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Femtosecond synchronization system for advanced accelerator applications

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Summary. — Some next future experiments involving particle accelerators require a very precise synchronization between very short (< 200 fs) particle beams, laser pulses and RF accelerating waves. In fact, experiments like generation of short Free Electron Laser (FEL) radiation pulses, coherent x-ray production from laser-electron backscattering, high gradient acceleration techniques based on Plasma Wake Field Acceleration (PWFA) with injection of an external electron beam demand a synchronization performance that can vary from 500 fs to few fs between the pulses involved. The presentation is an overview of synchronization systems using electrical or optical reference distribution and shows their performance and range of application.

PACS 29.20.Ej – Linear accelerators.
PACS 42.81.Qb – Fiber waveguides, couplers, and arrays.
PACS 52.38.Kd – Laser-plasma acceleration of electrons and ions.

1. – Introduction

This paper wants to describe the principles of synchronization systems used in experiments requiring very precise timing control of short (< 200 fs) particle (electron) beams or laser pulses. Such systems are distributed around the world to satisfy the high precision timing requirements for different experiments [1-4]. The performances of the systems, in terms of time jitter between the arrival time of two pulses in the interaction point, vary from sub-1 ps_{RMS} (in the case of standard FELs, coherent x-ray production from laser-electron backscattering, etc.) to few fs (in the case of PWFA with injection of an external electron beam, FEL pump and probe experiments, etc.). Such experiments are normally performed by means of an high brightness photo-injector and a linear accelerator in combination with one or more laser system. The principle of synchronization is to have a stable and precise reference clock, usually called Master Oscillator (MO), and to lock all the other slave oscillators (both electrical or optical) to it by using a high-precision phase locked loop (PLL). Since the Master Oscilator can be obtained by using i) a crystal RF

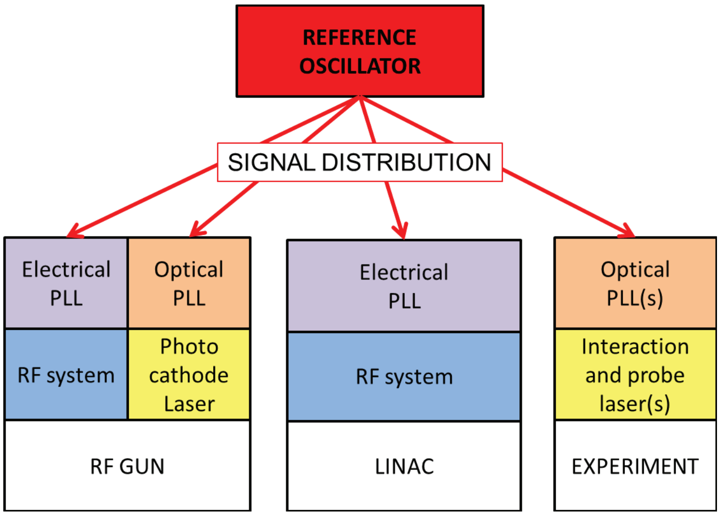

Fig. 1. – General synchronization system architecture.

oscillator or ii) an optical reference system (a fiber laser is normally optioned), the way to distribute the reference signal and to lock the different synchronization clients could be very different. The general architecture is given in fig. 1.

For machines with time jitter specification of 1 ps–100 $\mathrm{fs_{RMS}}$, the synchronization system architecture can be of the first type, *i.e.* constituted by an electrical master oscillator and coaxial cables for the reference signal distribution. In sect. **2**, the description of such a general system is given, and the results achieved at the SPARC_LAB complex in Frascati [5] are reported as an example. For tighter specifications ($< 100\,\mathrm{fs_{RMS}}$), the system should be designed to have an optical architecture and the signals are diffused along the machine by means of fiber links. The reason to choose the optical architecture to reach such stringent specifications relt on the higher resolution in optical phase detection devices. In fact an electrical phase comparison could lead to a maximum resolution of tens of fs, while an optical one can reach the sub-fs level. Details are given in sect. **3**. The aim of the document is to describe and to report the performances of the single blocks depicted in fig. 1 both for the electrical and the optical system architecture.

