

AWAKE LASER SYNCHRONISATION AND OPTICAL TIMING DISTRIBUTION NETWORK*

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Abstract

Synchronisation of distant sub-systems is a key challenge for the AWAKE experiment at CERN, which demands femtosecond-level arrival-time stability between interacting electron bunches and laser pulses. After upgrades due for completion in 2029, the distributed AWAKE laser system must be synchronised to below 30 femtoseconds. To synchronise multiple new additional subsystems across the enlarged facility, a new optical clock distribution network is being developed to deliver time-of-flight stabilised clock pulses to distant end-stations.

INTRODUCTION

AWAKE aims to study proton-driven plasma wakefield acceleration (PWFA) driven by SPS proton bunches. ~300 ps (picosecond) proton bunches injected into rubidium plasma displace free electrons from the central axis generating a perturbation in charge density. The expelled electrons experience an axial and radial restoring force, and exhibit strong oscillatory motion with transverse and longitudinal field components, known as wakefields. The proton bunch is much longer than the plasma wavelength, so regions where the wakefield phase is focusing or defocusing modulate the transverse size of the proton bunch. Defocused protons are periodically driven off-axis to form a long train of short proton microbunches which further amplify the wakefield amplitude towards saturation [1]. In previous AWAKE Runs (1, 2a, and 2b) long electron bunches injected into the plasma wakefield sampled every phase of the wakefield bucket. Particles at the correct wakefield accelerating phase were captured and experienced strong acceleration from resulting high gradients [2].

In previous runs, wakefield seeding was achieved using a short laser ionisation pulse a few hundred picoseconds ahead of the proton bunch. For Run 2c in 2029, the option to seed wakefields using electron bunches will be made available by repurposing the existing electron injector to insert seed bunches ahead of the proton bunch. A second 165 MeV injector will place shorter (200 fs, 100 pC) electron witness bunches into the accelerating phase of the wakefields. AWAKE Run 2c must remain able to switch between the laser-seeding mode and the new electron seeding mode. In both modes accurate laser-to-laser synchronisation is essential to ensure timely photocathode pulsing and plasma ionisation

such that incident electron bunches are synchronised with the wakefield bucket.

Additional time-of-flight (TOF) perturbations experienced by electron bunches transiting injection lines degrade any gains made to the AWAKE synchronisation system. Accordingly, a timing distribution network is being developed to distribute 88.173 MHz laser clock pulses to critically-timed subsystems. The networks must synchronise laser systems to each other, as well as to the low-level RF system. Additional links must also provide trigger signals to precision instrumentation such as streak cameras.

Recent developments in pulsed laser oscillators have advanced timing metrology and its application for the synchronisation of large scale facilities. The intrinsic stability of an optical cavity oscillator enables timing jitter reduction down to the femtosecond-range [3, 4] at high carrier-offset frequencies above 10 kHz. Limited phase-noise performance at frequencies close to the carrier is compensated by locking the oscillator to a highly stable RF source with a phase-locked-loop (PLL) over a bandwidth (BW) of near-DC up to the cross-over point where optical phase-noise performance exceeds the RF reference, typically a few kHz. Such schemes are extensively detailed in literature where residual integrated timing jitter close to the carrier has been observed down to 2.9 fs (10 mHz - 10 kHz) [5]. At higher offset frequencies where optical oscillators exhibit lower phase-noise, commercial solutions offer timing jitter down to 2 fs (10 kHz - 10 MHz) when free-running [6].

MOTIVATION

Changes made to AWAKE for Run 2c will enhance the synchronisation requirement for the experiment to reach baseline performance. These include:

- The witness electron bunch will be shortened from 3 ps to 200 fs [7].
- The electron witness bunch will originate from a new 165 MeV electron injector, while the existing 18 MeV injector will seed the wakefield phase [7].
- The experiment will introduce a second laser oscillator to pulse both electron photocathodes [8].
- Laser-based seeding will remain as a second, separate operating mode.

