High-reliability bunch arrival time monitor with fs precision

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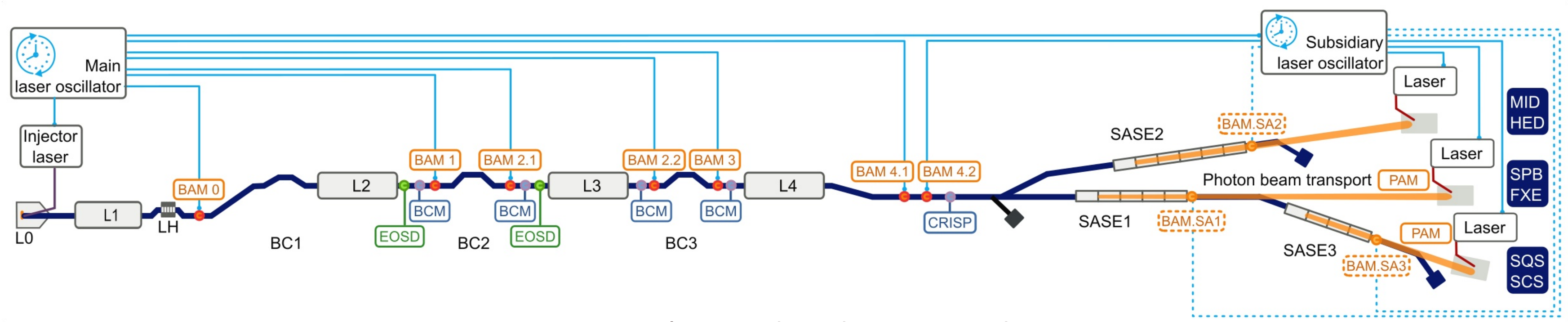
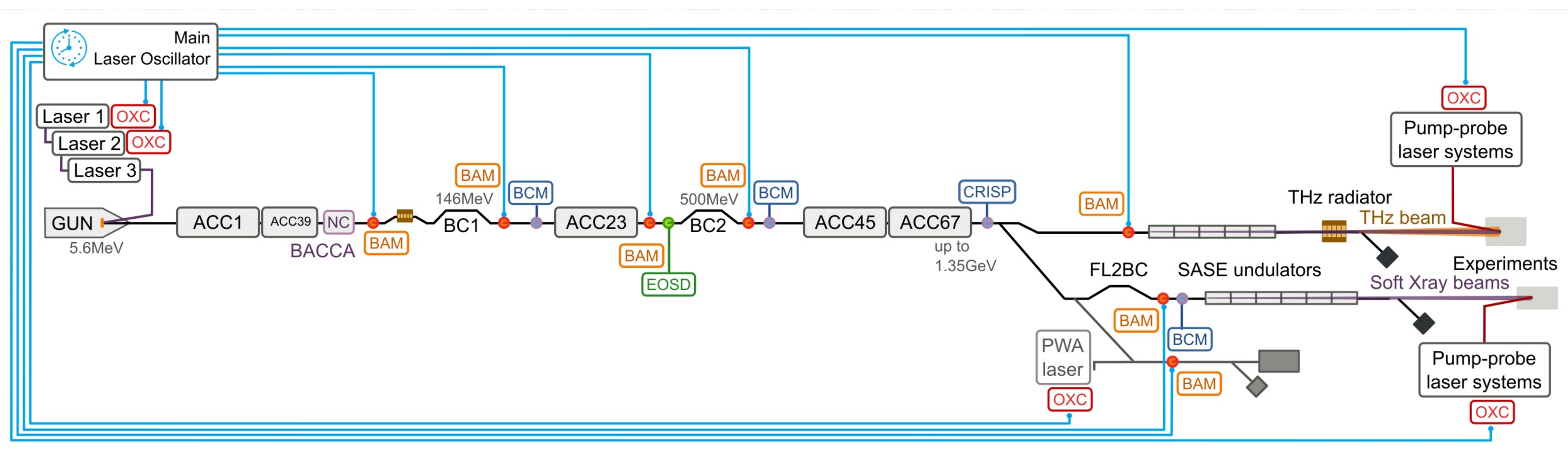


