SUPERRADIANT TERAHERTZ RADIATION GENERATION AT EUXFEL: FROM DESIGN TO INSTALLATION

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Abstract

Accelerator-based THz sources offer high energy and repetition rates, making them attractive for pump-probe experiments at X-ray free-electron lasers. The superradiant terahertz radiation generation (STERN) experimental chamber was recently successfully integrated into the European XFEL electron beamline during its long installation and maintenance period. The setup incorporates Cherenkov wakefield structures and a diffraction radiation screen to generate superradiant terahertz (THz) pulses from the electron beam, covering a combined spectral range between 0.3–30 THz. This work describes the design and installation of the experimental hardware, with emphasis on the THz generation and transport components. It reports on the wakefield structure assembly, the 10 m transport line and the laser-based alignment of the elements inside the chamber.

INTRODUCTION

Pump-probe experiments at the European X-ray free-electron laser (EuXFEL) increasingly demand synchronised, high-field THz pump sources that match the repetition rate of the X-rays [1, 2]. The EuXFEL injector accelerates trains of up to 2700 bunches in a 10 Hz burst mode, with a repetition rate inside the train of up to 4.5 MHz [3]. External laser-based THz sources face synchronisation challenges at the few-femtosecond level and cannot reach the high repetition rates of the modern XFELs with sufficiently high pulse energies. Accelerator-based sources are able to operate at the machine repetition rate and exhibit intrinsic timing stability, since both the THz and X-ray pulses derive from the same underlying RF reference and photocathode laser.

The superradiant terahertz radiation generation (STERN) experiment is an R&D project to investigate accelerator-based THz generation at EuXFEL. Two complementary radiation mechanisms are employed: Cherenkov wakefields in dielectric-lined waveguides (DLW) and diffraction radiation (DR) from an aluminum screen [4–10]. A combined spectral range of 300 GHz–30 THz is targeted. The generated pulses are transported via a mirror-based transport line to a dedicated THz diagnostics laboratory, where spectral diagnostics and an electro-optical sampling setup will be installed.

The design of the experimental chamber and THz transport line was described in earlier work [11]. The present contribution reports on the transition from design to installation: DLW production and installation, chamber and beamline assembly and optical alignment of the transport line. An image of the finished installation is shown in Fig. 1.

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Figure 1: The STERN experimental chamber installed in the EuXFEL tunnel.

EXPERIMENTAL SETUP

STERN Chamber

The STERN experimental chamber is installed in the EuXFEL tunnel, downstream of the SASE2 undulator section. The chamber houses two types of THz sources sharing a common electron beam axis. The DLW assembly generates narrowband Cherenkov wakefield radiation, while an aluminum screen with 2 and 4 mm diameter holes produces broadband DR. Both sources produce radially polarised fields with an intensity profile that resembles a Laguerre-Gaussian L_0^1 mode in the far field. Figure 2 shows the design of the experimental chamber and the THz transport line. The middle mirror just below the experimental chamber is retracteable to allow either DR or DLW radiation to pass through the line.

The ELPHI Waveguide Block

The DLW assembly, referred to as ELPHI, is a precision-machined aluminium block designed to house several dielectric-lined waveguides. The block and the dielectric materials used are shown in Fig. 3. Stepper motors attached to ELPHI provide six mechanical degrees of freedom: transverse positioning and yaw rotation using small stages directly under the block, longitudinal travel on a rail system, and height, pitch and roll adjustment through three out-of-vacuum actuators.

