TIMING AND SYNCHRONIZATION IN LARGE SCALE LINEAR ACCELERATORS*

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Abstract

New coherent light sources are based on large scale linear accelerators; the adopted single pass acceleration scheme allows the preservation of bunch 6D phase space leading to ultra short (<$100fs_{FWHM}$) and ultra bright (average Brilliance = 10^{24} (1) ph/sec/mm^2/mrad^2/0.1%bw) pulses of coherent radiation in the DUV-x-ray regions.

Femto-second lasers are deeply integrated in the electron bunch and photon pulse generation, in diagnostic set-ups and in time resolved experiments: the timing may be as low as 10% of pulse duration. The requirements on the stability of RF acceleration call for distribution of ultra-stable and ultra-low phase noise reference signal for the Low Level RF feedback loops.

A breakthrough into the adoption of optical and O/E techniques is on-going taking advantage on five order of magnitude reduction in the period of the carrier.

Being the current limit represented by the carrier-envelope stabilization techniques, sub-fs jitters have been demonstrated in the laboratory; the preservation of *laboratory levels* of jitters and stability over the whole accelerator premises is the next step. On-going efforts and results let us be optimistic.

INTRODUCTION

FERMI@elettra is the new 4th generation light source (4GLS) presently under construction at the Sincrotrone Trieste laboratory, in Italy. In its final configuration, FERMI is a two stage harmonic generation seeded FEL providing coherent radiation at wavelengths ranging from 100nm to 10nm. Being based on the seeded FEL scheme and aiming at a routine operation in the "fresh bunch" configuration, a state of art timing and synchronization (T&S) system has to be designed and implemented.

In the frame of the new activities that have been started at ELETTRA to cope with this new project, a collaborative effort has been set-up with some of the main laboratories worldwide active in the field (MIT, LBNL, SLAC and DESY) where the FERMI Technical Optimization Study (TOS) has originated from. Within the FERMI TOS, a strong working group (MIT, LBNL and DESY) has started collaborating in 2005 on the T&S issues; in this context each of the participating laboratory has the opportunity to study and to demonstrate its own state of art solutions.

Furthermore, in the frame of the FP6 Design Study EUROFEL, ELETTRA is leading the working group DS3 dealing with the T&S and related issues for the new 4GLS. Therefore ELETTRA is the right place for studying and for designing new and innovative T&S systems.

In this paper, we present the critical aspects of T&S systems originating from the 4GLS adopted schemes and associated requirements. The proposed solutions for state of art T&S systems are presented as well and the achieved performances listed.

CRITICAL ISSUES IN T&S

To our understanding, a *timing system* has to generate and to distribute throughout the facility the Reference signal, which all synchronized sub-systems are referred to. A synchronization system has the main task of keeping the jitter / drift of the relevant sub-systems (i.e. the electron bunch) with respect to the reference within stringent design values.

Having this definition in mind, it's easy to understand how the *timing* is a machine sub-system itself, whereas the *synchronization* is spread over many different sub-systems and is therefore a critical function to be implemented. This concept is represented in table 1.

Table 1: Timing and Synchronization Chart

		accelerator sub-systems						
		LL RF	mag. & PS	undul.	diags.	timing	lasers	ctrl
accelerator sections	inj	x	x		x	x	x	x
	low en linac	x	x		x	x		x
	bunch compr.		x		x	x		x
	linac	x	x		x	x		x
	spread		x		x			x
	hν gen		x	x	x	x	x	x
	beam lines				x	x	x	x

Machine Layout T&S Critical Issues

T&S are critical to the correct operation of a 4GLS, mainly due to:

- *energy and charge/bunch stability* requirements: in order to have a stable (in time and frequency) radiation out of the seeded FEL process the energy and the charge of the bunch has to be stable shot to shot better than 0.1% and 10% respectively.
- *100s fs bunch length*: the sub-ps bunch length achievable in single pass linear accelerators is of paramount importance to obtain the required peak current, but it poses demanding requirements on some longitudinal diagnostics as the "bunch arrival monitor"
- *massive ps and fs laser adoption:* ps and fs laser systems are deeply embedded in both the bunch generation (photo-cathode, laser heater)

*Work partially supported by the EU Commission in the Sixth Framework Program, Contract No. 011935 – EUROFEL

and radiation production (seed laser) processes; furthermore fs time resolved experiments also call for a synchronization at a level smaller than the σ_{LASER} (typically equal to $100fs_{FWHM}$).