European XFEL arrival time and synchronization schematics

Schematics credit: M.K.Czwalinna



FLASH arrival time and synchronization schematics

Motivation

1) Provide world's first 24/7 accelerator synchronization

Electro-optical bunch arrival-time measurement (BAM) is a well established method. Yet no machine provides synchronization as a default operation mode. A range of pump-probe experiments depend heavily on the precision and stability of the pump-to-probe timing.

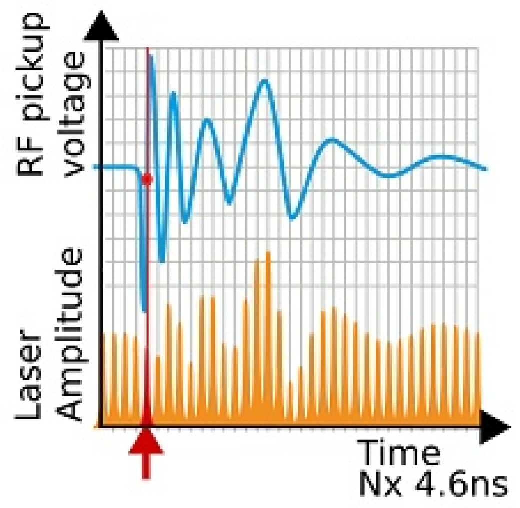
2) Improve system resolution below 1 fs rms

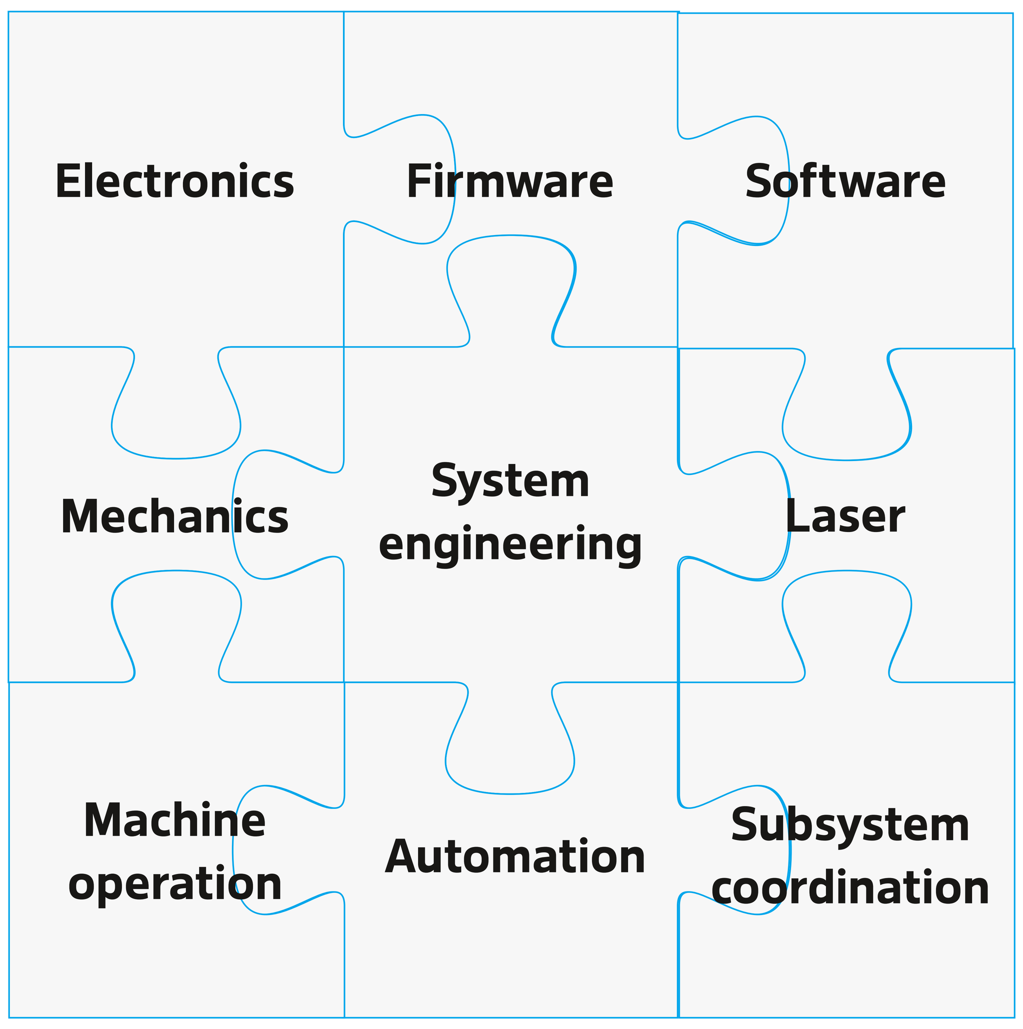
Ultra-fast atomic and molecular dynamics are the key to understanding some of the fundamental processes in the nature. Providing attosecond-level accelerator synchronization gives unprecedented access to the dynamics in question.

