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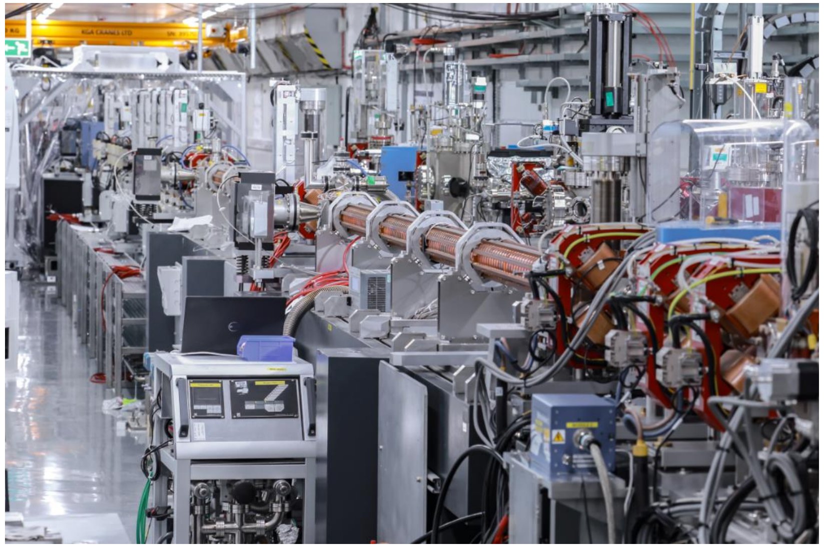
Optical Synchronisation Systems on CLARA

INFN LLRF Topical Workshop, INFN, Frascati

Alexander Aiken,
STFC Daresbury Laboratory
29th October 2024

Introduction and Background

- Synchronisation engineer with the Accelerator Science and Technology Centre (ASTeC) based at Daresbury Laboratory, UK.
- Based within the Femtosecond Lasers and Timing (FLT) Group, ~10 staff working on photoinjector laser, high power laser and optical synchronisation systems for ASTeC projects.
- Compact Linear Accelerator for Research and Applications (CLARA) forms a large part of current effort.



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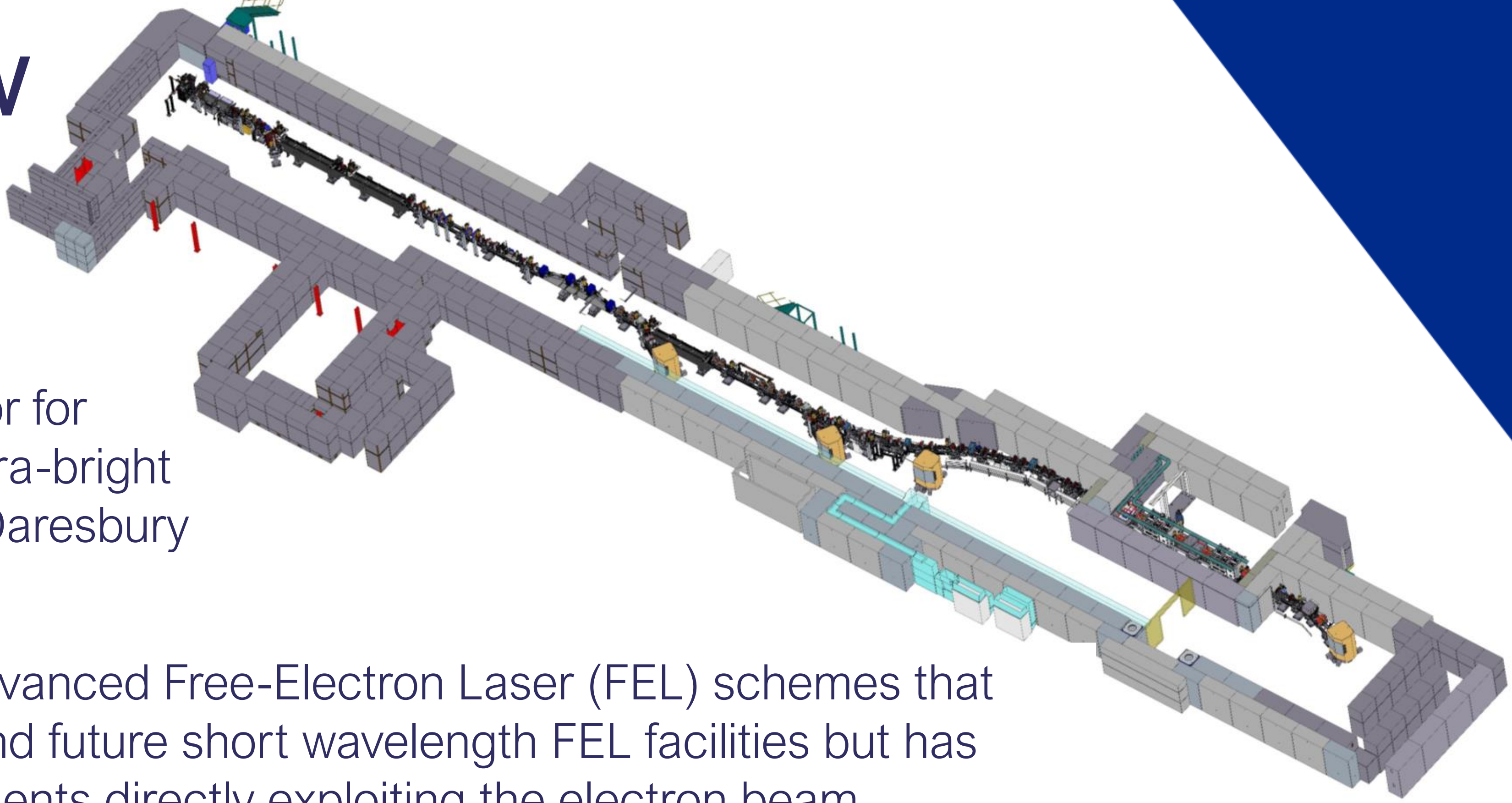
CLARA Overview



CLARA (Compact Linear Accelerator for Research and Applications) is an ultra-bright electron beam test facility at STFC Daresbury Laboratory.

The facility was conceived to test advanced Free-Electron Laser (FEL) schemes that could be implemented on existing and future short wavelength FEL facilities but has additionally found a niche in experiments directly exploiting the electron beam.

From 2025 onwards, CLARA will run as a user facility allowing scientists to perform a wide range experiments including novel acceleration (plasma/dielectric/THz), VHEE radiotherapy, light source development, accelerator diagnostic development.

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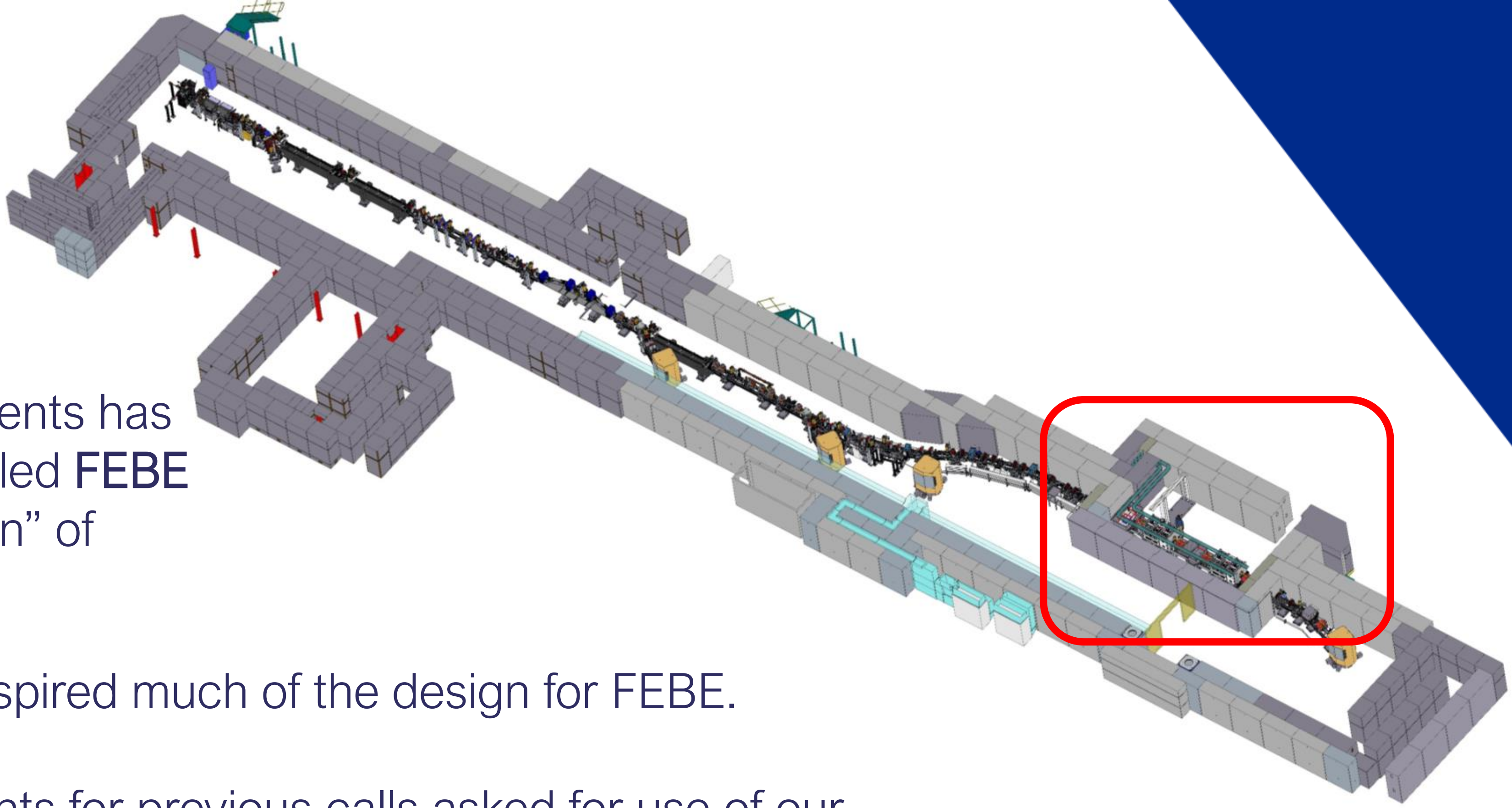
CLARA Design Details: Angal-Kalinin D, Bainbridge A, Brynes AD, Buckley RK, Buckley SR, Burt GC, Cash RJ, Castaneda Cortes HM, Christie D, Clarke JA, Clarke R. Design, specifications, and first beam measurements of the compact linear accelerator for research and applications front end. Physical Review Accelerators and Beams. 2020 Apr 1;23(4):044801.

CLARA - FEBE



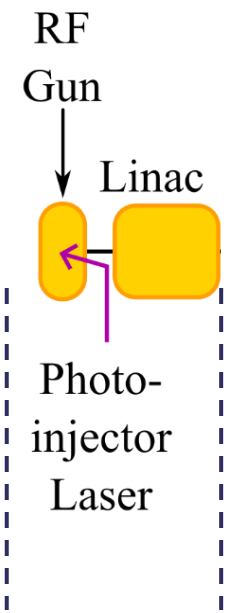
A dedicated space for user experiments has been constructed, this has been called **FEBE** or the "Full Energy Beam Exploitation" of CLARA.

