D1.4

Realisation of the MHz-tomoscopy prototype

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Task description

The primary objective of WP1 Task 1.5 was to develop and validate a prototype system capable of multi-projection X-ray imaging with MHz-range sampling rates. This task was critical for demonstrating the feasibility and performance of advanced imaging techniques within the broader context of the Pathfinder project goals. It was considered high-risk due to two major factors: the potential difficulty in, or very limited access to, XFEL beamtime—an essential requirement for timely and effective validation of the prototype—and the challenge of obtaining high-quality HPHT diamond crystals with the required specifications. Both challenges were successfully overcome, enabling the task to be completed as planned.

Abstract

We have successfully constructed, installed, and commissioned the MHz Tomoscopy prototype with vertical scattering geometry (sigma configuration). As compared to our early feasibility experiments performed with early demonstrators in pi-configuration [https://doi.org/10.21203/rs.3.rs-2978487/v1] (horizontal scattering plane) setting allowed to improve significantly the throughput of the system. Together with careful optics optimization (high NA objectives) and scintillator efficiency we constructed efficient setup proving up to 4 projections (budget limited). The prototype was assembled at the SPB/SFX instrument during 2024, with initial commissioning carried out in April 2025. The final validation measurements were completed in April 2025.

We aligned four Bragg reflections—(111), (220), (311), and (422)—of HPHT diamond, which had been fully characterized and delivered just in time for the experiment. Using a photon energy of 10 keV, we successfully recorded validation data on two dynamic processes: water flow in a Venturi tube and laser-induced bubble formation in a capillary.

These results demonstrate a state-of-the-art X-ray imaging method, enabling new insights into ultrafast phenomena in materials science, biology, and energy applications. This milestone paves the way for further advancements in the real-time visualization of transient processes at unprecedented temporal and spatial resolution.

1. MHz Tomoscopy Prototype

1.1. Mechatronics

The key design and assembly work for the prototype was carried out by SUNA. Installation was performed in close collaboration with the SPB/SFX group, and the prototype was integrated into the main hutch at the SPB/SFX instrument.

The installation followed an iterative approach, beginning in April 2024. Initial tests involved a single detector arm and one Bragg reflection. Full installation and system integration—including the mechanical structure, detector mounts, and sample environments—were completed by December 2024.

This modular, staged approach allowed early testing and troubleshooting while progressively scaling up the complexity of the system.