Principle schematic, RF signal modulates laser amplitude

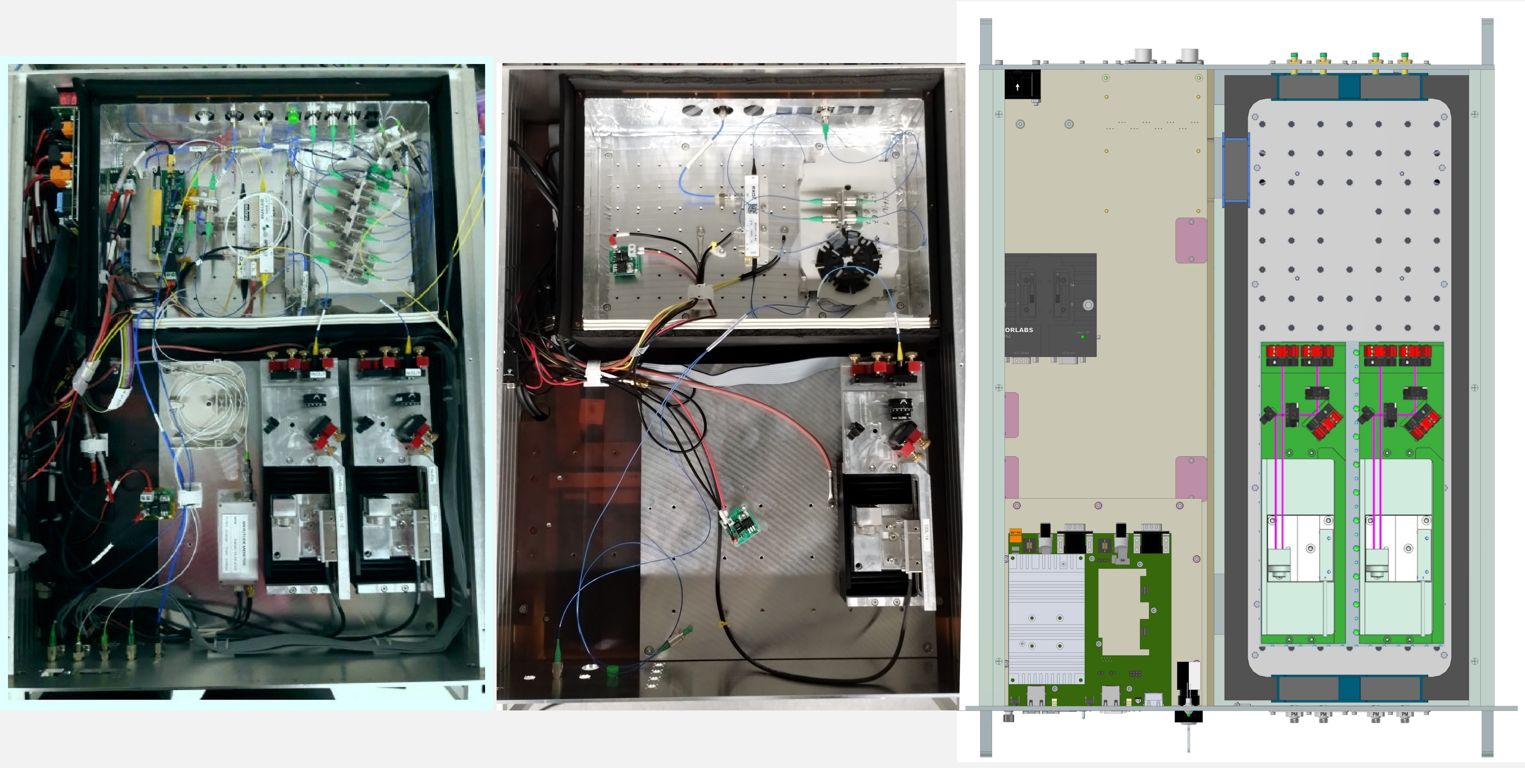
Content

This poster present the steps that were taken to achieve continuous 24/7 synchronization operation and sub fs rms resolution