2. – Electrical architecture

As previously mentioned, the system architecture aimed to achieve the sub-ps performance can be of electrical type.

2·1. *Master Oscillator*. – The core of this kind of system is the Reference Master Oscillator (RMO) that is typically constituted by a Oven-Controlled Crystal Oscillator (OXCO) that can guarantee a frequency stability up to 0.0001 PPM over a temperature range that could cause 10 PPM variation to the same microwave oscillator without oven. Since the reference frequency is usually equal to the linac RF frequency (so in the GHz range), and the OXCO's one is in the 100 MHz range, the output of the crystal is split, divided, treated and recombined to achieve the correct frequency output. Also other synchronized frequency can be generated, such as the digital LLRF LO, IF, or sampling

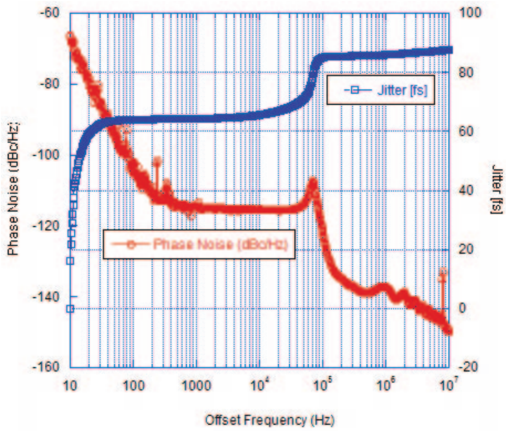

Fig. 2. – Typical SSB phase noise power spectrum and integrated jitter of a RMO.

frequency or the laser oscillators pulse repetition rate. It's best practice to have more than one coherent ouput form the RMO to ensure a correct feeding of more than one client. A typical SSB phase noise power spectrum measurement [6], obtained using the Agilent SSA *E*5052, is reported in fig. 2. A commercial oscillator for spectral purity purpose can reach an absolute jitter below 20 $\mathrm{fs_{RMS}}$ (integrated from 10 Hz to 10 MHz).

2˙2. *Reference distribution*. – In case of electrical distribution, coaxial cable can be used. The aim of the cabling network is to transport the signal to the synchronization system clients without affecting the signal stability. One can consider to use a low attenuation and also a temperature elongation compensated coaxial cables to locally reduce drifts of the client phase reference. Anyway, if the residual drifts are above specifications, correcting algorithms, based on measuring probe signals sent through the cables [7], can be implemented.

2˙3. *RF clients*. – The RF clients are basically the LLRF systems (analogue [8] or digital [9, 10]) that feed the RF power stations (modulators + klystrons). In the case of electrical distribution on the RF client side it is not necessary any signal transduction. They can be directly feeded by outputs of the RMO. Of course the clients have to satisfy some requirements in spectral purity since the manipulation of the RMO input signal should not introduce a degradation in the phase noise performance.

2˙4. *Laser clients*. – The laser clients are typically IR laser oscillators with repetition rate of hundreds MHz. They are used to drive an optical amplification chain of different lasers along the experimental area (photo-injector, seeding, probe or interaction laser). A large BW (typically > 5 GHz) photodiode can be used to extract an electrical replica of the output pulse repetition of the laser oscillator to be used for synchronization. In fact, as shown in fig. 3, this replica is phase-compared to the RMO signal to close an electro-opto-mechanical PLL around the oscillator cavity. The phase comparison is preferably performed at high frequency to obtain a good phase detection sensitivity to drive the piezo motor correction whit high performance. The BW of the loop cannot exceed few kHz, that is the typical limit frequency response of a standard piezo crystal controlling the optical cavity length. This means that the RMO phase noise high-frequency components