Firstly, the shortened witness electron bunches no longer extend over the full length of the wakefield plasma bucket. Hence they only sample a small phase interval of the longitudinal accelerating field. For event-to-event repeatability the witness bunch must be placed precisely at the correct

* With thanks to STFC UK for supporting and funding this studentship, as well as AWAKE UK.

accelerating phase with respect to the plasma bucket. This tightens the timing requirement for injection from several picoseconds to a fraction of the 200 fs witness bunch length.

The leading electron seed bunch sets the wakefield phase. Hence the residual jitter between the two electron bunches must be small relative to the plasma wavelength (~ 1 mm) for the witness to observe the correct accelerating phase.

Of particular relevance is the synchronisation between the two laser oscillators which ionise the plasma in the laser-seeding mode and pulse the photocathodes. In previous runs, a single laser oscillator fulfilled both functions. Both lasers must now receive stabilised reference signals from additional synchronisation infrastructure.

In the electron-seeding mode, the electron bunch timing specification is defined as sub-30 fs residual timing jitter of the delay between the AWAKE seed and witness bunches. The bunch spacing is on the order of a few hundred picoseconds, and must be stabilised to better than 30 fs [9]. Similarly in laser-seeding mode the timing specification is defined as the residual timing jitter of the delay between the witness bunch and the plasma ionisation pulse in the plasma, and must be synchronised to the same level of accuracy.

OPTICAL CLOCK DISTRIBUTION

The upgraded AWAKE optical clock distribution network will use a pulsed laser source at 1560 nm, with 88.173502 MHz repetition-rate, and 100 fs pulse duration. Optical power is split and distributed to multiple end-stations in a star-network configuration over SMF28 single-mode (SM) fiber. An example layout is shown in Fig. 1. Client sub-systems include laser synchronisation hardware, bunch arrival-time monitors, cavity controllers and streak cameras.

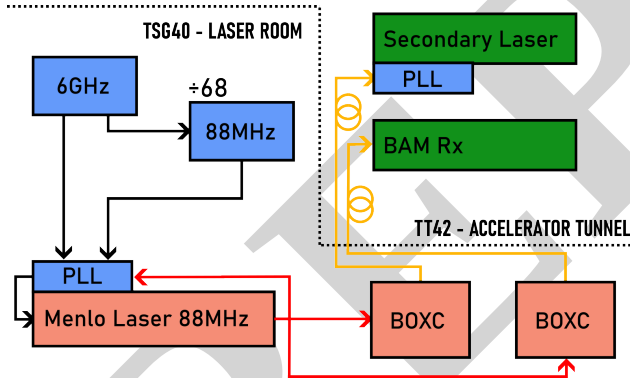


Figure 1: Overview of AWAKE synchronisation scheme. The MENLO optical oscillator dual-stage locking system is shown, as well as the planned layout of the 88 MHz clock distribution system.

The MENLO C-Fiber 780 main optical oscillator is locked to the AWAKE RF reference source in a dual-stage configuration at the AWAKE fundamental frequency, 88.173502 MHz, and at the 68th harmonic. The coarse lock is achieved by direct photodetection and RF phase detection in the accompanying MENLO RRE Syncro unit. The second locking stage

at 5995.798136 MHz is more sensitive, and is performed in an external MENLO optical-microwave phase detector.

Round-trip TOF errors in each link are detected in a balanced cross-correlator (BOXC) unit. A fraction of inserted light is stored in a short reference arm which can be assumed to be stable. A TOF perturbation on the long-link is associated with non-ideal overlap of the returning pulse with respect to the stored reference when made colinear in a Periodically-Poled Potassium Titanyl Phosphate (PPKTP) crystal. Spatio-temporal overlap in the crystal is indicated by a weak sum-frequency generation (SFG) signal. The two pulses are distinguishable by cutting the crystal to optimise for Type-II phase-matching [10], such that no SFG signal is generated when only one pulse is present. Periodic-poling preserves optical phase-matching by periodic inversion of the crystal domain which limits destructive interference for the SFG signal [11, 12]. Coupling between the fundamental and harmonic is therefore maintained over the full crystal length, thereby maximising SFG conversion efficiency. The PPKTP crystal from Svenska Laserfabriken is 2 mm long with a poling period of 45.4 μm , and features a harmonic separator (HS) coating applied to the rear face. Configuration of the BOXC unit is shown below in Fig. 2.