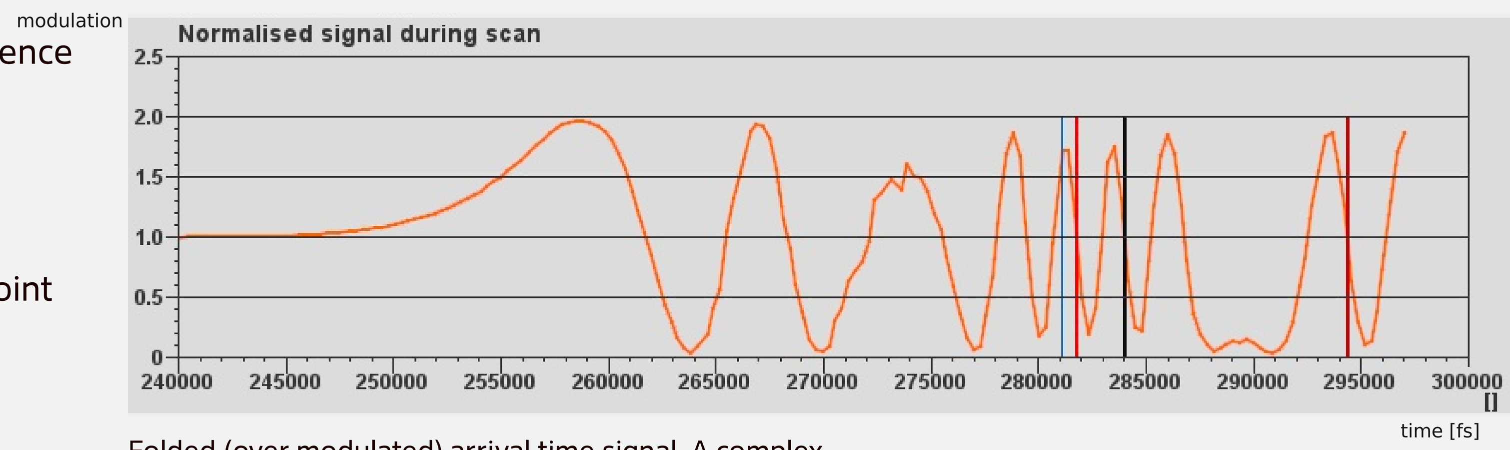
System simplification



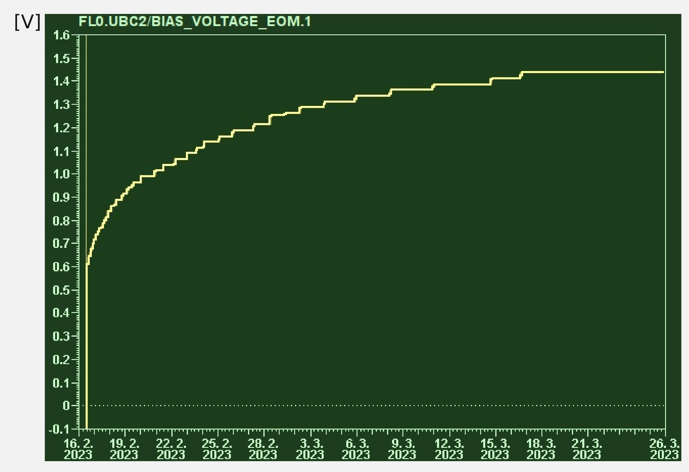
- Main objective oriented architecture, permanently assembled sub-modules, integration
- Measurement needs define the mechanics, vibration damping, whole chain thermal stabilization
- Production quality control, reproducibility, qualification and reference measurements
- Component qualification and selection

Automation

- Automated power-up sequence
  - Clock synchronization
  - Trigger synchronization
  - Gain adjustment
  - ADC sampling phase
  - Electro-optical working point
- Single-click calibration
  - Beam finding
  - Time vs amplitude calibration
  - Dynamic range optimization
- Drift stabilization
  - Long-term beam drift tracking
  - Component drifts monitored
  - Feed-backs



Folded (over modulated) arrival time signal. A complex probabilistic algorithm locates the unity crossing with perfect accuracy. Independent on the level of over modulation.



Long term bias voltage drift of the electro-optical modulator corrected with feedback

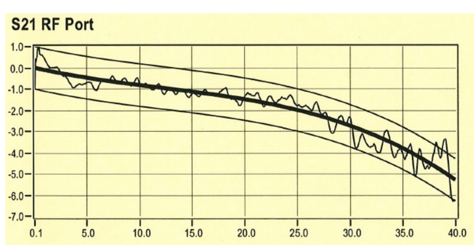
Three-step resolution improvement

1) Noise reduction

- Optical chain optimization leads to higher quality sampling light
- Supporting electronics noise reduction
- Cabling improvements

2) Bandwidth improvement

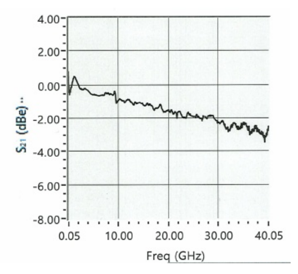
- Chromatic compensation
- Thorough modulator component selection
- RF chain optimization