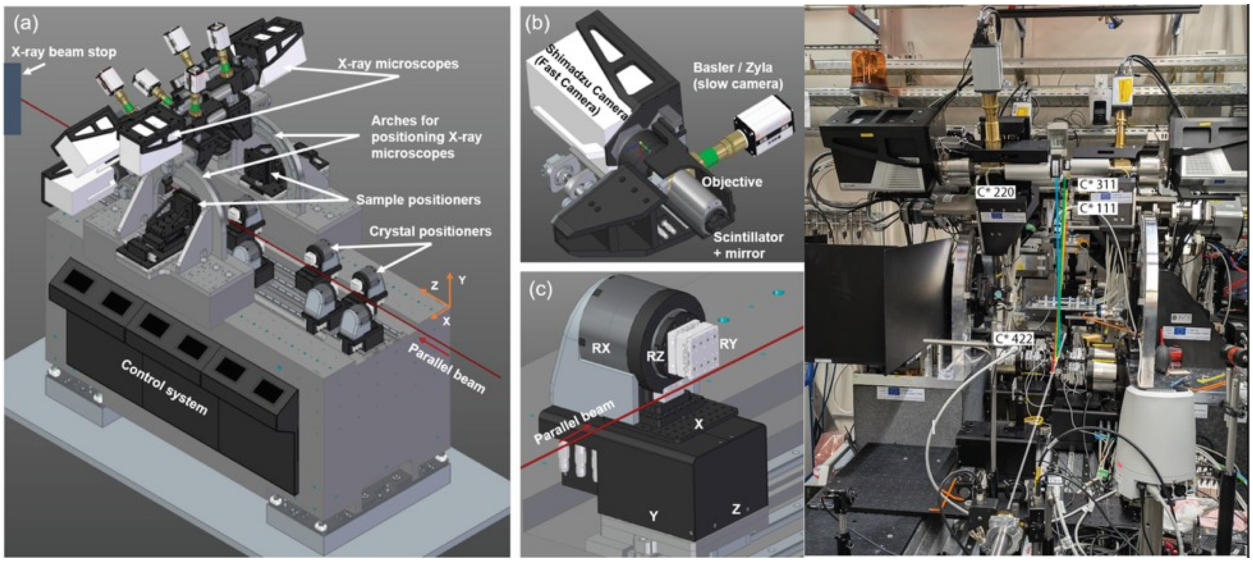

Figure 1. Mechanical assembly and integration of the MHz Tomoscopy prototype at the SPB/SFX hutch.

1.2. Crystal optics

The crystal optics form the core of the MHz Tomoscopy system, enabling simultaneous multi-projection X-ray imaging through Bragg diffraction. These components require materials with exceptional structural and thermal properties. Key features include:

- **Optical-grade HPHT diamond** (High-Pressure High-Temperature): selected for its outstanding X-ray performance, including low absorption, high thermal conductivity, and minimal imperfections (e.g., dislocations and inclusions).
- **Material selection**: Alternative crystals such as silicon and germanium were evaluated but deemed unsuitable due to their higher X-ray absorption and susceptibility to heat-induced deformation under intense XFEL pulses.
- **Durability**: Experimental validation confirmed that HPHT diamond optics withstand prolonged XFEL exposure without deformation or visible damage.
- **Bragg reflections**: The crystal was precisely aligned to produce four simultaneous reflections—(111), (220), (311), and (422)—enabling the acquisition of four spatially distinct projections in a single exposure, each captured by an independent MHz-rate X-ray detector.

The use of HPHT diamond optics is fundamental to the system's performance, ensuring robust, high-resolution imaging under extreme conditions.

Figure 2 Diamond HPHT crystals purchased via project

Performance Comparison and Outlook

To benchmark the performance of diamond optics against more conventional alternatives, we conducted comparative experiments using a 30 µm-thick silicon crystal splitter and a 100 µm-thick HPHT diamond splitter, both operated at **10 keV** photon energy. The results are shown below:

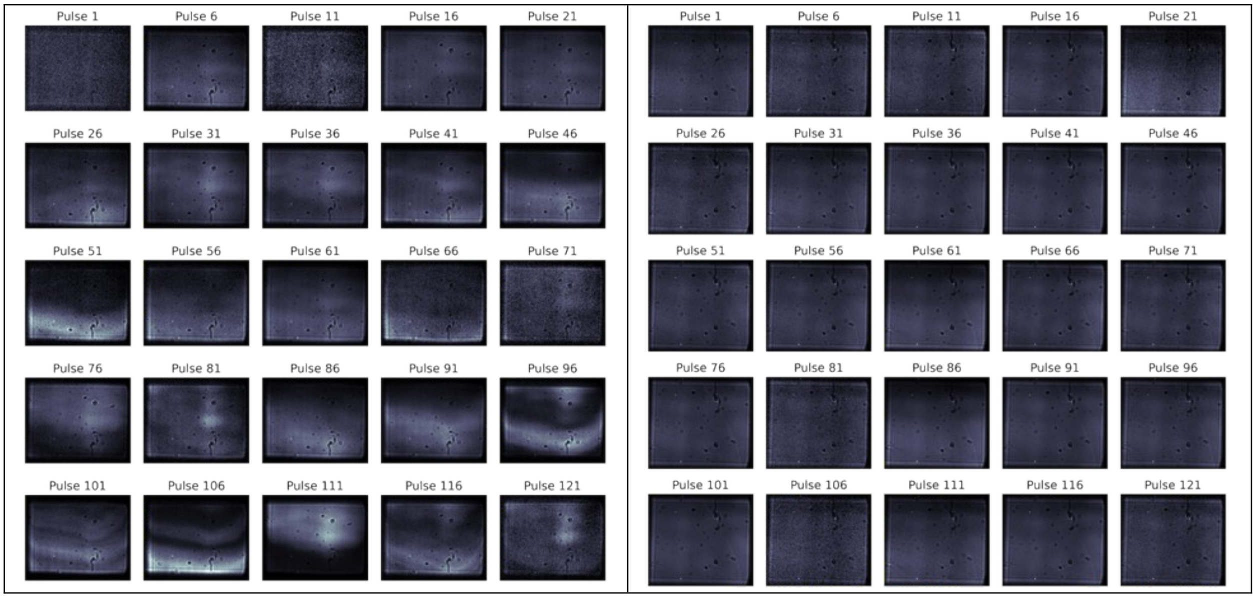

Figure 3. *Recorded Bragg reflection intensity across XFEL pulse trains for (a) Si(220) from thin 30 um thick silicon membrane and C(220) from 100 um thick HPHT diamond.*