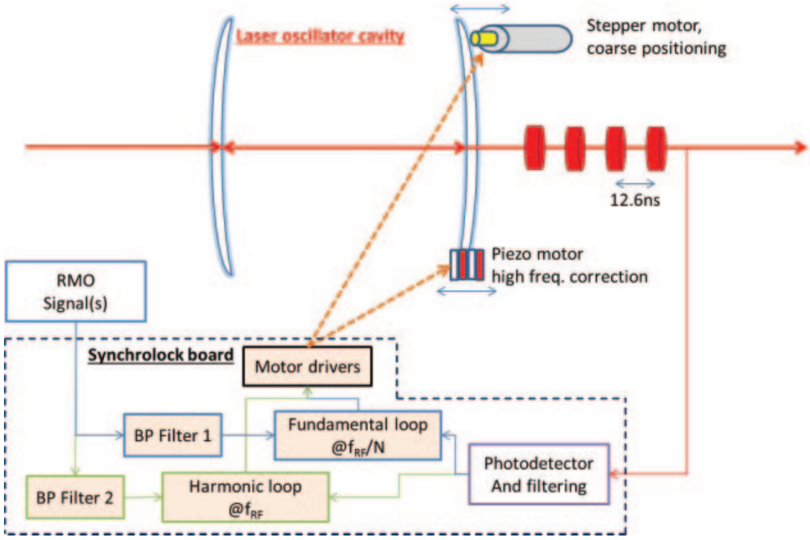

Fig. 3. – Locking scheme in electrical architecture for a laser oscillator client.

can not be corrected and should be very low to ensure a low time jitter between laser pulse and RF linac phase.

Only one pulse at each experiment trigger (typically tens of Hz) is extracted out of the train to feed the optical amplification chain. The "fundamental" loop at the laser repetition rate is important to ensure that every time the "harmonic" loop is closed, time difference between the amplified pulses is constant. In fact, since the laser rep rate is $f_{OSC} = f_{RMO}/N = f_{RF}/N$, the harmonic loop alone, when activated, can lock the laser in N different time positions, saparated by $T_{RMO} = 1/f_{RMO}$. Figure 4 reports the performance of such a locking system, recently measured at SPARC_LAB. The PLL has been accurately designed and tuned changing the gain and the frequency response of the loop filter, to achieve the best performance.

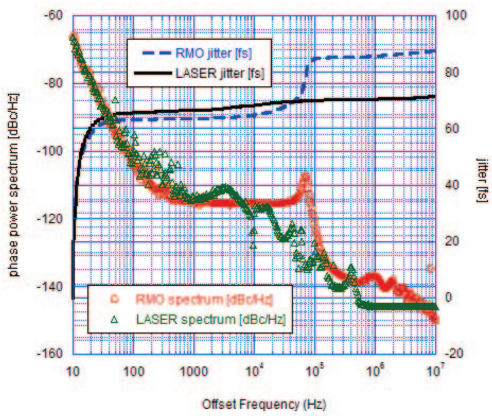

Fig. 4. – Performance of a laser client locking system at SPARC_LAB.

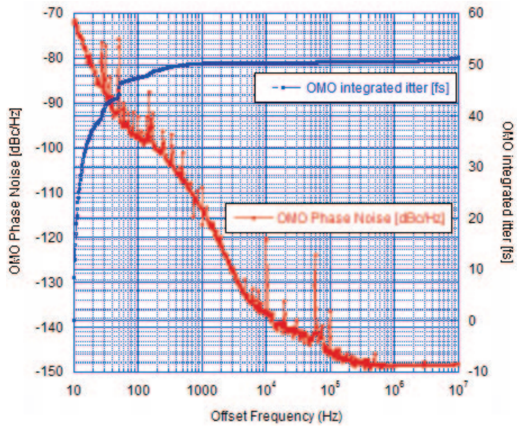

Fig. 5. – Performance of a commercial fiber laser OMO.

The analysis of the measurement shows that the two oscillators are very coherent in the low frequency (< 5 kHz) range and the contribution to the phase noise outside the PLL BW is not so important (about 20 fs for the RMO and < 10 fs for the laser). So the relative jitter can be estimated to be < 50 fs, that is well inside the system specification for an electrical architecture type.