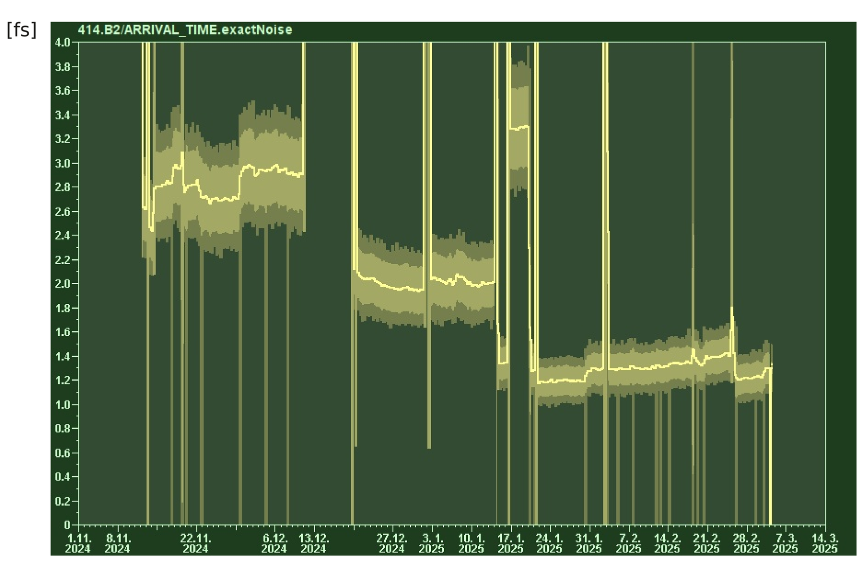


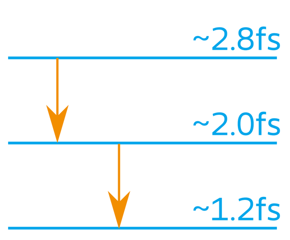
"40 GHz" modulator

3) New readout electronics - prototype tests in progress

- Improved trans-impedance amplifier
- Bandwidth, gain and dynamic range optimization
- Low noise design