This replaces beam area 1 which inspired much of the design for FEBE.

Around half of all the user experiments for previous calls asked for use of our terawatt laser system and we had demand for higher intensities on target. To expand the capabilities of the facility and better meet the demands of users, a band new 120 TW laser system will be available to users in the experimental area.

FEBE design details: [E Snedden et al, PRAB, 27, 041602 (2024)]

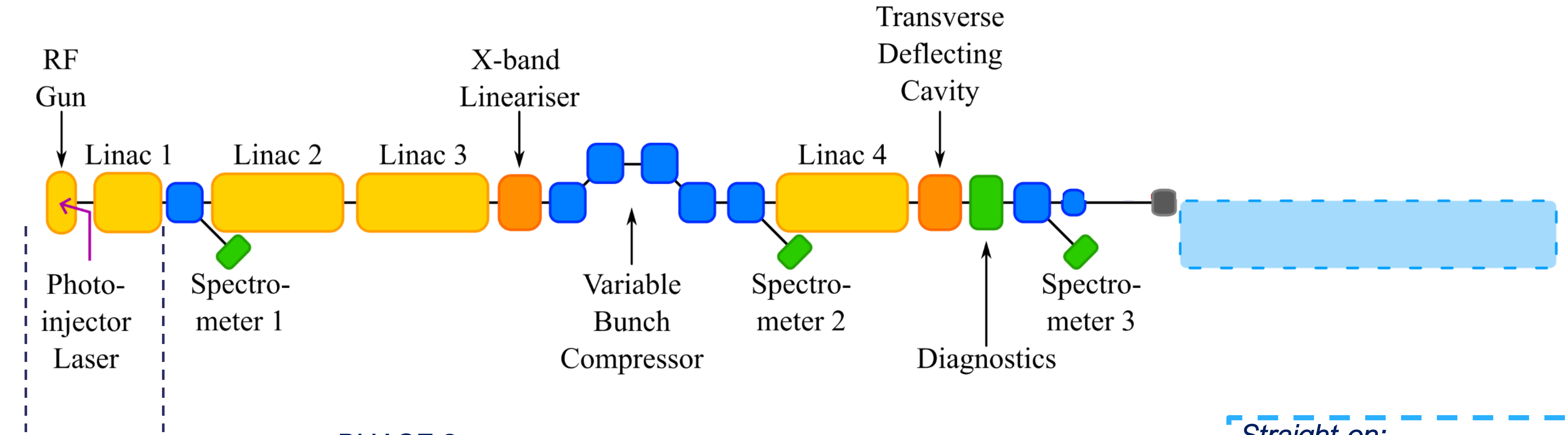
CLARA & FEBE Overview



PHASE 1:
50 MeV,
250 pC, 10 Hz

- Beam moved to VELA line after linac
- Transported to “Beam Area 1” (BA1) for beam exploitation.

CLARA & FEBE Overview



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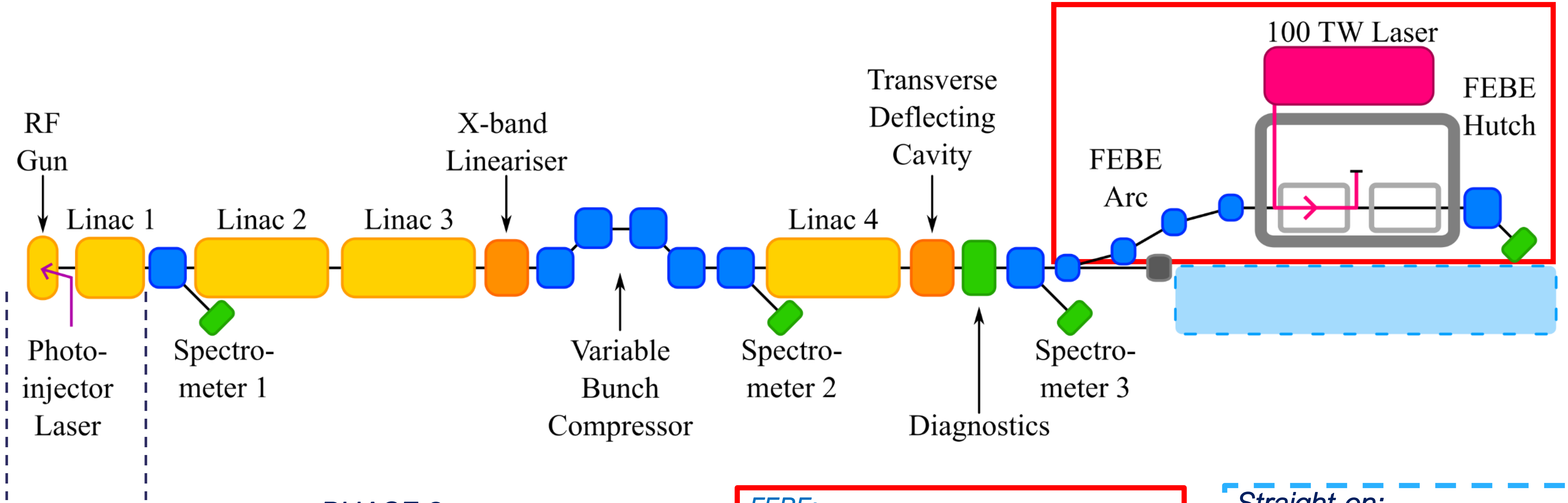
PHASE 2:
250 MeV ASSEMBLED & INSTALLED OFFLINE

- 2022/23: Installation
- 2023/24: Commissioning

Straight-on:
FEL technology development
NOT YET FUNDED

- Tied to UKXFEL CDR and decision on next stages

CLARA & FEBE Overview



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FEBE:
SHIELDED USER FACILITY

- Branch line to shielded hutch
- Flexible user exploitation space
- 100 TW class laser

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NOT YET FUNDED

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FEBE Experimental Hutch

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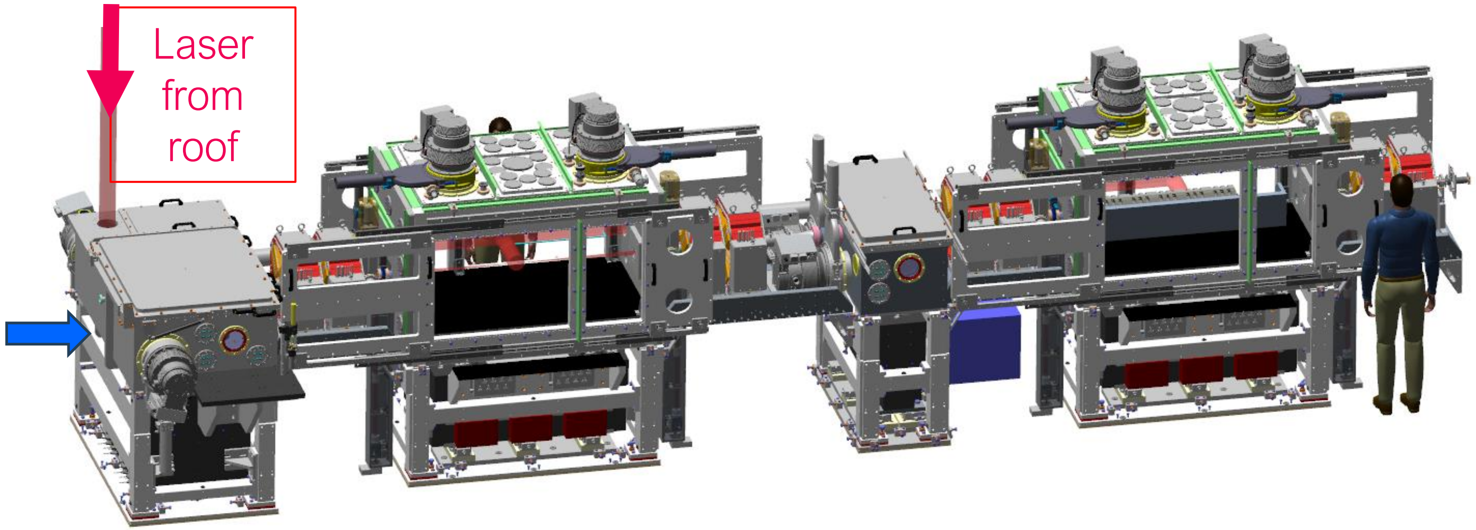
Two chambers: possible route to 'interaction' and 'characterisation' experiments with novel components.



250 MeV FEL ready e- beam

FEC1
Primary IP
~1.5m length

FEC2
Flexible array of diagnostics

FEBE design details: E Snedden et al, PRAB, 27, 041602 (2024)

Offered parameters to evolve
'Day 1' → *Nominal* → *R&D*

Parameter	High charge	Low charge
Energy [MeV]	250	250
Charge [pC]	250	5
RMS t [fs]	100 (10)	50 (≤10)
σ_E/E [%]	<5 (1)	<1 (<1)
RMS x [μm]	100 (50)	20 (1)
RMS y [μm]	100 (50)	20 (1)
ε_N x @ 250 MeV [μm]	5 (<5)	2 (1)
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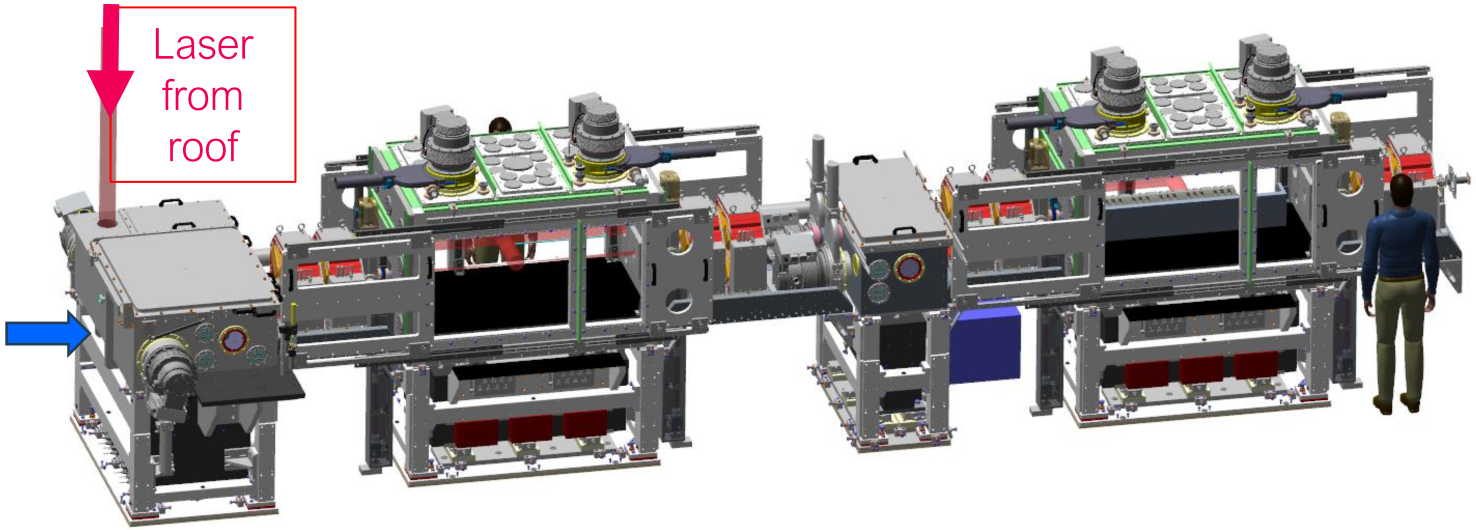