ELPHI houses 43 cylindrical DLWs spanning inner diameters from 140 m to 4 mm and lengths from 4 cm to 15 cm. The dielectric materials featured in the first experimental run are quartz, aluminum oxide, PEEK and PI Mikro. An exact overview of the waveguide selection will be presented in a forthcoming publication [12]. The estimated radiated energy and frequency coverage is shown in Fig. 4. The block also houses anti-resonant fibers (ARF) cut at different lengths and

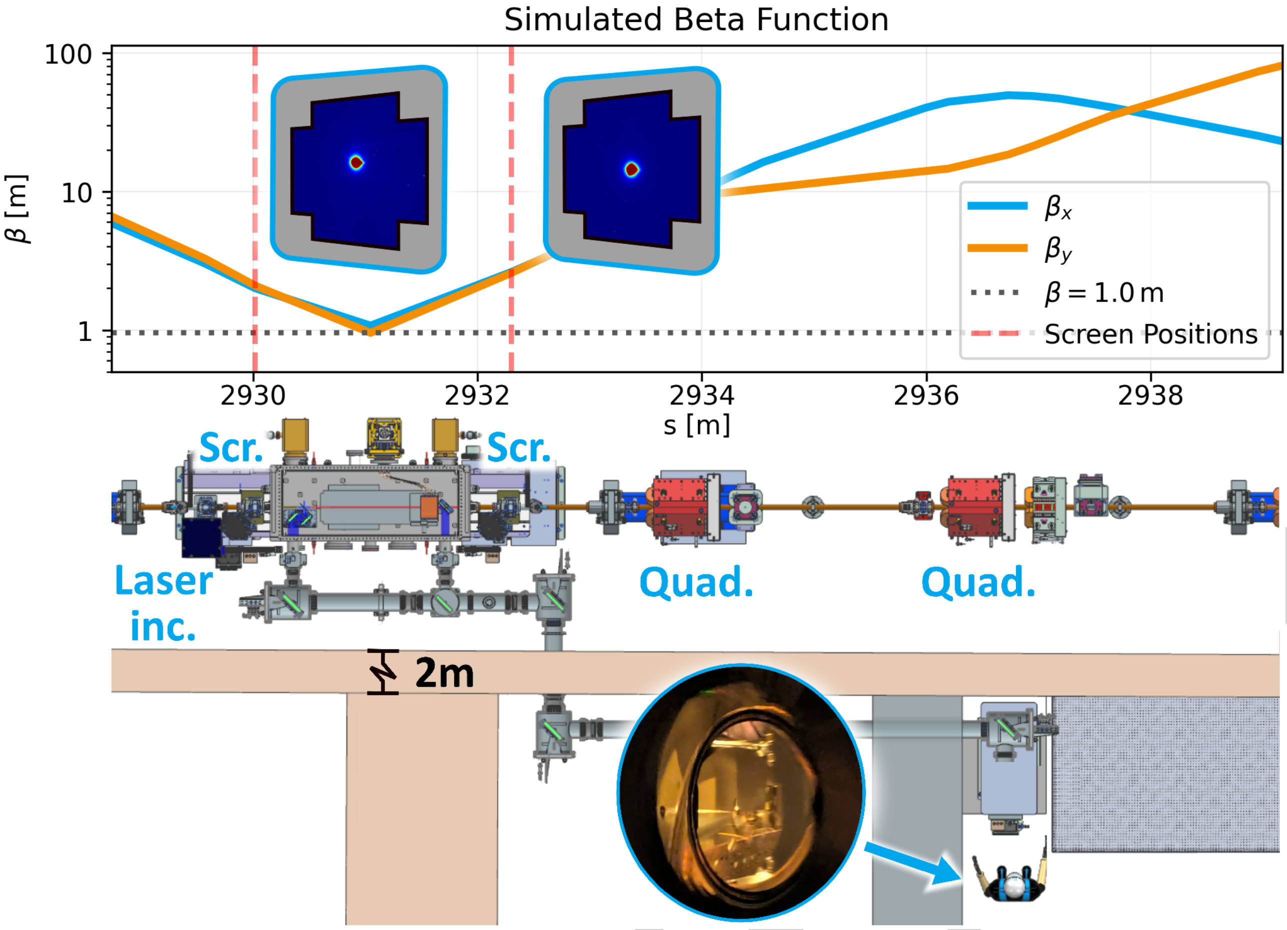

Figure 2: Top: Electron beam size simulated with OCELOT around the STERN experimental area. The horizontal axis roughly matches the image below. Bottom: Design of the STERN experimental chamber and THz transport line. The light is transported through two layers of radiation shielding concrete towards the THz diagnostics laboratory. Two insets show the measured round beam spots at the scintillating screens before and after the chamber. The inset on the right shows a picture of ELPHI taken from the THz diagnostics laboratory.