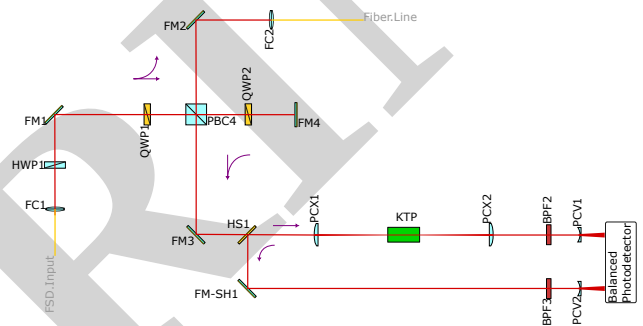


Figure 2: Layout of the BOXC unit. HWP: Half-Wave Plate; QWP: Quarter-Wave Plate; FM; Fast Mirror; FC: Fiber-Coupler; PBC: Polarising Beam-Cube; HS: Harmonic Separator; PCX: Plano-Convex Lens; BPF: Bandpass Filter; PCV: Plano-Concave Lens; FM-SH: Fast Mirror - Second Harmonic.

The HS coating reflects unconverted signal back through the crystal, generating a second backwards-travelling SFG signal. As the SFG conversion process is inefficient (on the order 10^{-5}) we assume non-depletion of the fundamental signal for the two passes. Both SFG signals are separately filtered with a 780 ± 10 nm bandpass and converted into electrical signals by a Thorlabs PDB250A balanced detector with a 1 MHz BW.

A voltage imbalance between the two photodiode outputs is indicative of a TOF error. Both photodiodes are connected in series, which subtracts their outputs generating a bipolar voltage error signal which is amplified by transimpedance and variable-gain amplifiers. The error signal is recorded using a NI-5734 16 bit 125 MS/s 4 ch ADC, and processed by a PID routine embedded on a field programmable gate array (FPGA). PID output drives two correction actuators; a

fast piezostretcher which limits the PID bandwidth to around 2 kHz, and a slow 660 ps optical delay-line.

Space constraints in the AWAKE Laser Room have motivated the design of a small production model of the BOXC unit. Figure 3 shows the compact design layout with a footprint approximately 70 % smaller than the prototype.

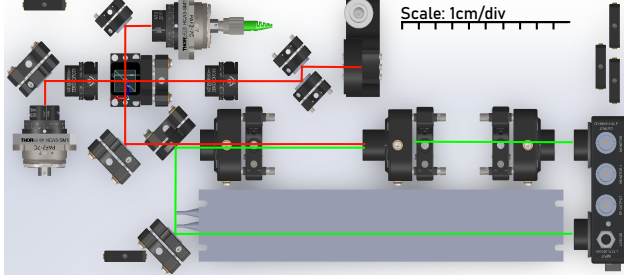


Figure 3: Miniaturised optomechanical layout of the BOXC unit. The harmonic signal is shown in green, and the fundamental signal is in red. Component layout is congruent with Fig. 2. Footprint dimensions are approximately 16 cm by 37 cm.

Stability of a 160 m fiber link is measured using two identical BOXC units for in-loop and out-loop characterisation (Fig. 4). Optimisation of PID gains is achieved with reference to a Rohde & Schwarz FSWP Phase Noise Analyser (PNA) to achieve optimal performance. Actual TOF stability of distributed clock pulses with respect to the laser reference is inspected out-of-loop (OOL).