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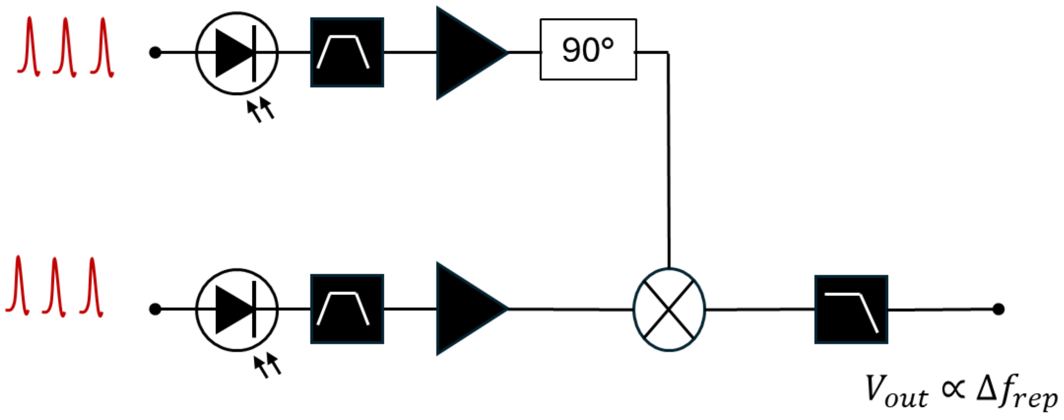
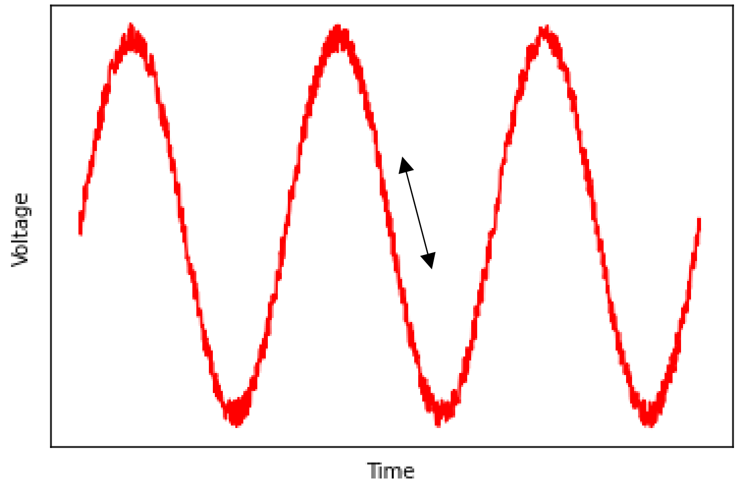
A Case for Optical Synchronisation Systems

- The process of photodetection limits the performance that can be expected by a purely RF/microwave-based solution.
- The timing sensitivity of microwave phase detectors + AM-PM conversion processes and noise properties of photodiodes limit their resolution.
- For the resolution below 10s fs timing measurements, better to exploit optical and/or electro-optic techniques.

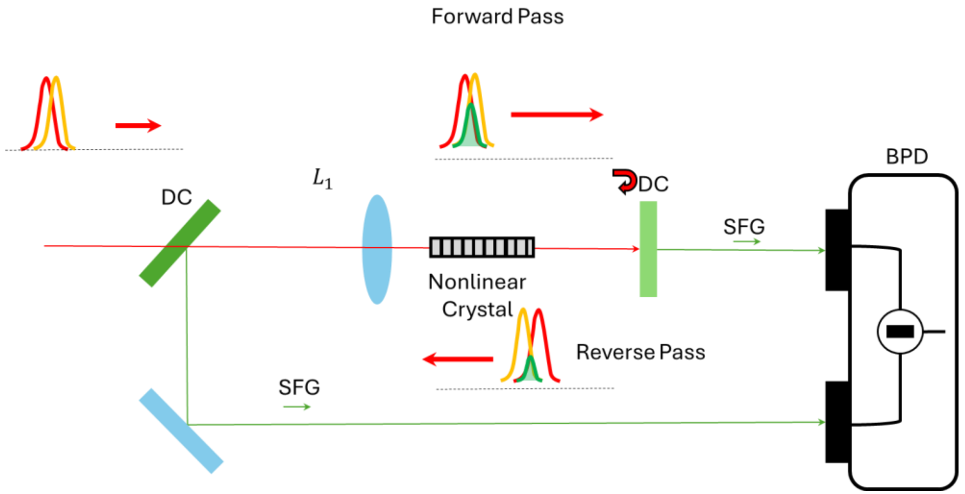


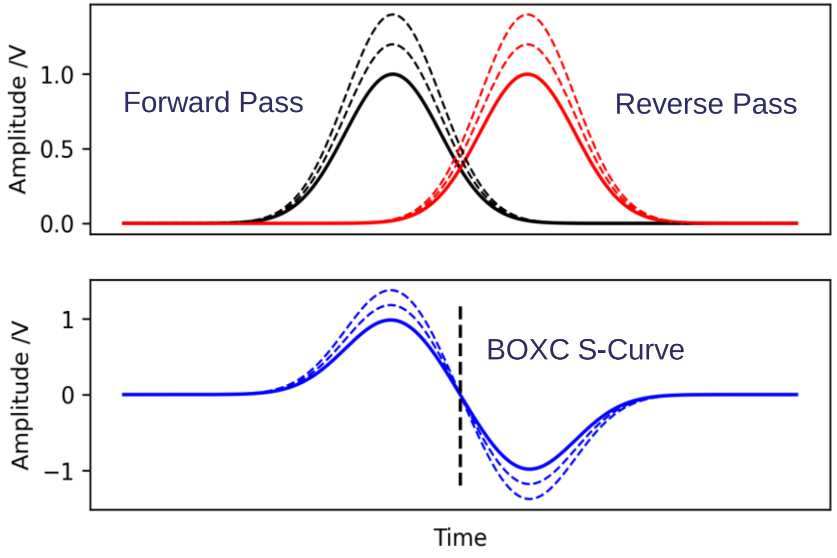


Typical Output

Optical Cross Correlators

- Nonlinear optical processes e.g. SFG can be extremely time/position sensitive.
- By switching the mixing process to the optical domain, we can detect changes much smaller than the duration of the pulses used.
- With access to ultrashort pulses, we can therefore make very sensitive phase detectors.
- Optical cross correlators perform this function. The optical design will vary slightly depending on the wavelengths involved/ sources to be synchronised.
- Through taking a balanced optical measurement of the incident light, common mode sources of noise between the lasers are also eliminated.
- The timing sensitivity curve of the device is a characteristic S-Curve





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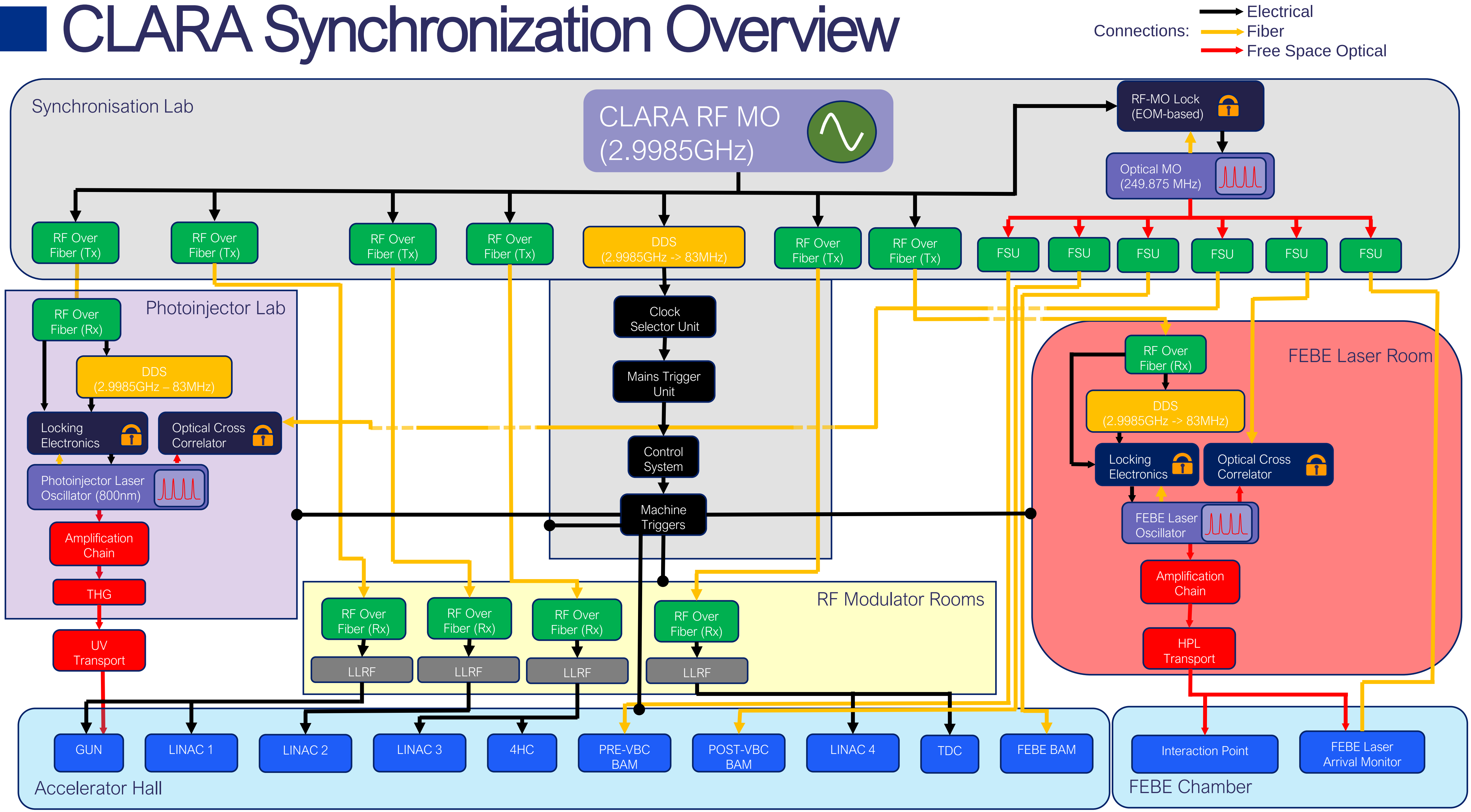
CLARA Synchronization Overview