- The average pulse energy during the test was **<300 µJ per pulse**, representative of reduced machine settings at 14 GeV.
- **Diamond (C220)** shows **stable and consistent reflection intensity** across the entire pulse train, indicating excellent thermal and structural stability under repeated high-intensity illumination.
- **Silicon (Si220)** shows **progressive degradation in intensity** across the pulse train, attributed to **heat-induced deformation** of the crystal lattice. This confirms the known thermal limitations of silicon at high repetition rates.
- Under higher pulse energies (e.g., >1 mJ), this deformation in silicon becomes **even more severe**, compromising its usability in MHz-rate imaging at soft to medium X-ray energies.

Despite this, for **higher photon energies (>16 keV)** where the heat load is reduced and absorption in silicon is lower, thin Si crystals remain a **viable, cost-effective alternative**. In collaboration with INFN Ferrara, we have developed **ultra-thin silicon membranes (<10 µm thick) (see report INFN/FERARA)** to explore this path further in future high-energy MHz imaging experiments.

1.3. Detector system

Detector System

The detector system is based on **indirect X-ray conversion**, optimized for ultrafast, high-efficiency imaging at MHz. It comprises:

- **Fast scintillator screens**, specifically **GAGG:Ce (Gadolinium Aluminum Gallium Garnet doped with Cerium)**, selected for their **high light output** and **fast decay times on the order of hundreds of nanoseconds**, supporting operation at high repetition rates.
- **Shimadzu HPV-X2 high-speed visible-light cameras**, capable of acquiring up to **10 million frames per second (10 Mfps)**. These cameras are synchronized with the XFEL pulse structure for precise time-resolved measurements. Due to XFEL and camera clock mismatch we can reach setting where full buffer of camera is synchronized within buffer duration to pulse train with relative shift of succeeding pulse to frame of 4 ns for 1.128 MHz pulse train. To reach maximum repetition rate 4.5MHz while keeping camera buffers in synchronisation would need cameras upgrade.
- Despite the scintillator decay time, **no motion blur is present**, as the **illumination duration is extremely short (~20 femtoseconds)**, effectively freezing even the fastest dynamics.
- The scintillation luminescence light is projected onto the camera sensors using **high-resolution, long working distance Mitutoyo objectives**, ensuring excellent spatial fidelity and efficient light transfer.
- The optical path and detection system are optimized for minimal distortion, high efficiency, and resistance to radiation damage.

This system enables state-of-the-art ultrafast X-ray imaging by combining femtosecond-scale exposure, MHz readout capability, and high-quality indirect optical detection.