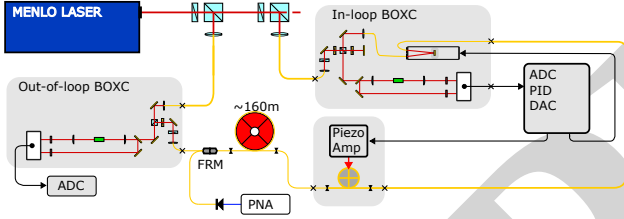


Figure 4: Laboratory setup for the AWAKE stabilised link units. Two correlators inside and outside the closed PID loop allow measurement of in-and-out loop link performance in terms of the phase-noise of distributed clock signals. PNA: Phase Noise Analyser; FRM: Faraday Rotator Mirror.

MEASUREMENT OF PPKTP RESPONSE

The cross-correlation response curve of the PPKTP crystal for incident 1560 nm link and reference pulses is measured using SFG conversion, where coincident signals are converted into the 780 nm second harmonic. Coarse longitudinal alignment of the reference and link pulse is achieved with a 660 ps fiber-coupled delay stage and a fast photodiode connected to an oscilloscope. Fine alignment involves searching for the SFG signal by incrementing the delay-stage in 10 fs ($3 \mu\text{m}$) intervals. Length-matching of normally-dispersive SMF28 SM fiber with anomalously-dispersive DCF4 SM fiber in the longer link arm minimises group-velocity-dispersion-induced (GVD) pulse-broadening, which maximises pulse peak-power P_k in the crystal and therefore SFG conversion efficiency η , which goes as $\eta \propto P_k^2$ [10].

Incident power at the crystal is 8.2 mW; the incoming signal is evenly split between the orthogonally-polarised link and reference pulses (4.1 mW each). SFG pulse power is isolated by a 780 nm bandpass and measured in a silicon optical power meter sampling at 300 Hz with window-averaging over 20 samples. The rate of data recording is limited by the delay-stage translation speed of approximately 1 ps per minute, with the full data set recorded in around 100 s. The 160 m fiber spool depicted in Fig. 4 is excluded for data shown in Fig. 5 to minimise drift-induced distortion of the correlation curve.

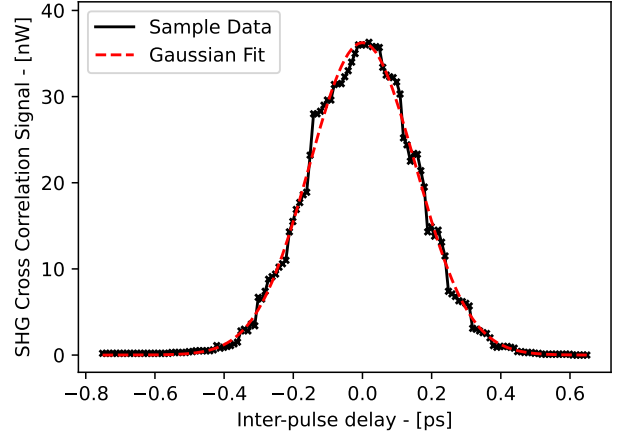


Figure 5: Scanned SFG cross-correlation signal for changing inter-pulse delay, with Gaussian fit overlaid in red. The 1σ full-width is 312 fs, corresponding to 360 fs FWHM.

By assuming that the reduced-length fiber limits drift-induced timing jitter to a minimal level over the recording period, the cross-correlation scan shown in Fig. 5 is equivalent to a 1-D convolution of the two fundamental gaussian pulses. Longitudinal misalignment is indicated by a reduced pulse overlap and limited SFG signal. Amplitude noise slower than 500 kHz is eliminated by applying the balanced scheme. We anticipate stabilisation of optical fiber links to below 30 fs using optical cross-correlation.

CONCLUSION

We report the development status of the AWAKE optical clock network required for Run 2c. The utility of this system is dependent on demonstration of the performance necessary for AWAKE from 2029. We show that optical cross correlation is possible and effective using ancillary signal from the existing AWAKE optical master oscillator, with work progressing to establish a functional clock-signal distribution. Key future milestones include closing of the PID-loop to stabilise the round-trip time of a distributed clock pulse, and scaling of the BOXC units to fit in the constrained tunnel space.

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