3. – Optical architecture

As previously described, the optical synchronization is needed if the relative jitter of the interacting pulses has to be < 100 fs. The great advantage of using such an architecture is that the time jitter detection of two short pulses can be done in the optical domain. The non-linear interaction between the pulses in a double balanced cross correlator [11] is used, extracting the relative time of arrival information. Since the rise time of such short pulses is very short (< 100 fs), it is possible to achieve a time jitter measurement resolution $< 1\,\mathrm{fs_{RMS}}$, much better respect to an electrical comparison that can achieve $\approx 10\,\mathrm{fs_{RMS}}$.

3·1. *Optical master oscillator*. – The core of an optical synchronization system is the Optical Master Oscillator (OMO). Typically it is constituted by a pulsed fiber laser with repetition rate of about 100 MHz in the telecommunication wavelength range (1560 nm) and an optical badwidth of 10–20 nm that leads to pulse duration < 200 fs (measured FWHM). The integrated power sent in the distribution network for each fiber optic link is of the order of 10 mW to avoid distortion due to self-modulation. The phase noise spectrum of such devices is very low at high (> 1 kHz) frequencies, while the slow drifts of the repetition rate frequency are worse than a standard RMO. Thus the OMO is locked to an external stable reference (an RMO) by means of a PLL similar to the "harmonic loop" described in sect. **2** to ensure the long term stability of the central frequency.

The recent development of fiber lasers to achieve very high spectral purity, yielded to absolute phase noise jitter $< 1\,\mathrm{fs_{RMS}}$ [12]. A measurement of absolute phase noise performed at SPARC_LAB on a commercial synchronization fiber laser is reported in fig. 5. A total integrated jitter of $51\,\mathrm{fs_{RMS}}$ has been calculated. The integrated jitter for the frequency offset region > 1 kHz is only few fs, while for lower frequencies the spectrum of the OMO is close to the RMO's.

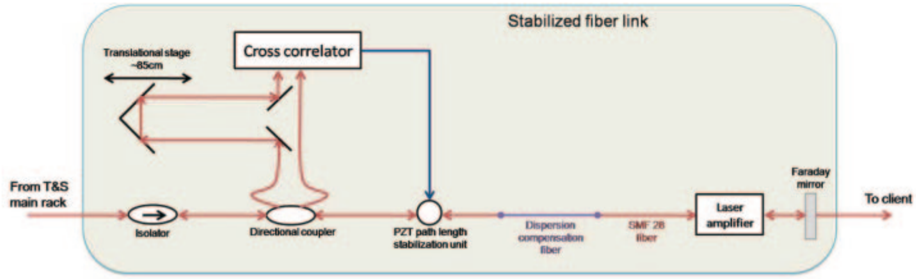

Fig. 6. – Stabilized fiber link layout.

3˙2. *Optical reference distribution.* – Once a timing signal in form of an optical pulse train is generated from the OMO, it should be distributed to the remote RF or optical subsystems that we aim to synchronize with minimal residual noise. Precise transfer of timing signals through fiber links for timing information distribution has been recently demonstrated. Stabilized fiber links are now standard commercial products, capable to distribute the reference optical signal in a km scale complex with a residual phase noise down to $< 10\,\mathrm{fs_{RMS}}$. Figure 6 reports the operating principle of such a link. If the fiber length is L, one has to assume that no length fluctuations are faster than $2L/c$, where c is the speed of light in the fiber. Relative fiber expansion by temperature change is typically on the order of 10^{-7}/K, which can be compensated by a fiber length control loop. The phase error information is extracted from a double balanced cross-correlator that use the non-linear interaction between the back reflected pulse from the fiber end with the forward pulse coming from the OMO output. The error signal is then sent to a fast actuator (typically a piezo-stretcher) that slightly changes the fiber link length to compensate the elongation (due to thermal drift or mechanical vibrations).