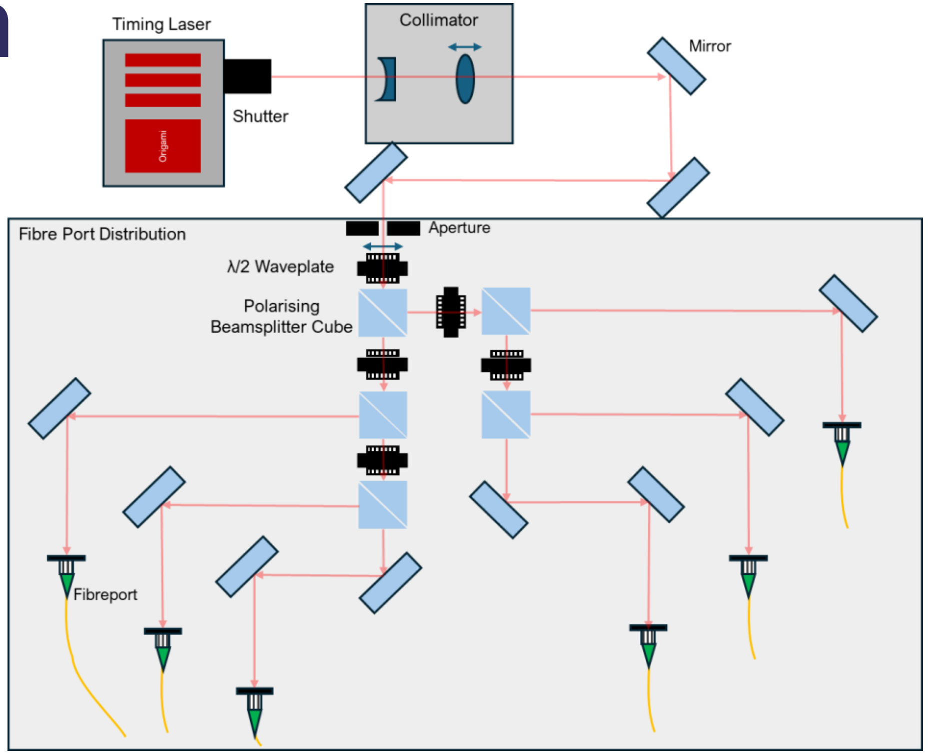


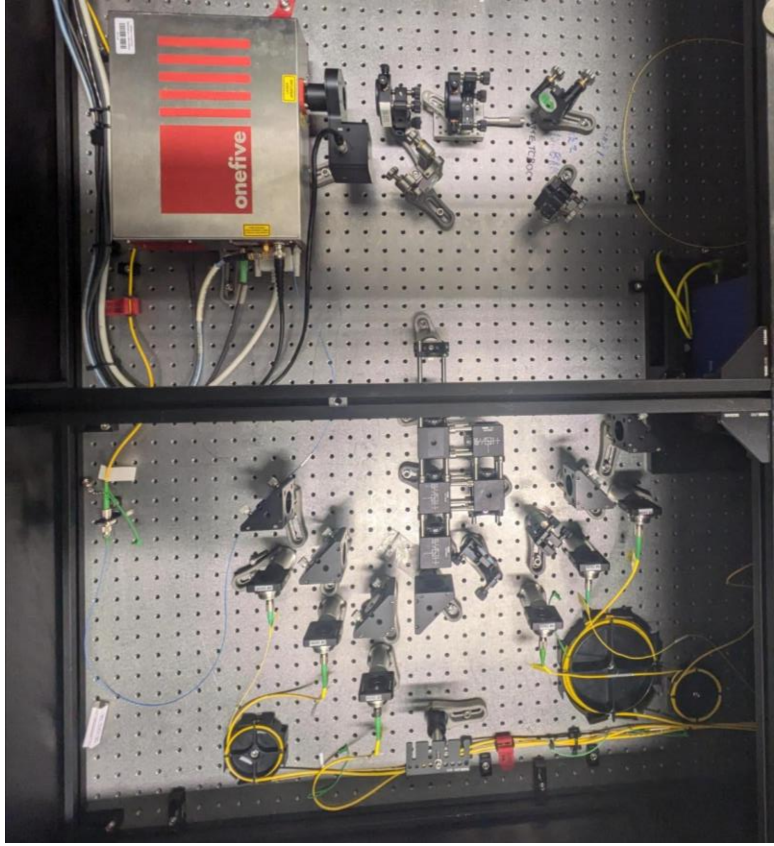
CLARA Synchronization Laboratory

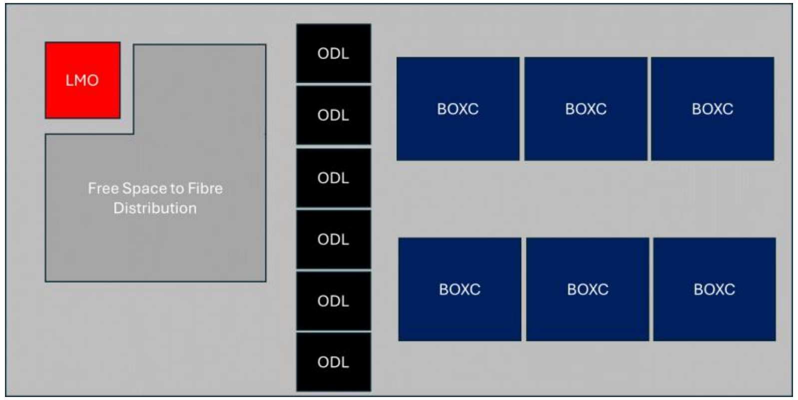
- Hosts:
  - RF Master Oscillator (2.9985 GHz, Laurin AG)
  - RF-over-Fibre Reference Transmitters (Instrumentation Technologies Libera Sync3)
  - Laser Master Oscillator (249.875 MHz, OneFive Origami-15)
  - LMO reference distribution + fibre stabilisation units (FSUs)
  - Synchronous 83MHz Generation, basis for control system and generating various machine triggers.

LMO Distribution

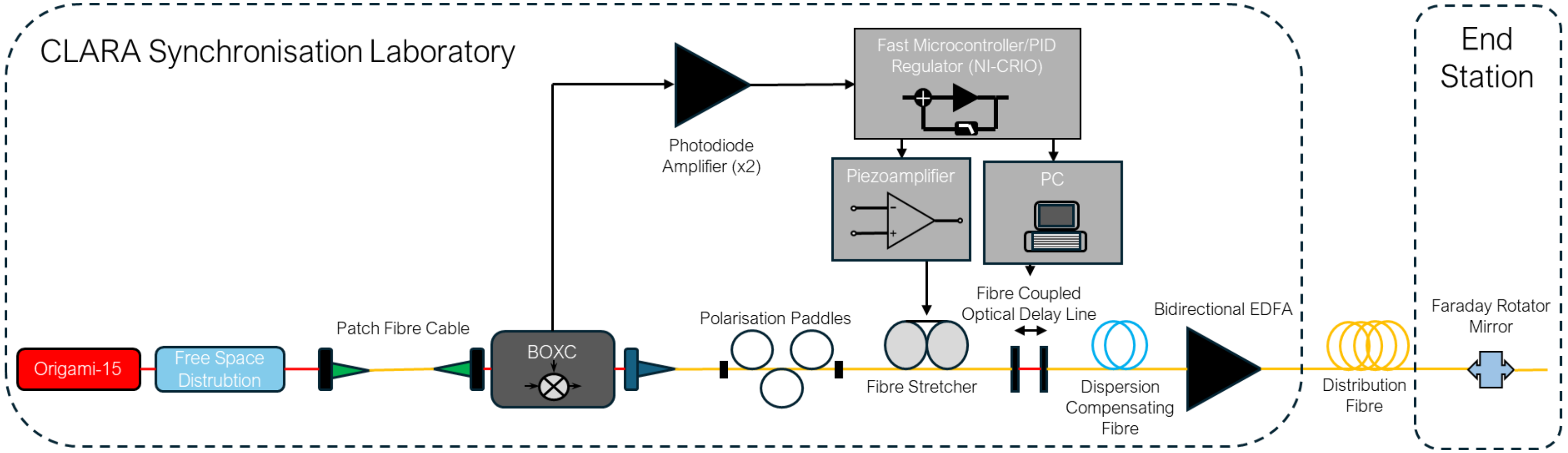
- Timing laser output equally split and coupled into 6 fibres for distribution across the accelerator
- Equal distances to all fibre ports/ODLs/BOXCs to reduce the effect of differential drifts to a minimum.