- *fresh bunch:*
  in the fresh bunch seeding scheme, the seed laser pulse has to stay, shot-to-shot, well within half of the electron bunch. Being the flat (useful) part of the bunch about $500fs_{FWHM}$ long, the peak-to-peak relative arrival time of the electron bunch has to be <200fs, i.e. $50fs_{RMS}$.

Schematic Representation of a T&S System

The main components of a T&S system are shown in figure 1.

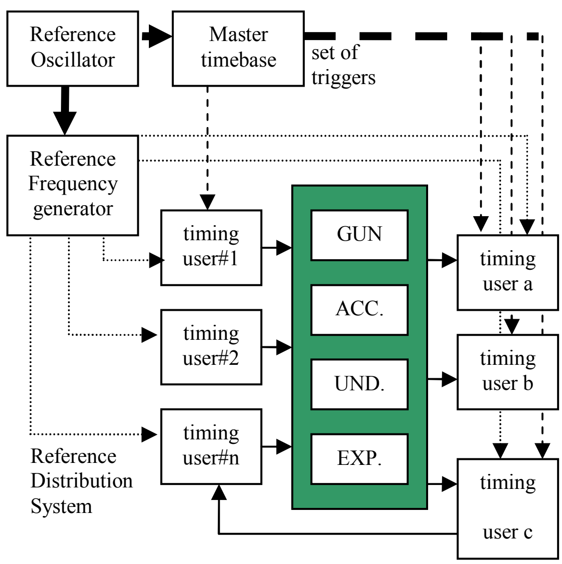

Figure 1: Schematic representation of a T&S system.

The whole machine is here schematically represented with its main sub-systems: the gun, the accelerating sections, the undulator section and a generic beam-line (labelled as: experiment). The reference oscillator is synchronizing the whole machine providing the required “low frequency jitter” and drift stability.

Two main units are directly linked to the reference oscillator: the generator of the reference frequencies and the master time base. The former generates the L-band, S-band or X-band (depending on the acc. set up) frequencies, the laser repetition rate and other IF needed in the machine. The latter generates the machine trigger, typically “digital signals” like as: the bunch repetition rate, various gates and triggers for the diagnostics, etc. .

These two classes of signals (reference frequencies and triggers) have different requirements in terms of allowed jitter and therefore may be distributed using different techniques. The Reference distribution system distributes around the machine the reference frequencies keeping their phase noise at the level of the reference oscillator (i.e. $<20fs_{RMS}$). On triggers and gates, a jitter $<10ps_{RMS}$ is tolerated and a less performing (i.e. less expensive) distribution system can be adopted.

In a T&S system we can identify several classes of *timing users* (or clients). Classification criteria are based on the physical level of the reference signal they need be connected to: optical or electrical. Furthermore, we can identify *timing users* acting on accelerator sub-systems (labelled in fig. 1 as: 1, 2,...n) like the lasers, the RF system and the RF deflectors. Other *timing users* (labelled in fig. 1 as: a, b, c) may receive inputs from the accelerator in different forms (either electrically or optically) or are even closely interacting with the bunch. Within this second class we have diagnostics like: bunch arrival monitor, streak cameras and Electro-Optical sampling stations. In some cases, the information about the relative (bunch to reference) measured time difference is fed back to one of the users of the 1st class, to implement a “synchronization” task.

Why a T&S System is Critical to Implement

We list in the following some of the critical aspects of such a system.

