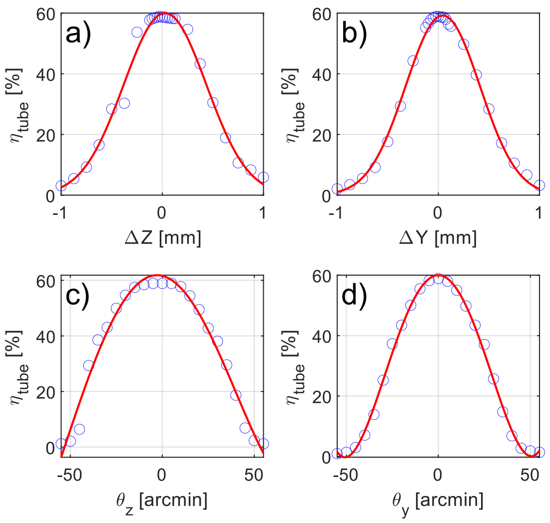

Figure 3: Transmission efficiency as a function of misalignment for a) ΔZ, b) ΔY, c) θ_z, and d) θ_y.

at least 90 % of the peak transmission efficiency is maintained, for both configurations. The results are summarized in Table 2.

These results show that the system exhibits similar tolerances for axial and lateral misalignments, with FWHM values around 0.43–0.45 mm and 90 % transmission ranges near 0.16–0.17 mm. For angular misalignments, the system tolerates slightly larger deviations in vertical tilt (θ_y) compared to horizontal tilt (θ_z), likely due to the non-circular shape of the alignment laser beam.

Figure 4 shows the beam profiles for misalignment of ±37.5 arcmin in θ_y and θ_z and ±1000 µm in ΔY and ΔZ. The images are taken at the position of the second scintillator screen.

To interpret the beam profile images in Fig. 4, note that each frame corresponds to a specific type and direction of misalignment applied to the laser beam. Lateral displacements (ΔY, ΔZ) cause the beam to shift spatially on the screen, while angular misalignment (θ_y, θ_z) induce both displacement and beam shape distortion due to beam clipping at the tube aperture.

In several images, especially under angular misalignment, diffraction rings can be observed. These rings likely originate from the beam interacting with inner surface of the tube. Their presence provides additional diagnostic and

Table 2: Alignment Tolerances (FWHM and 90 % Ranges) for Horizontal, Vertical, and Angular Misalignments

Misalignment in	FWHM	90% range
ΔZ [mm]	0.450	0.174
ΔY [mm]	0.425	0.165
θ_z [arcmin]	30.12	12.44
θ_y [arcmin]	31.16	13.05

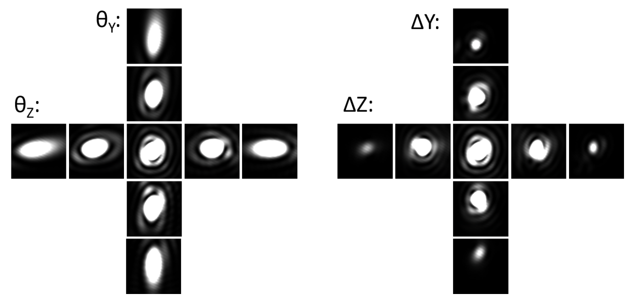

Figure 4: Beam profile images under vertical and horizontal displacement ΔY and ΔZ as well as vertical and horizontal tilt θ_y and θ_z

helps confirm the beam's path relative to the aperture edges. Monitoring these rings during alignment may therefore aid in fine-tuning angular positioning for optimal transmission.

CONCLUSION

An alignment system for the STERN experimental area at the European XFEL has been described. The setup uses a 530 nm alignment laser to emulate the electron beam trajectory and enables positioning of THz-generating components, particularly dielectric-lined waveguides.

The alignment setup includes a telescope to reduce the laser beam diameter, resulting in significantly higher optical power at the tube entrance and improved control over beam divergence. The setup demonstrated consistent tolerances for axial and lateral misalignments, while angular tolerances were influenced by the elliptical shape of the laser beam.

The system shows good reproducibility and sufficient alignment precision to ensure efficient coupling of the electron beam into millimeter-scale waveguide structures. In the future we will use a differnet laser with a round beam profile and better M^2 to improve agreement with simulations results and to allow for alignment of even smaller apertures.

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