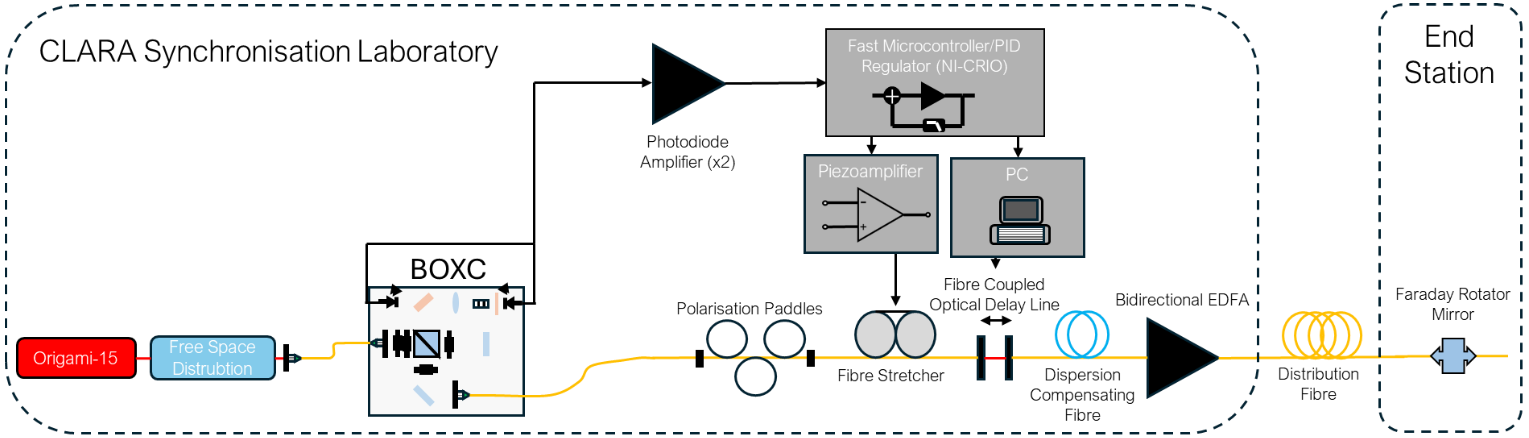


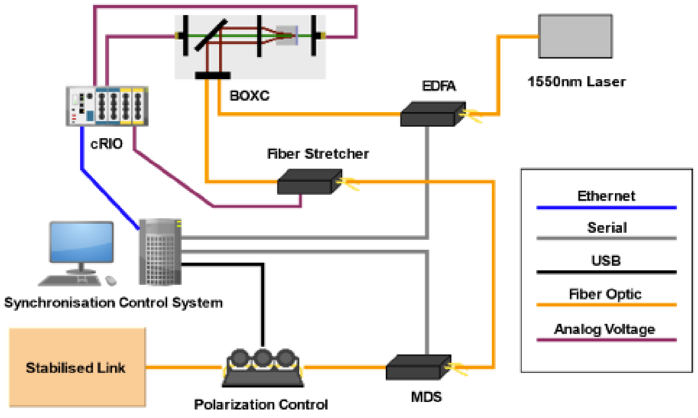
Optical Table Layout

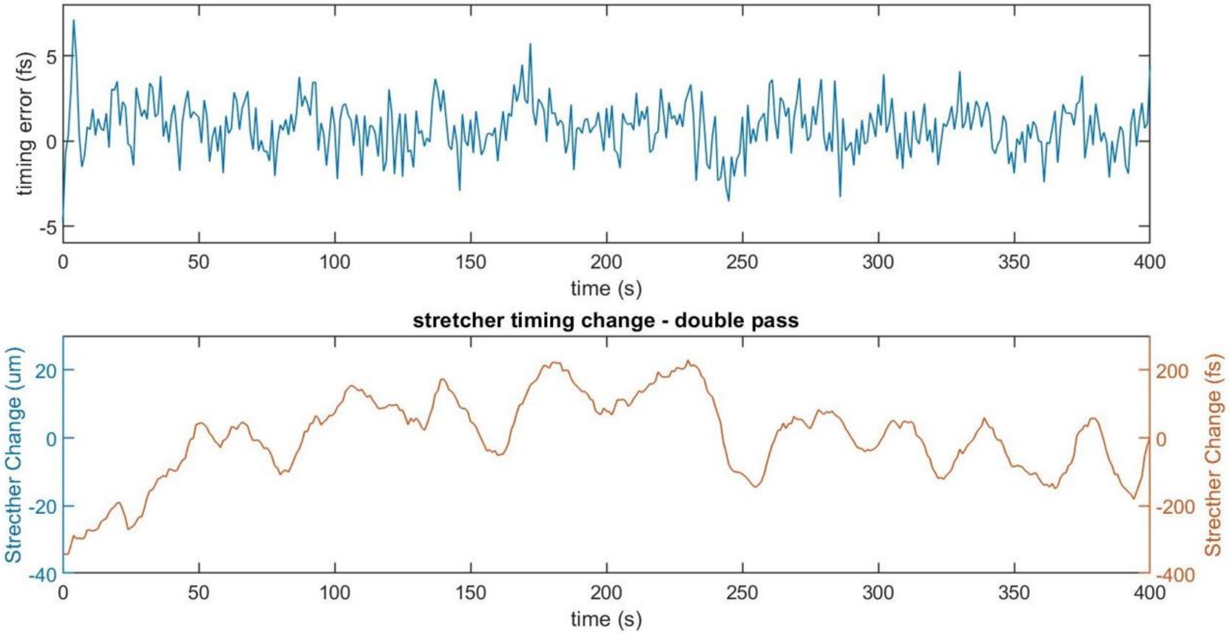


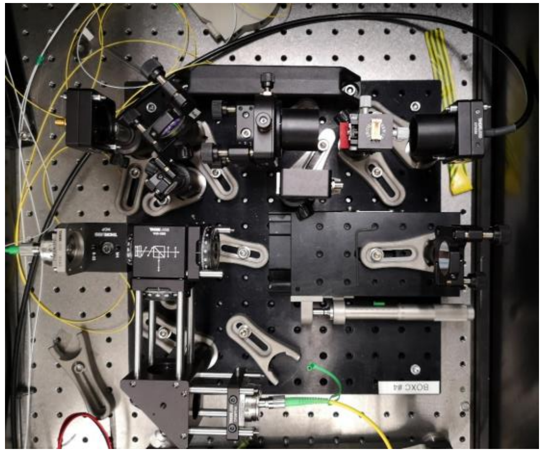
Stabilised Fibre Optic Links

- Stabilised transport fibres for the optical clock distribution across the full ~120m length of CLARA
- Development link system achieved <5fs peak to peak, 1.5fs rms jitter (in loop measurement).
- Revised due to a need for out of loop stabilisation measurements for commissioning in lab. Design was limited by optical power losses.







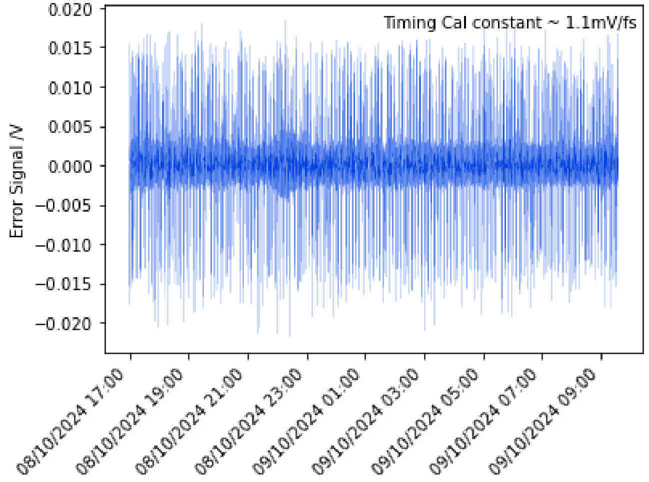


Stabilised Fibre Optic Links

- Close to recreating performance of development design on Pre-VBC Bunch Arrival Monitor link. Still some problems to smooth out.
- Beginning to see drifts and interesting behaviour in the facility. Too early to comment on sources and whether the drift is problematic!
- A well-controlled laboratory reference link and links to other parts of CLARA are needed to compare against.
- FEBE laser link and remaining 2 BAM links are soon to follow.

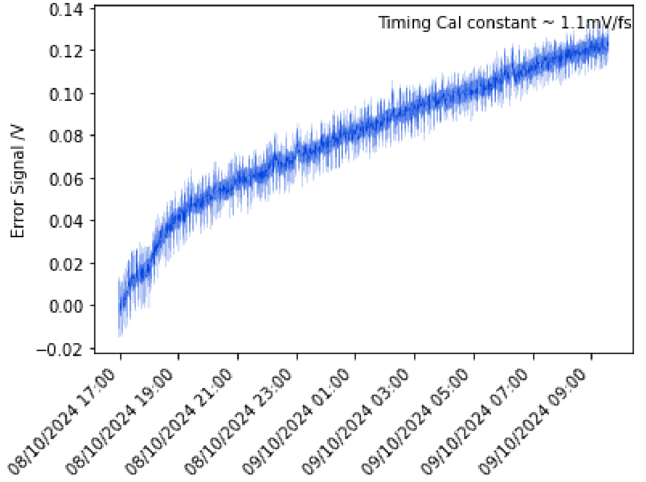
In loop BOXC Error

*~20fs peak to peak jitter due to a bad ODL. Nominally <5fs is estimated.