3˙3. *RF clients.* – To satisfy RF clients requirements, it is crucial to convert this optical signal into a low-jitter, drift-free RF signal with a satisfactory power level in a long-term stable way. It has been shown that the extraction of an RF signal from an optical pulse train using direct photodetection is limited in precision by excess phase noise. The major contribution to this excess noise was identified to be the amplitude-to-phase (AM-to- PM) conversion in the photodetector that was measured to be in the range 1–10 ps/mW. For an Er-doped fiber laser with $0.03\%_{rms}$ relative intensity noise, this may result in 5 fs excess jitter when $10mW$ of power is applied to the photodetector. Therefore, if this residual jitter is above the system specs, it is highly desirable to use a phase-locked loop (PLL) between an optical pulse train and a high-quality RF voltage-controlled oscillator (VCO) to prevent those undesired AM-to-PM conversion and drifts due to the photodetection process. This can be achieved by means of a balanced optical-microwave phase detector that was proposed and demonstrated in [13] and is now an engineered product. The measured integrated in-loop jitter is 3 ± 0.2 fs integrated from 1 Hz to 10 MHz when it is locked. Currently, the measurement setup system is limited by the thermal noise from electronic amplifiers and has not reached ultimate shot noise limited performance yet. It is now under study the suppression of the timing jitter to below 1 fs by increasing optical and RF power levels as well as optimizing loop characteristics.

3˙4. *Laser clients.* – The principle of locking the laser clients to the optical reference pulse train, is the same used for the electrical architecture, described in sect. **2**, but,

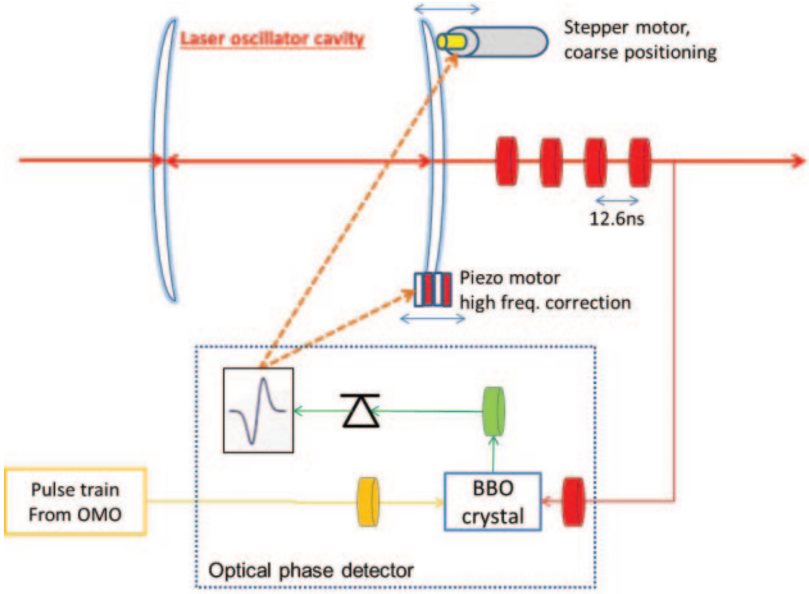

Fig. 7. – Laser locking system for an optical architecture.

as already specified, the upgrade to an optical system yields to an enhanced relative time jitter sensitivity (up to 0.1 fs/mV). Figure 7 shows a schematic of the laser locking system. As you can see the standard electrical mixing is replaced with a full optical phase detection, driving the piezo-motor for the optical path correction. Standard results achieved wit this layout could lead to a residual relative time jitter $< 10\,\mathrm{fs_{RMS}}$ relative to the OMO reference signal.

4. – Conclusion

The document gave an overview of the state-of-the-art synchronization systems, necessary for advanced experiments involving the interaction between particle short bunches and and high power laser short pulses ($< 200\,\mathrm{fs}$). In particular the electrical and the optical architectures have been described, with emphasis on the different achievable performance regarding reference signal generation, distribution and client locking systems. The total achievable time jitter between different pulses is $< 500\,\mathrm{fs_{RMS}}$ for electrical and $< 10\,\mathrm{fs_{RMS}}$ for optical architecture. The paper did not treat the measurement systems for the time of arrival of particle and photon pulses in the point of interaction because it goes beyond the scope of the document. Anyway, interesting references in this field are [14-16].

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