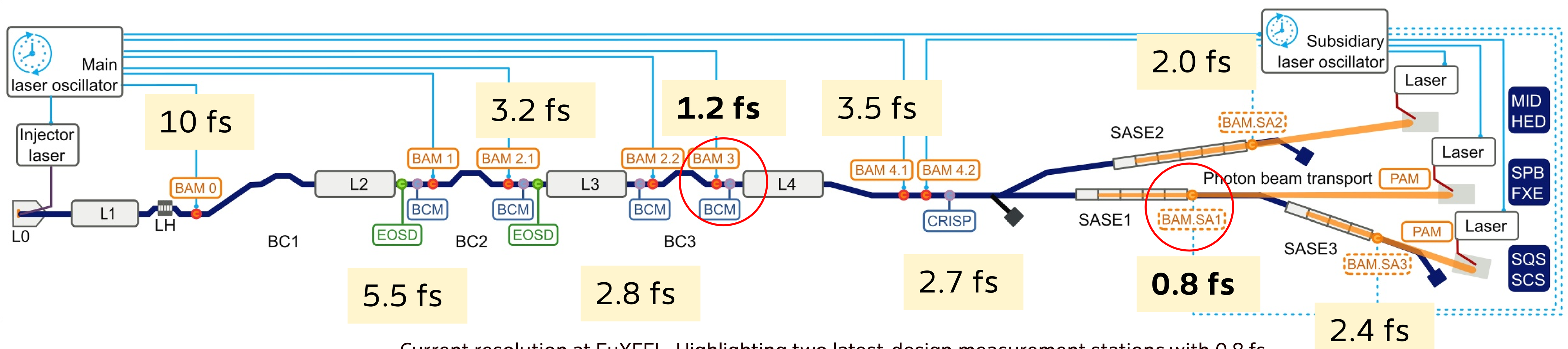

Real 40 GHz modulator



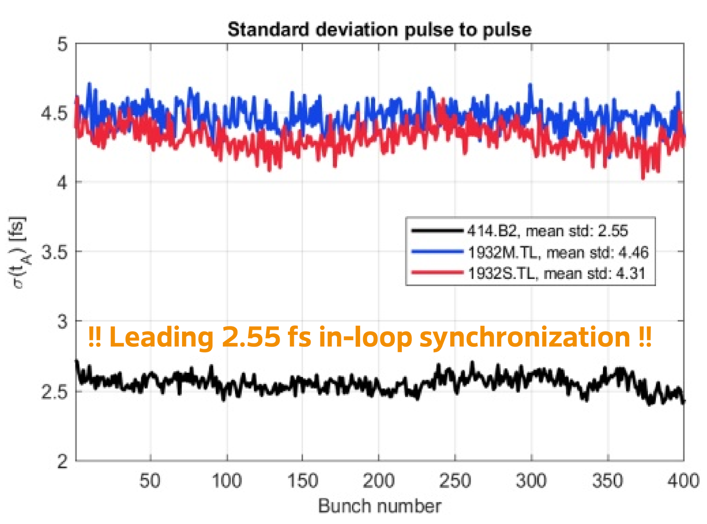


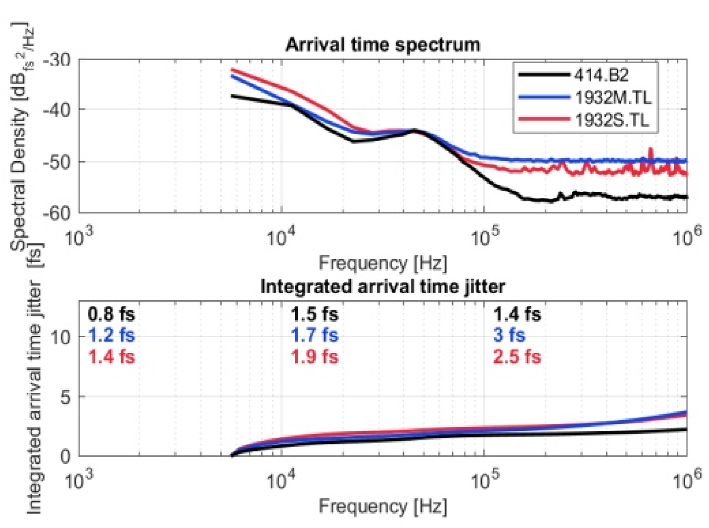
EuXFEL station 414 meter, behind the last bunch compressor.
100 kHz - 100 MHz online noise measurement shows two improvement steps
First step: Noise reduction and chromatic dispersion
Second step: Amplitude and bandwidth

State and measurements

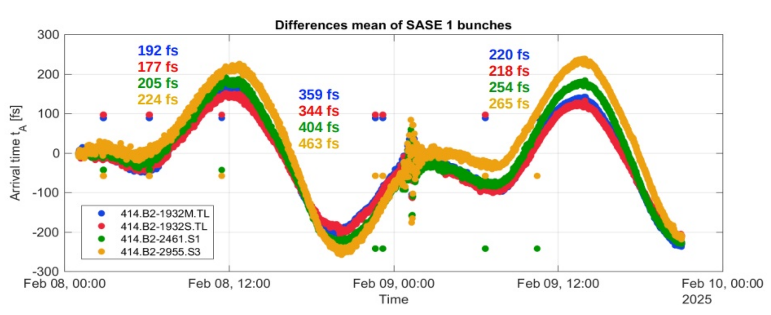


Current resolution at EuXFEL. Highlighting two latest-design measurement stations with 0.8 fs and 1.2 fs resolution. 250pC, 100 kHz - 100 MHz measurement bandwidth.

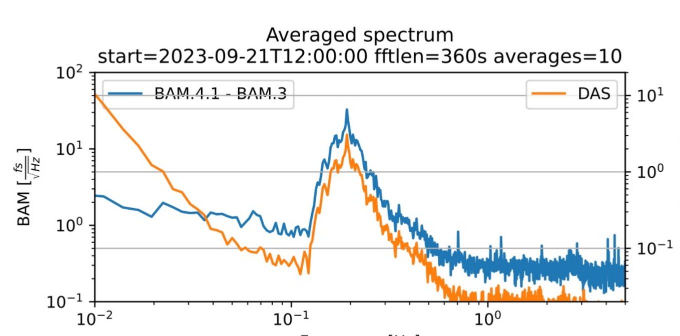




Single shot jitter measurement, 250 pC, aperture 40.5mm in linac, 22.5mm in photon tunnels, 400 bunches, 100 macropulses, fast intra-train feedback in and out of the loop (1.5 km later) synchronization measurement.



Tidal effects as measured by BAMs at different locations.



Ocean wave effects measured by BAM vs DAS system. [Erik Genthe, et al., High Power Laser Science and Engineering 2025]

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