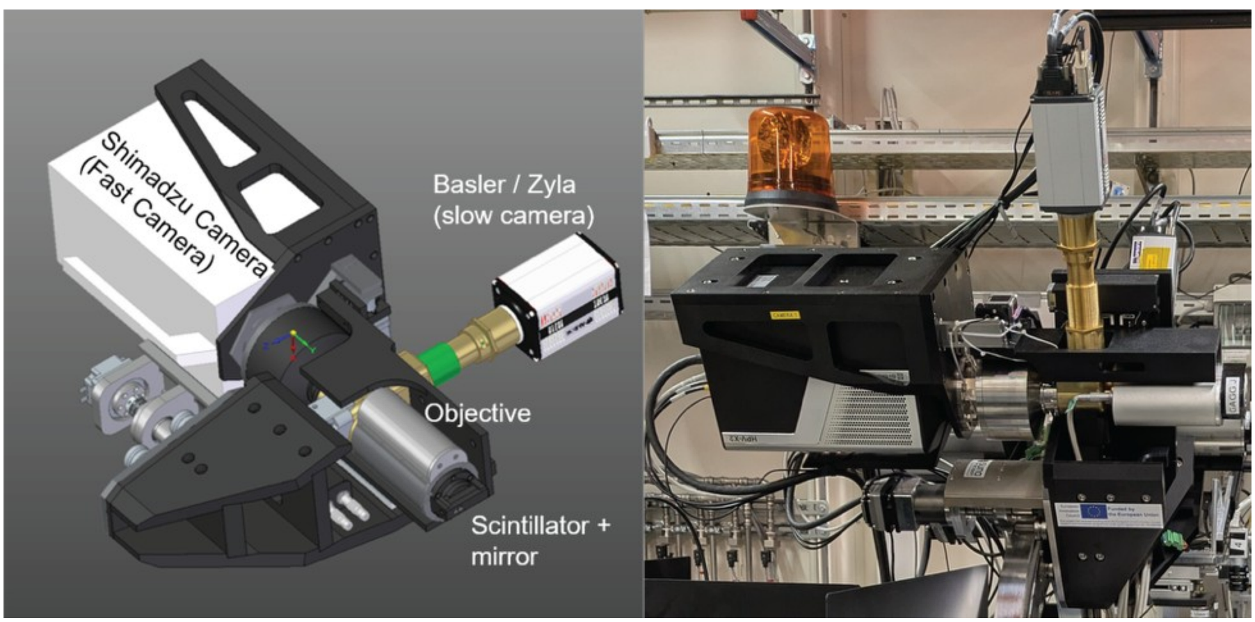

Figure 4 MHz Tomoscopy detector system model (left), one unit mounted on the MHz-TOMOSCOPY prototype.

1.4. MHzTOMOSCOPY prototype validation.

The final validation of the MHz Tomoscopy prototype was carried out at the SPB/SFX instrument during dedicated XFEL beamtime in April 2025. The objective was to demonstrate the system's full functionality in a realistic experimental environment and to confirm its ability to perform simultaneous multi-projection imaging at MHz repetition rates.

Experimental Setup

- **Photon energy**: Experiments were conducted at 10 keV, which provides a suitable compromise between Bragg reflectivity and sample penetration. But also due to low energy seeting of machine 14 GeV instead of 16.5 GeV.
- **Crystal configuration**: The HPHT diamond crystal was aligned to generate four Bragg reflections—(111), (220), (311), and (422)—resulting in four distinct angular projections.
- **Detector configuration**: Each reflection was recorded using an independent detection module, consisting of a GAGG:Ce fast scintillator, 10x HR Mitutoyo long-working-distance objective, and a Shimadzu HPV-X2 high-speed camera, synchronized with the XFEL pulse train.

Validation Experiments

Two dynamic scenarios were selected to test the performance of the system across a range of physical phenomena and timescales:

1. **Water flow in a Venturi tube**
   This experiment provided a repeatable, continuous flow scenario ideal for assessing projection consistency and system synchronization. The system successfully captured multiple single-pulse projections for tomographic reconstruction of transient flow structures.
2. **Laser-induced bubble formation in a capillary**
   A highly transient, shock-driven event was used to evaluate the system’s capability to resolve rapid interface motion and nonlinear dynamics. Single-shot imaging clearly captured the bubble evolution with no observable motion blur, validating the effective femtosecond-scale exposure time.