- The required performance in terms of the ultra-low phase noise of the reference signal is greatly restricting the number of viable solutions that can be adopted for the Reference Oscillator.
- The physical extension of a large scale linear accelerator facility (from several 100s meters to few km) is another constraint to feasible solutions, along with the achievable level of temperature control that can be achieved on the subsequent, large volume of the machine premises.
- As mentioned above, there are different kinds of timing users which calls for ad-hoc solutions for each. Some users are electrical, “quasi Continuous Wave (CW)” users, calling for a sinusoidal reference signal; others maybe optical “pulsed” devices, needing a precise time stamp typically at a very low repetition rate. Such “optical devices” (lasers or diagnostics) in principle are welcome as higher performances are achievable with optical techniques, but anyway they increase the overall complexity of the T&S system.
- Longitudinal diagnostics, providing a resolution at the 10s fs level, have been developed specifically for this kind of accelerators and new ideas are still coming up. Let’s stress here the point that the “low duty cycle” and the “single-shot intrinsic nature” of most of these machines are not easing the task of implementing high accuracy diagnostics, due to the low energy of the information signal. A bunch period of tens of milliseconds compared to the acceleration cycle of 330ps (S-band) and to a bunch duration even shorter (100s fs) is strongly limiting the possibility of applying efficient averaging algorithms to improve the resolution, according to the known law 1/SQRT(N), being N the number of samples over which the average is computed.

Set of Requirements for a 4GLS T&S System

In July 2006 an ELETTRA internal technical note has been issued on the FERMI Timing and Synchronization system. From that note the set of requirements for the timing system are reported here, as an example drawn from a real machine.

Table 2: Requirements for the FERMI@elettra Timing and Synchronization System

Subsystem	Requirement, fs RMS	Number of lines
RF, S-band	167	12
RF, X-band	69	1
Photoinjector laser	200	1
Seed laser	100	1
Endstation laser	100	2
Streak camera driver	500	2
Streak camera fiducial	100	2
Accelerator diagnostic	100	6

In table 2, the different sub-systems of FERMI to be synchronized are listed. The numbers represent the total expected jitter for that sub-system, as a global effect on the bunch; they have been defined by means of sensitivities studies, using numerical modelling. The jitter shown here is due partially to the reference jitter at the remote location and partially to the phase noise of the sub-system itself. We'll cover deeply this topic later on in this paper.

LET'S GO OPTICAL

Since the projects for the new 4GLS machine have been around, T&S experts have looked with great curiosity into the realm of optical fiber systems, fiber laser and O/E devices to find answers to their boss request: "I want a jitter less than 50fs!".

Anyone having ever tried to trigger a sampling scope, maybe with a 50GHz bandwidth, connected to a wideband photodiode (25GHz) illuminated by a $20ps_{FWHM}$ light pulse, having a rep rate of 1MHz (i.e. looking for a 60ps pulse over a 1μs time window) can hardly imagine how a pulse of 1ps looks like; not to speak about $50fs_{RMS}$ jitter... . This is to say that electronic systems, instruments and associated time domain measurement techniques are roughly limited to the "$1ps_{RMS}$ domain". Two fundamental steps have to be taken to go beyond that point:

- to increase the carrier/clock frequency
- to adopt frequency domain measurement techniques and instruments.

Main Advantages of the Optical Domain

There are a number of good reasons for adopting optical solutions for T&S at the 10s fs level.

Thanks to the ultra wide band available on optical cables the jitter that can be achieved is smaller when compared to coaxial cables solutions, especially when broadband transmission channel is needed (distribution of pulses).

Among the key sub-systems to be synchronized in a 4GLS there are lasers that are ideally suited for a direct connection to an "optical clock" (i.e. to be synchronized by means of cross-correlation techniques); furthermore, a number of ultra low phase noise optical oscillators are today available on the market (fiber and bulk pulsed lasers), very well suited to provide the reference optical clock over standard single mode fiber (SMF).

An important issue for a state of art timing system is to stay "optical" as much as possible in order not to deteriorate the ultra low phase noise when converting the reference signal from optical to electrical physical form.

Fibers and fiber systems are economically viable and typically the installation of optical cables is less cumbersome than with the coaxial ones.

Let's here also remind that the huge improvements in the domain of "optical clocks" brought the 2005 Nobel Prize in Physics to John L. Hall and Theodor W. Hansch: "*for their contribution to the development of laser-based precision spectroscopy, including the optical frequency comb technique*".