encased in PEEK tubing. All waveguides are aligned with the downstream face of the block, to ensure outcoupling is not affected by the aluminum holder itself. Every DLW was encased in indium foil and fitted into a cylindrical channel.

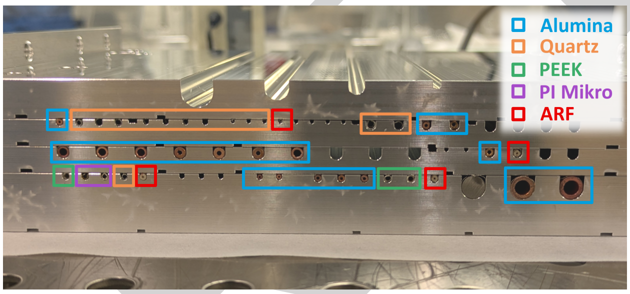

Figure 3: Downstream face of the ELPHI waveguide block installed inside the STERN chamber. The different colors represent the material of the dielectric used in the DLW.

The THz Transport Line

Two interchangeable outcoupling mirrors with 10 cm projected diameter and focal lengths of 7.5 cm and 30 cm are mounted downstream of the block. Both mirrors have a through hole for the electron beam with a 2 mm diameter. The rail position serves as an additional optimisation parameter for frequency-dependent outcoupling efficiency [11]. Lower frequencies diverge fast and therefore require ELPHI to be as close to the parabolic outcoupling mirror as possible. This is the position shown in Fig. 2. Inversely, higher frequency pulses require more distance to become sufficiently separated from the electron beam. The rail allows movement upstream, the final position being almost in contact with the DR screen. During experiments, the rail position can be optimised for maximal transport through the full transport line. DR radiation is coupled out by two static, 10 cm diameter parabolic mirrors, after which it is sent into the same transport line as the DLW radiation.

After the THz radiation exits the chamber it is transported over approximately 10 m to the THz diagnostics laboratory. The laboratory is shielded from the accelerator tunnel by 2 m of concrete. The transport line uses a sequence of focusing parabolic mirrors at every corner; mirrors outside the chamber have a diameter of 15 cm. The optical design was optimised using an OCELOT-based framework [11, 13]