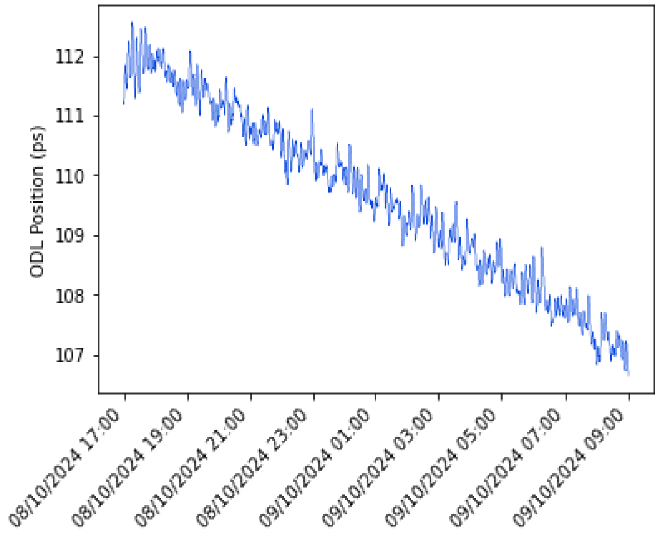


Out-of-loop BOXC Error

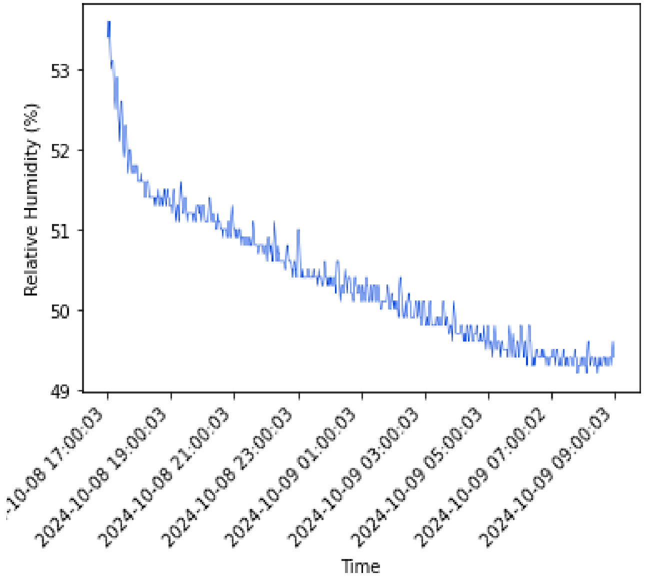
>100fs drift observed, origin TBC



In-Link ODL

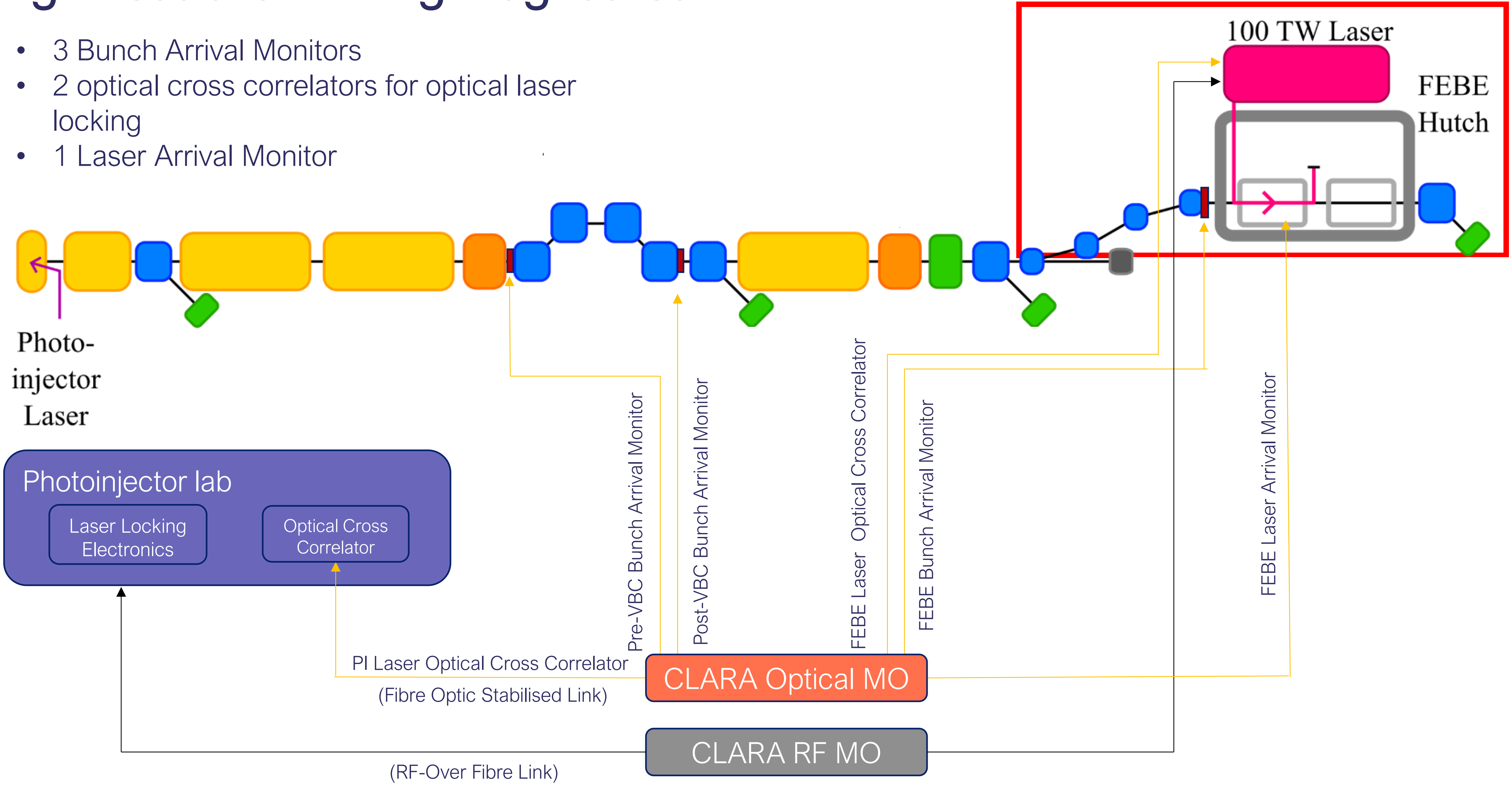


Laboratory Humidity



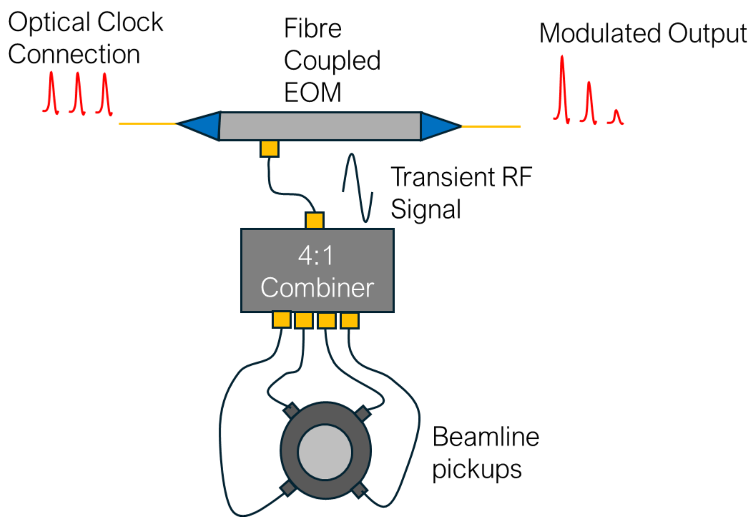
High Resolution Timing Diagnostics

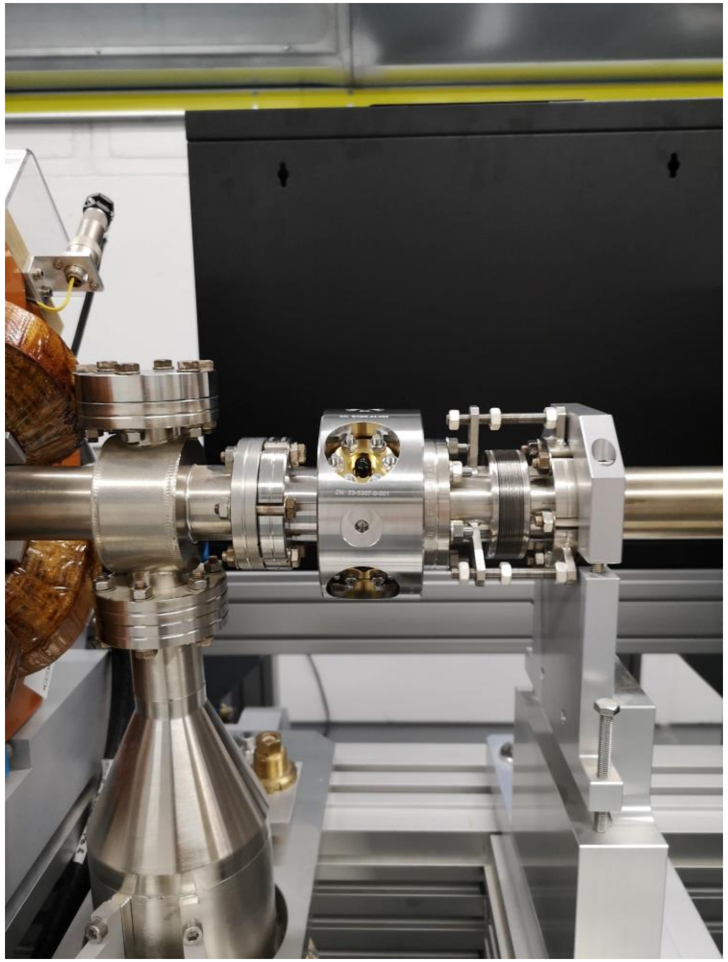
- 3 Bunch Arrival Monitors
- 2 optical cross correlators for optical laser locking
- 1 Laser Arrival Monitor



Electron Bunch Arrival Monitors

- High resolution timing diagnostic for the electron beam. To be used for FEBE area TOA measurement and fast feedback timing correction on variable bunch compressor.
- Procured from DESY, designed and created by MSK group.
- Due for commissioning with electron beam in spring/summer 2025.
- Based on performance at other facilities, <10fs timing resolution is anticipated [].





Beamline pickup unit

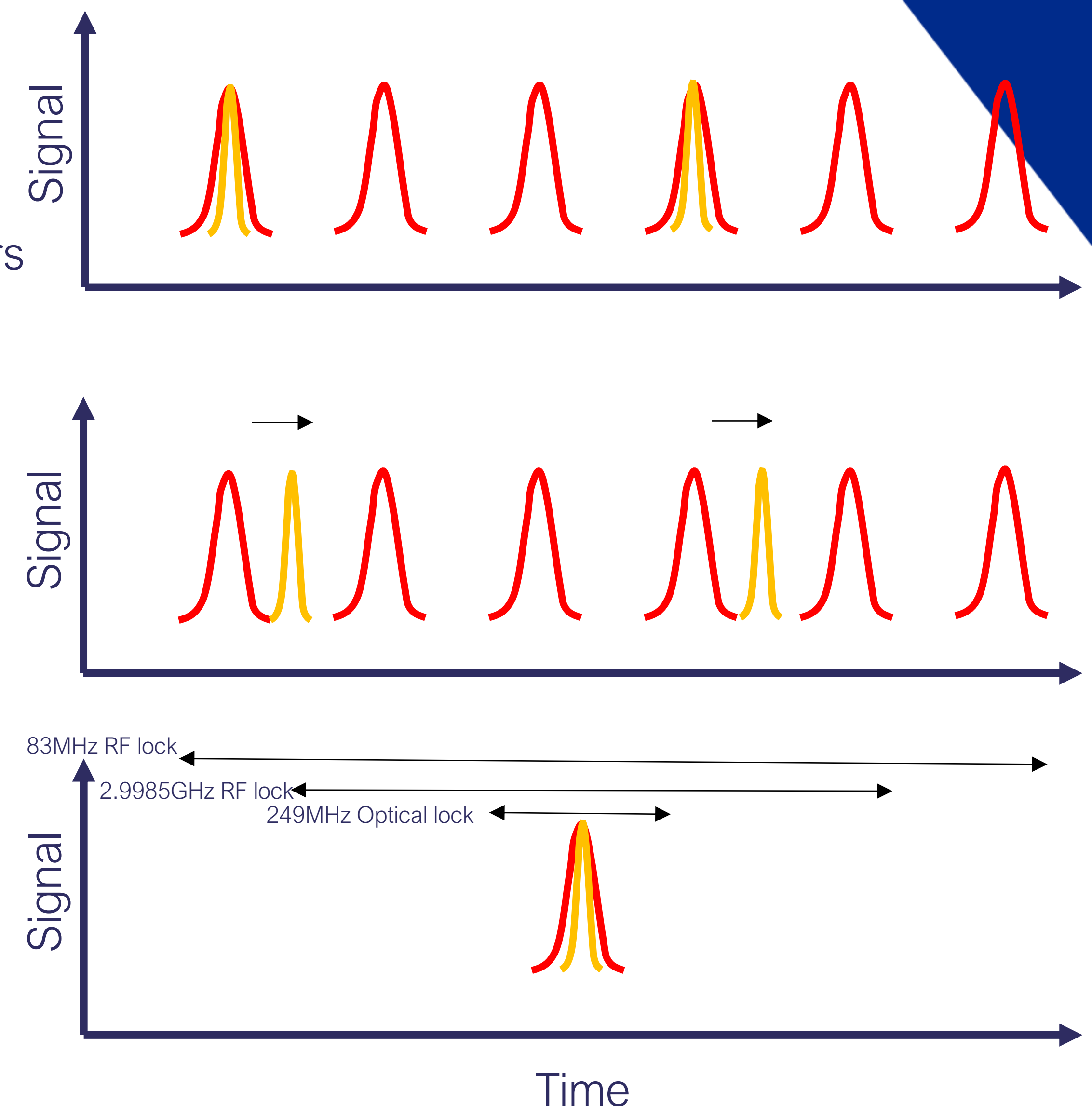
Electro-optic Special Diagnostics unit

Laser-Laser Locking

- To enable the delivery of pump-probe style experiments, the FEBE Terawatt and Photoinjector laser systems must be brought into the timing system and locked to the facility MLO.