Sources of Jitter in a Transmission System

In the following paragraph we'll estimate the jitter introduced by a generic transmission system (sketched in figure 2) when a time varying signal *s(t)* is transmitted through it.

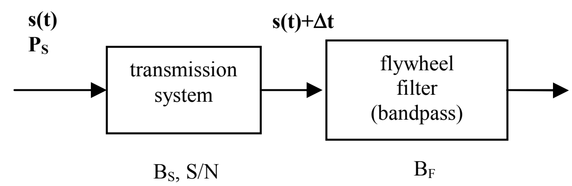

Figure 2: Block diagram of a transmission system plus band pass receiver filter.

B_S is the bandwidth of the transmission system, B_F is the bandwidth of a band pass (flywheel) filter that typically is adopted at the receiver side to improve the S/N, when transmitting sinusoidal signal (narrowband).

For such a system the following formulas hold:

$$\Delta t \cong \frac{1}{B} \cdot \left(\sqrt{\frac{S}{N}} \right)^{-1} \tag{1}$$

$$\frac{S}{N} = \frac{P_s}{N_0 B} = \frac{P_S}{P_N}$$

$$\Delta t \cong \frac{1}{B_S} \cdot \left(\sqrt{\frac{P_S}{N_0 B_S}} \right)^{-1} = \sqrt{\frac{N_0}{P_S B_S}} \tag{2}$$

$$\Delta t \cong \frac{1}{B_S} \cdot \left(\sqrt{\frac{P_S}{N_0 B_F}} \right)^{-1} = \sqrt{\frac{N_0 B_F}{P_S B_S^2}}$$

being Δt the timing jitter added to the signal by the transmission system, P_S the signal power at the receiver, N_0 the noise spectral density.

The fact that the jitter is proportional to $1/B_S$ is easily understood considering that the faster a signal is, the lower its jitter and that the rise time [ns] is equal to 0.35/B [GHz]. By applying the relationships (1) and (2) to some real cases, we get the results listed in table 3.

Table 3: Jitter for Different Transmission Systems

system	B_S [GHz]	P_S [dBm]	B_F [GHz]	PN [W]	S/N [dB]	Δt [fs]
COAXIAL wideband	1	0	-	4.10^{-14}	-	64.34
COAXIAL narrowband	1	0	0.010	4.10^{-12}	-	6.43
FIBER non coherent	10	10	-	-	90*	3.16
FIBER non coherent	10	0	-	-	70*	31.6
FIBER coherent	200 [THz]	10	10	-	60	0.005

* The S/N for the fiber systems has been computed assuming that: at P_0=-25dBm, $(S/N)_e$=20dB; therefore with P_0=10dBm, we have an increase of 35dB_{OPT} yielding +70dB_e. The total $(S/N)_e$ is then equal to: 20+70=90dB. For P_0=0dBm, $(S/N)_e$=70dB.

It is evident the benefit of using fiber especially for broadband transmission systems.

Classification of Phase Noise: Spectral Aspects

At the sub-ps_{RMS} level, the phase noise of an oscillator is measured in the frequency domain and it is quantified in dBc/Hz, which indicates the strength of a jitter component at a given frequency offset from the carrier per Hz of BW. This representation is very convenient as it clearly indicates at which frequencies there are the major jitter contributors. For the FERMI TOS we have classified the phase noise vs. frequency as:

- drift: DC to 10Hz (Fermi initial rep. rate)
- jitter: 10Hz to $F_{rep\ laser}/2$

This classification leads us to the concept of *phase noise spectral components*. It is very important to know the sensitivity to the various phase noise spectral components for each sub-system that need to be synchronized to optimize its reference signal.