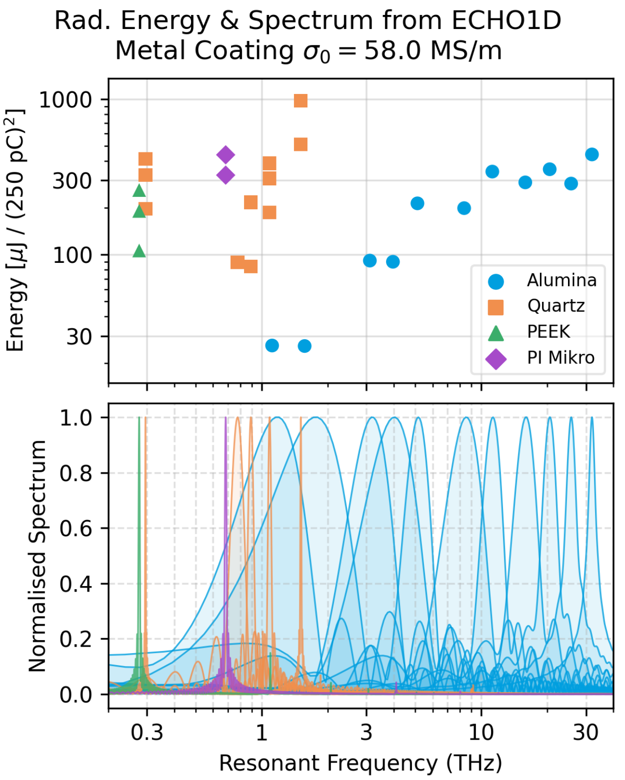

Figure 4: Estimated energy radiated and normalised Fourier spectrum using ECHO1D simulated steady-state wakefields. The exact measured lengths of the DLWs are taken into account to estimate the pulse lengths, as well as a coating conductivity of $\sigma_0 = 57.97\,\mathrm{MS/m}$, corresponding to room-temperature copper. The bunch is assumed to have a form factor of $F = 1$.

and achieves transport efficiencies exceeding 70% across the 0.3–30 THz range. Figure 2 illustrates the physical layout of the experimental chamber and THz transport line into the THz diagnostics laboratory. The simulated beam size is shown after start-to-end simulations of the EuXFEL lattice using OCELOT [14, 15].

INSTALLATION AND ALIGNMENT

Chamber and Transport Line Installation

The STERN chamber and transport line were installed during the LIMP25 EuXFEL machine shutdown. The available space in the tunnel section is small and further constrained by adjacent beamline components, requiring careful sequencing of installation steps. The mirrors inside the experimental chamber were carefully aligned before closing and vacuum pumping the chamber. Using an alignment laser attached to the beamline flange, mirrors in the transport line were iteratively pre-aligned, after which the vacuum pipes were connected and full transport from the chamber to the laboratory was verified.

Laser Alignment Inside the Chamber

Precise alignment of the electron beam to the apertures of the DR screen, ELPHI and outcoupling mirrors is of high importance to avoid particle losses and optimize performance. A red, fibercoupled alignment laser was used as a proxy for the THz beam trajectory and is coupled in with a retractable mirror upstream. The procedure begins by recording the electron beam spot on the scintillator screens right before and after the chamber. Subsequently, the beam is turned off and the laser is coupled in. By use of four actuators on the incoupling mirrors outside of vacuum, the laser beam is steered to match the electron beam path. The different apertures inside the chamber are then moved in and adjusted until the laser beam passes through maximally. The focused laser spot has a $\sigma_{\mathrm{RMS}} = 353\,\mathrm{m}$, which is a factor of ~ 50 larger than the electron beam, such that maximising laser transmission is sufficient to ensure loss-free electron transport, without requiring 100% laser throughput. Offsetting either the outcoupling mirror or the DR screen deliberately allows the laser to impinge on the surface and couple into the transport line. By adjusting the mirrors of the transport line and ensuring laser transport into the lab, significant outcoupling of the THz radiation is also guaranteed. Finally, the apertures are moved back to the position that allows loss-free transport and the electron beam can be injected.

Encountered Challenges

Several challenges were encountered during the installation phase, the most critical of which involved the in-vacuum motors. Pending a full diagnosis, the longitudinal and horizontal travel of ELPHI are currently inoperative due to motor faults. Rotation and vertical motion were unaffected and remain fully operational.

CONCLUSION

The STERN experiment has been successfully installed in the EuXFEL tunnel during the LIMP25 shutdown. The ELPHI waveguide block, housing 43 DLWs across a range of dielectric materials, and the DR screen have been integrated into the experimental chamber and connected to the accelerator vacuum. The 10 m mirror-based THz transport line has been laser-aligned and verified to transport an image of the components inside the chamber. Motor faults affecting the longitudinal and horizontal degrees of freedom of ELPHI are under investigation. Once resolved, the full parameter space of the experiment will be accessible, and STERN will be ready to deliver superradiant THz pulses to its diagnostics laboratory.

ACKNOWLEDGEMENTS

This work was supported by funds of the European XFEL R&D program.

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