- Offering a versatile 3-level locking scheme is planned. Users will be able to perform scans of increasing timing precision but decreasing range:
  - RF lock at 83MHz (fundamental)
  - RF lock at 2.9985 GHz (Harmonic)
  - Optical lock using optical cross correlator

- Commercial solution currently under procurement.
- Several options available for the optical locking signal:
  - Commercial unit (Menlo BCC-PD).
  - In house two colour cross correlator.
  - Fibre-based two-colour cross correlator



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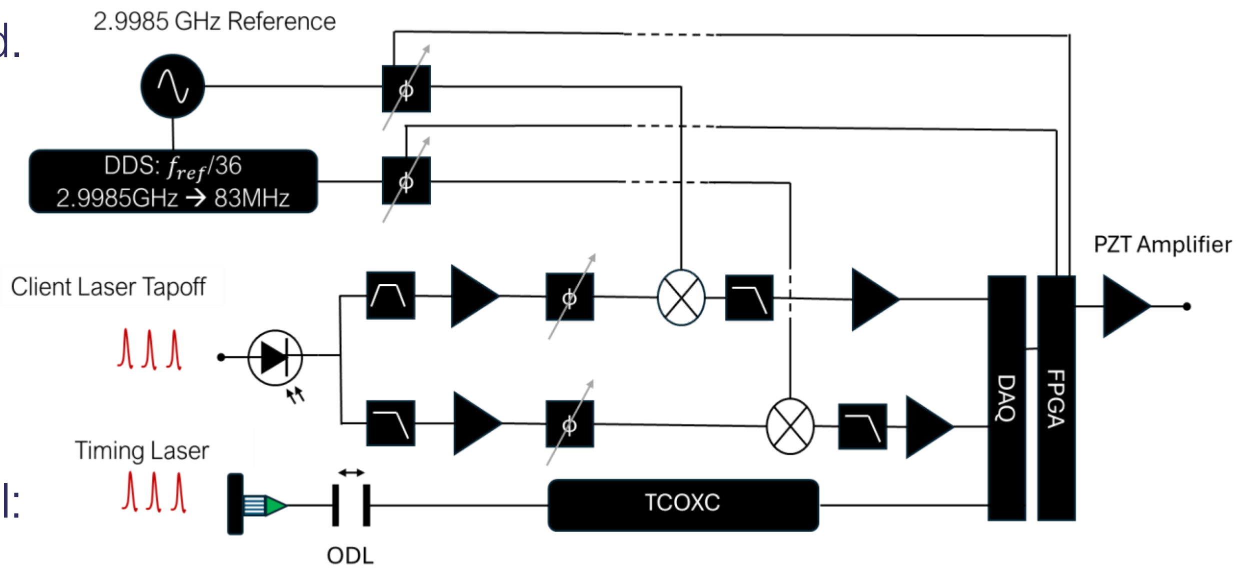

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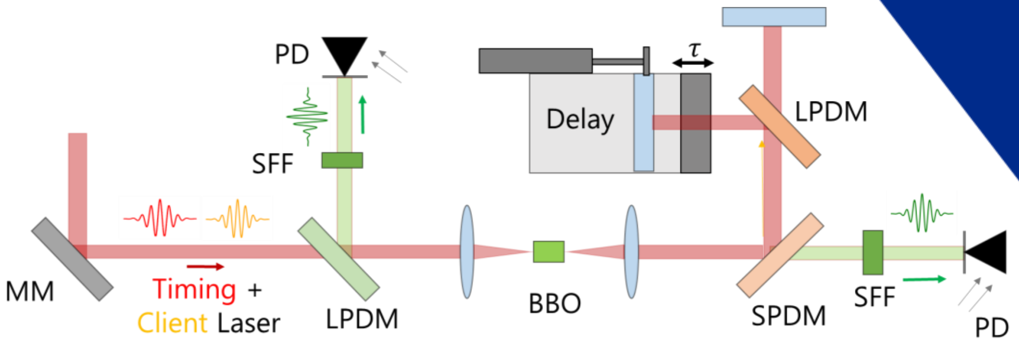
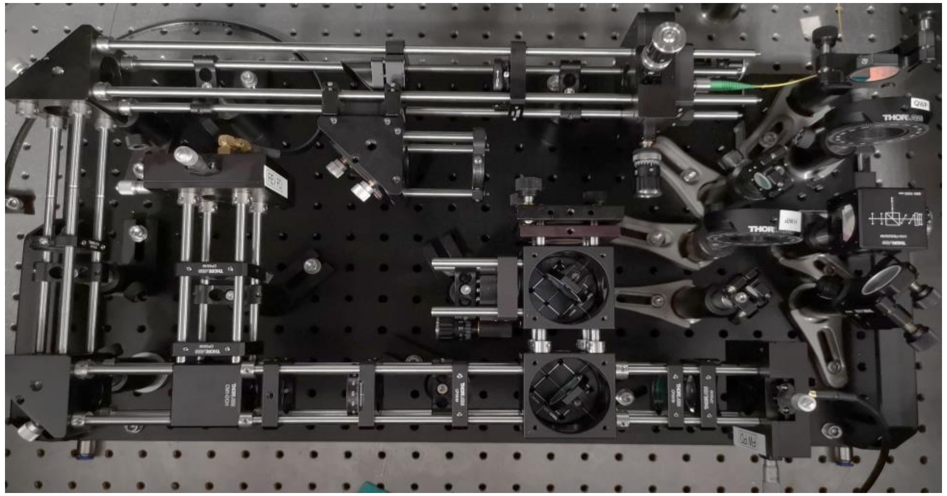
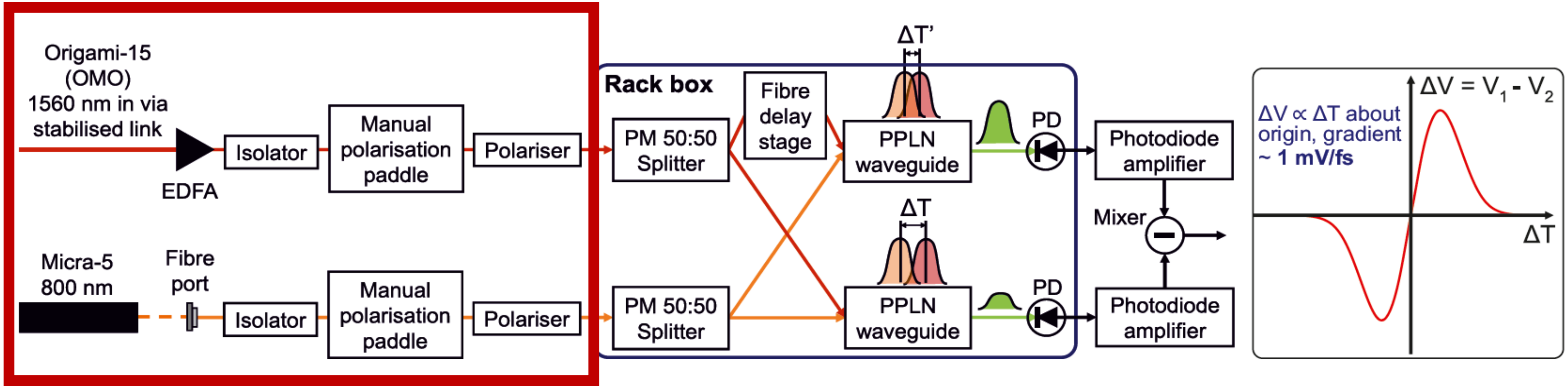




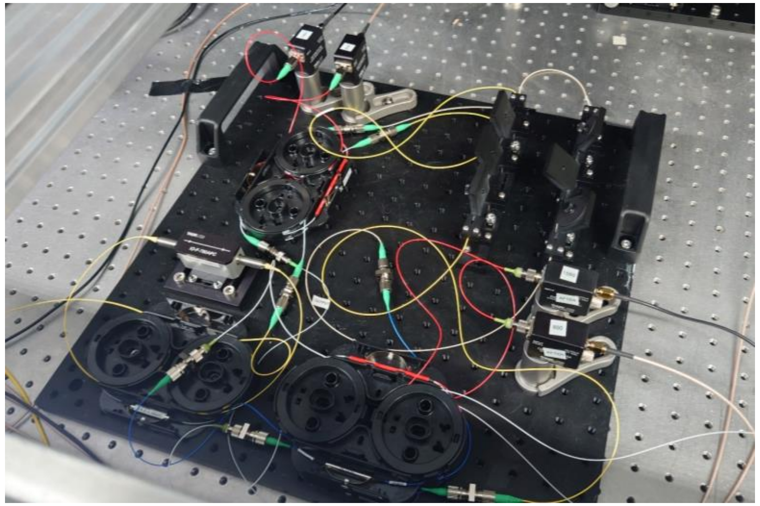
Fibre-based Two-Colour Cross Correlator



Coupling and Polarisation:

1560 nm and 800 nm coupled into fibre, travel to separate fibre polarisation paddles and polarisers to ensure correct polarisation for periodically-poled lithium niobate (PPLN) waveguides.

- Both wavelengths travel in optical fibre matched to respective wavelengths.
- After paddles, polarisation-maintaining (PM) fibre is used to prevent polarisation changes.



Christie J. *Femtosecond Synchronisation for Externally-Injected Laser Wakefield Acceleration at CLARA* (Doctoral dissertation, University of Liverpool).

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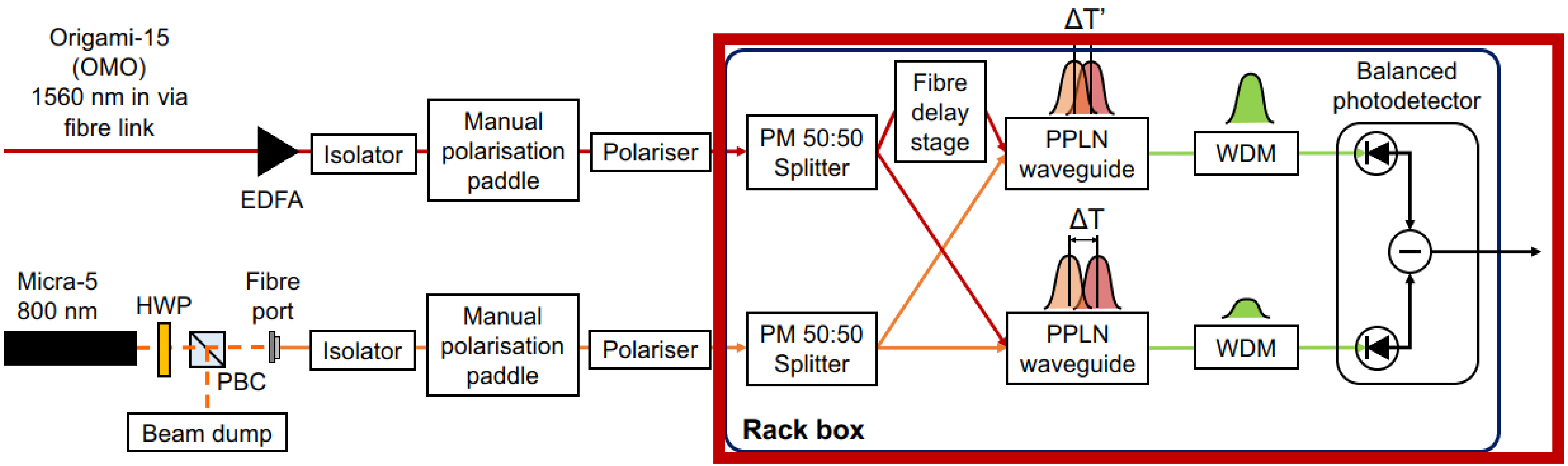

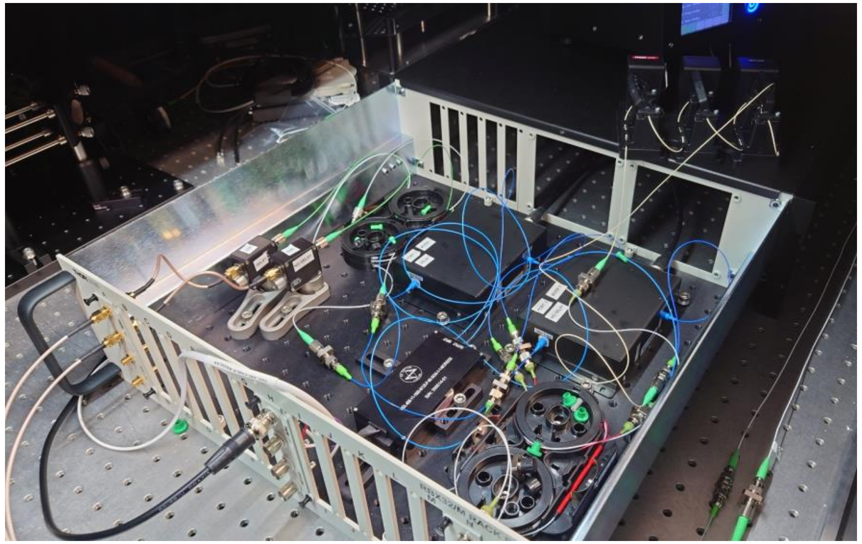

Sum-Frequency Generation:

Pulses are split 50:50 and sent to separate PPLN waveguides.