Table 4: Phase Noise and Associated Bandwidth for Each FERMI Sub-System that Need to be "synched"

Subsystem	Requirement, fs RMS	Synch syst. allotment
RF, S-band	167	118fs, DC-1kHz
RF, X-band	69	49fs, DC-1kHz
Photoinjector laser	200	140fs, DC-loop BW (~1kHz)
Seed laser	100	70fs, DC-loop BW (~1kHz)
Endstation laser	100	70fs, DC-loop BW (~1kHz)
Streak camera driver	500	350fs, DC-loop BW (~1kHz)
Streak camera fiducial	100	70fs, DC-50MHz
Accelerator diagnostic	100	70fs, DC-50MHz

In table 4 for each sub-system to be synchronized, its sensitivity to given spectral components of the phase noise is listed. Furthermore, the requirements for the total jitter (central column) are obtained by summing in quadrature the contribution from the reference signal, provided by the timing system, and from the phase noise of the sub-system itself.

DEVELOPMENTS ON TIMING AND SYNCHRONIZATION

Two major R&D efforts are on-going on the development of optical clock systems:

- MIT: a pulsed optical clock system has been demonstrated, in collaboration with DESY; it will be soon deployed on FLASH, at DESY.
- LBNL: a CW optical clock system is under development.

Both systems are fully consistent: each of them fulfils the requirements for a complete fs timing system. A detailed description of the two above mentioned systems is outside the scope of this paper.

Just as an example, here is shown how the same problem (stabilization of the fiber link) has been solved for the two different systems.

In figure 3, the MIT solution is schematically represented; as the optical clock comes as a time comb of pulses, a cross correlator is used to keep time aligned a transmitted pulse to the one originated by reflection at the remote end of the link.

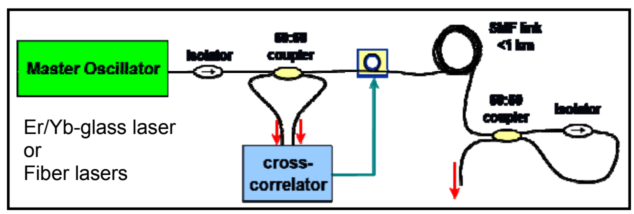

Figure 3: Fiber optics link stabilization "a la MIT".

The MIT stabilization techniques stabilizes the group velocity over the whole bandwidth of the optical channel.

At LBNL, relying on a CW ultra stable laser (λ=1530nm) they have achieved a sub fs phase velocity stabilization (figure 4) by optical mixing of the transmitted optical carrier with its replica reflected at the far end of the link by a Faraday Rotator Mirror and shifted in frequency by (55x2)MHz as the Fiber Frequency shifter is crossed two times.

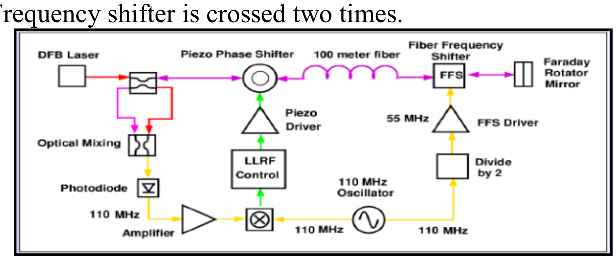

Figure 4: LBNL fiber optic stabilized link.

List of Achieved Performances

Several experiments and proofs of principle have been performed in the two laboratories, having DESY strongly supported MIT idea as they are planning to deploy the MIT concept for an Optical Clock system as an upgrade of the timing system at the operating facility FLASH in Hamburg.

Though a comparison between the achieved performances is not a straightforward task, in table 5 the major achievements in the field have been listed. The interested reader will find detailed information in the papers presented by the two (actually three) above mentioned laboratories at the main Accelerator and FEL conferences worldwide.

Table 5: List of Demonstrated Results on Timing

item	dev. at	value [fs_{RMS}]	bandwidth	notes
μ-wave ref. osc.	off-the-shelf	<10	100-10MHz	f_C=10GHz
Optical Master Clock	MIT/ DESY	10 <20	1kHz-Nyq. 1kHz-Nyq.	Er Fiber laser Er/Yb glass laser
Fiber Optic stabilized link	MIT field test at MIT-BATES	12	0.1Hz-10kHz	group delay stabilization
	LBNL	<2/°C 0.1/h	L=200m long term drift	phase delay stabilization
RF over FO trans-mission	MIT	8.8±2.6	1Hz-1MHz	Optical to RF conversion
	LBNL	15	1kHz-40MHz	11fs noise of the RF source

On a real application the above listed numbers for a complete timing link may be added up linearly. For the MIT system, the sum will include:

- μ-wave reference oscillator + Optical Master Clock + Optical to RF conversion

For LBNL, the summing terms will be:

- μ-wave reference oscillator + Frequency Generator + RF over fiber

Any of the above mentioned system has the potential to provide the requested minimum <$50fs_{RMS}$ jitter (see table 4) in the 10Hz-10MHz bandwidth.