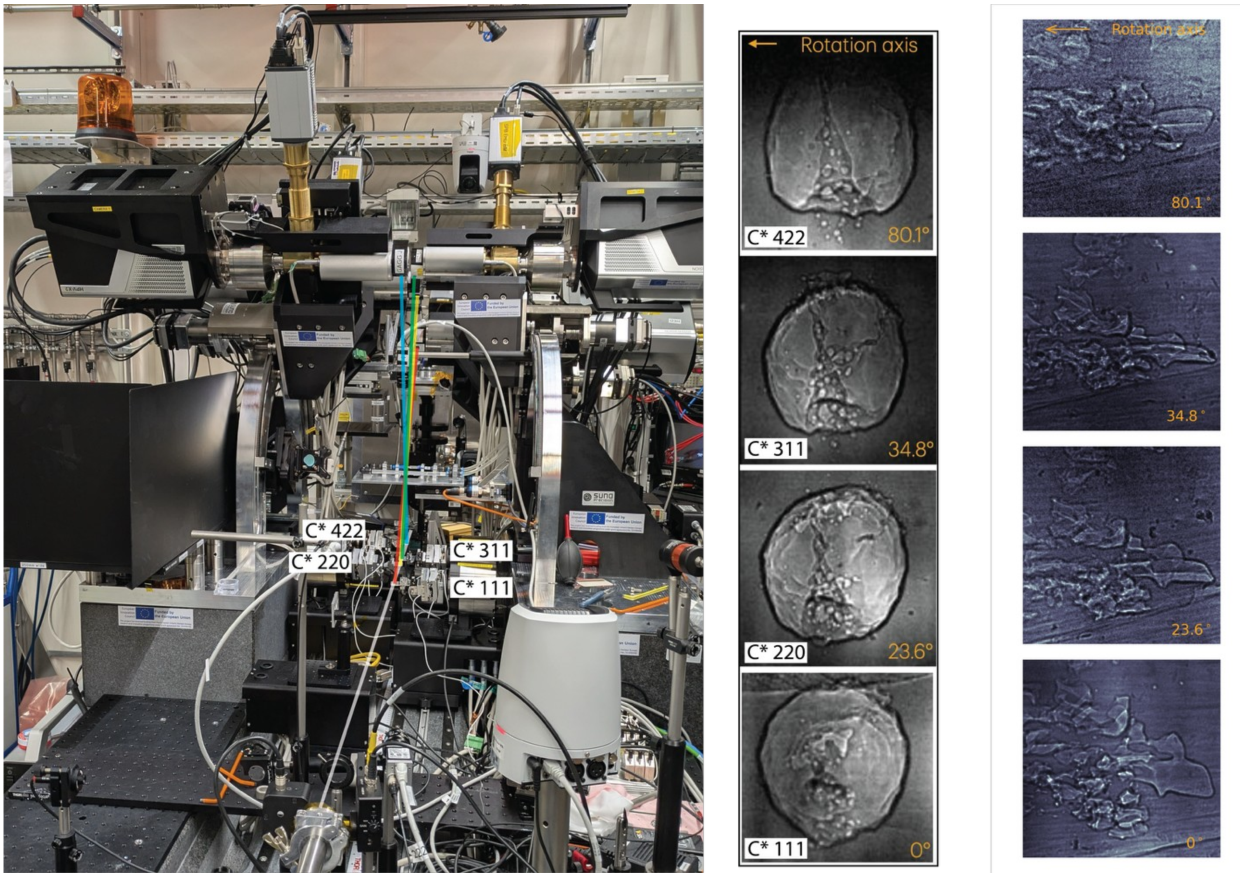

Figure 5. Experimental results shown for laser induced cavitation and cavitation flow in Venturi tube. Multiple simultaneous videos has been recorded. Images for one pulse clearly show multi-view imaging using 4 distinct angular views.

Performance and Observations

- **Projection fidelity**: All four channels reliably recorded simultaneous projections per XFEL shot, confirming mechanical alignment and optical synchronization.
- **Image quality limitations**: The overall image brightness and contrast were affected by the reduced XFEL pulse energy during the experiment. The accelerator was operated at **14 GeV**, providing only **0.7 mJ** energy per pulse, while up to 4 mJ is achievable at **16.5 GeV**.
- **Shot variability**: Despite the limited illumination, a substantial number of shots yielded sufficiently good data for analysis, allowing successful validation of system performance.
- **Thermal and optical stability**: No degradation or damage was observed in the optics or detectors during the experiment, confirming the robustness of the system under repetitive high-intensity exposure.
- **Future potential**: These preliminary results provide strong confidence that under full-power XFEL operation, the system will deliver high-quality images consistently. The design is scalable to **>16 keV photon energies**, which will benefit from improved beam quality and potentially thinner silicon optics.

The validation campaign confirms the prototype's readiness for advanced ultrafast imaging experiments. It also establishes the MHz Tomoscopy system as a viable platform for 3D imaging of transient phenomena across various domains, including materials science, fluid dynamics, and biomedical applications. The data are results are in evaluation and we are preparing set of manuscripts summarizing this work. For the future we aim to build dedicated MHz-Tomoscopy station for selected station at EuXFEL via third party funding.