- Fibre delay stage imparts additional time delay D to one of the 1560 nm components.
- Sets of pulses have different delays ΔT and ΔT' = ΔT – D.

Waveguides generate two sum-frequency pulses with different intensities due to different temporal overlap of pulses.

- Converted to electrical signals by identical photodetectors (PDs).

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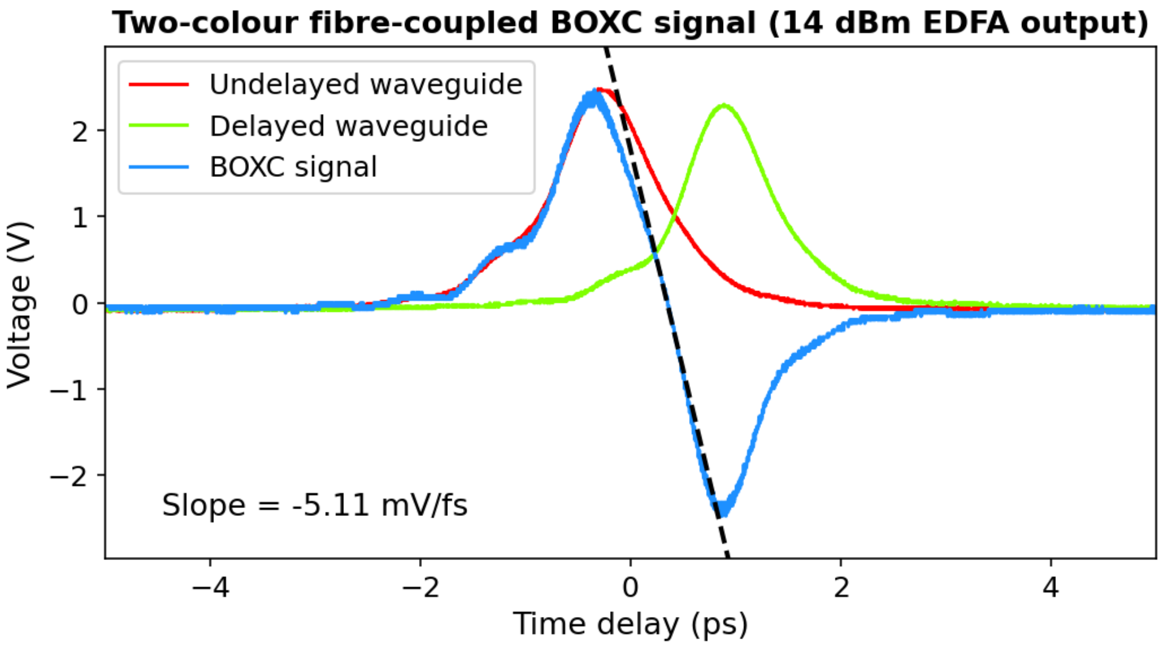
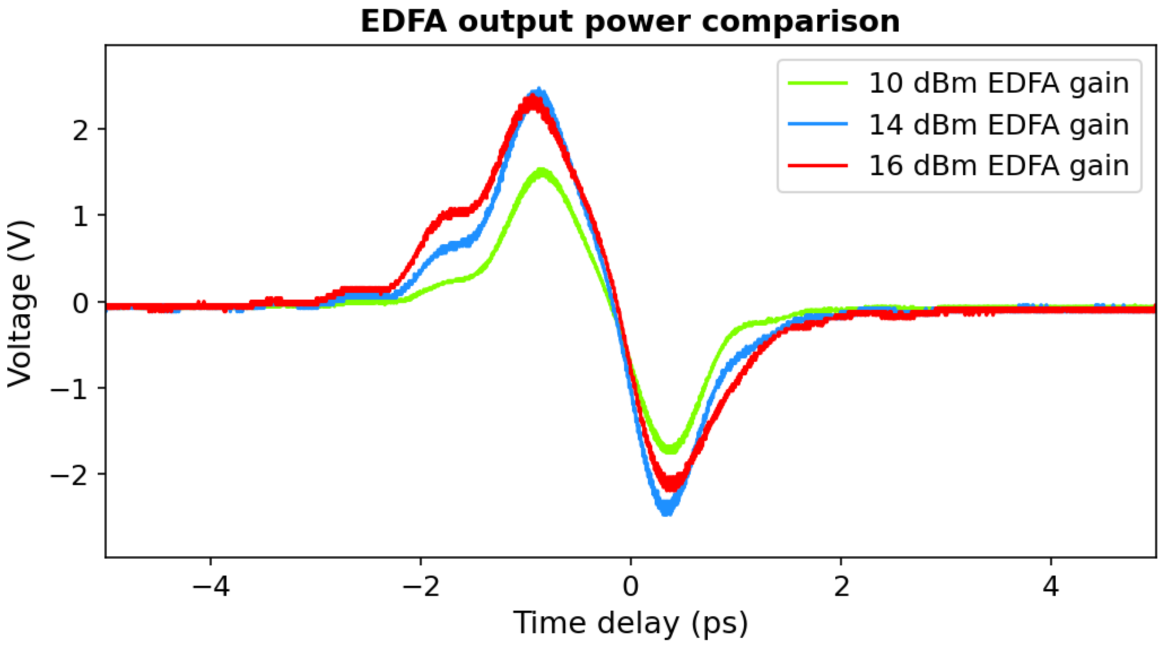
Fibre-based Two-Colour Cross Correlator





Using current setup, BOXC sensitivity of 5.1 mV/fs achieved.

- 5 times greater than current free-space two-colour BOXCs [1].
- Sensitivity increases with input power, up to a point…

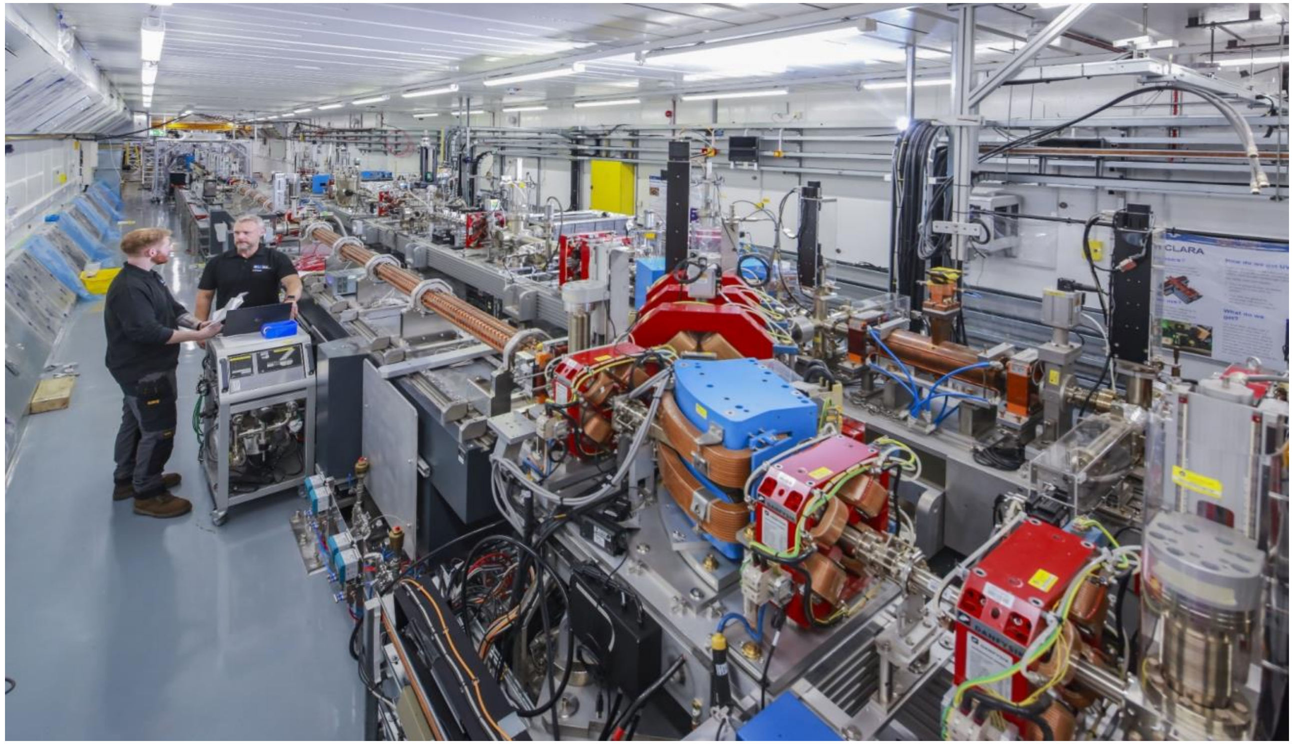
Sum-frequency signal much narrower than 800 nm pulse width.

- Due to large frequency chirp of 800 nm and 1560 nm pulses from fibre dispersion.
- Potential to increase sensitivity by reducing laser pulse durations via dispersion compensation.

[1] - C. Li *et al*, "Two Color Balanced Optical Cross Correlator to Synchronize Distributed Lasers for SHINE Project," *JACoW* IBIC2021 (2021) WEPP05.

Closing Remarks

- CLARA's optical synchronisation systems are aiming to deliver <10fs rms jitter between the electron bunch and laser beam TOA.
- Commissioning of optical clock distribution is making progress. However, there is still a large amount of progress to be made to reach our target.
- Majority of systems to be commissioned over the next year. Stay tuned for further updates.
- Thank you for listening!



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Thank you

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