FERMI CHOICE

The timing and synchronization system of FERMI@elettra will be an hybrid one, based on the consideration that each of the two proposed solutions is best suited for "synching" specific classes of sub systems (i.e. timing users, see fig. 1).

The MIT "time domain" concept will be deployed for the synchronization of "pulsed" users:

- lasers
- diagnostics

The LBNL "frequency domain" concept will be implemented to provide the Reference signal to the "quasi CW" users of the:

- Low Level RF

A schematic representation of this solution is given in the figure 5, here below.

The block diagram of figure 5 is one of the main results of the huge work done by the FERMI TOS team on timing and synchronization, whom the author is sincerely grateful to.

In the next coming, six months this diagram will be detailed at the board level and working out the details of each user interface (either optical or electrical).

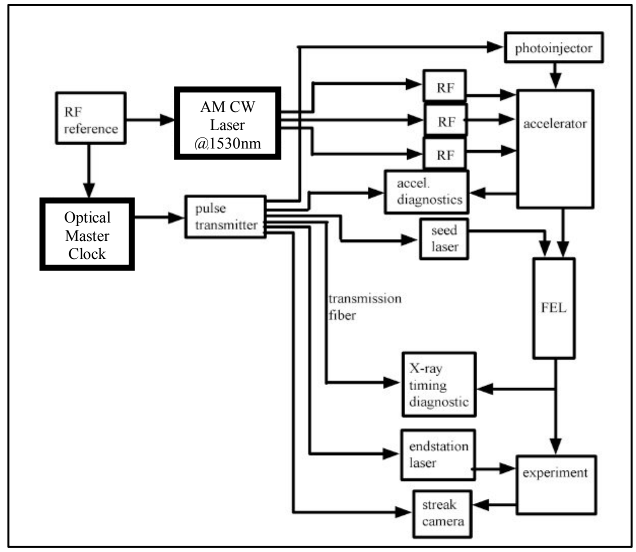

Figure 5: Schematic representation of the FERMI@elettra timing and synchronization system.

While doing this, the jitter budget will be checked for interactively for each sub-system. First field tests at ELETTRA of this new Optical Timing system are foreseen one year from now, which is a time frame fitting well to the FERMI@elettra global project timescale.

ACKNOWLEDGMENTS

Specifically for the preparation of this paper, the author is especially grateful to J. Staples, A. Winter, A. Ratti and to prof. M. Vidmar (Uni LJ, SLO). A few colleagues at ELETTRA have been also very patient in reading and contributing to it: "grazie" Giovanni (De Ninno) and Paolo (Craievich).

REFERENCES

Internet is (a little bit) changing our way of leaving; the i-net revolution had a positively dramatic impact on our community, by incredibly boosting the information exchange among us. Therefore, instead of listing the usual references, I will provide the interested reader with the "keywords" of this challenging work, i.e. the names of those who mostly and to my limited knowledge contributed to it. By just "googling" any of these names with the topic you are interested in with the name of one of our *TOP10* conferences (PAC, EPAC, FEL, LINAC, BIW or DIPAC) the reader will find a wide portfolio of papers and oral contributions on these subjects.

- **LBNL team**: R. Wilcox, J. Staples, L. Doolittle, J. Byrd and A. Ratti
- **MIT team**: Prof. F. X. Kaertner, J. Kim, J. Chen and F. O. Ilday
- **DESY team** A. Winter, F. Ludwig and H. Schlarb
- **@ELETTRA**: G. D'Auria, M. Danailov, L. Banchi and F. Rossi