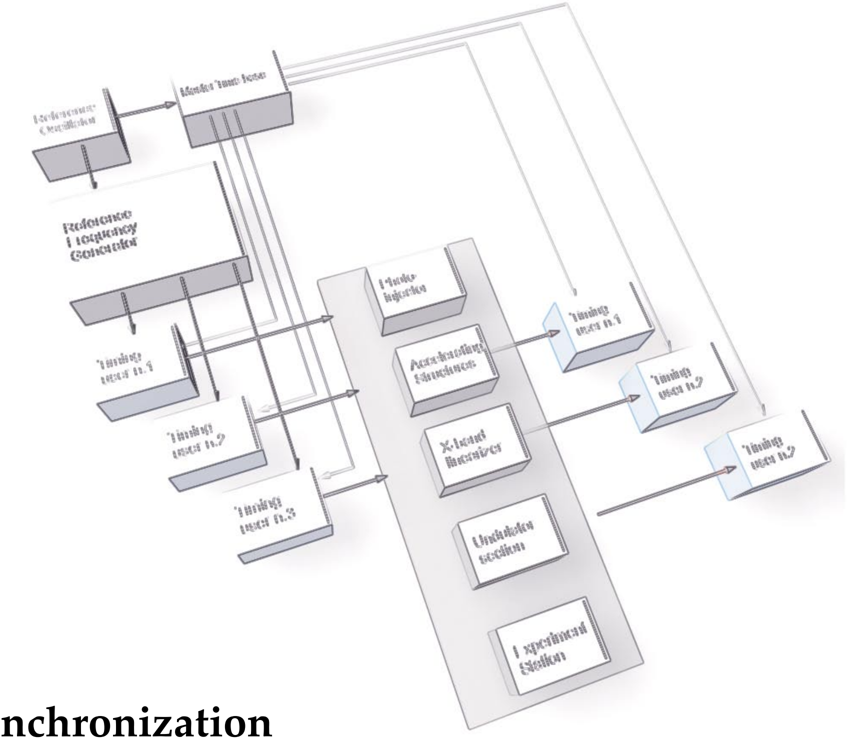

9 Timing and Synchronization

Synopsis

The FERMI timing and synchronization (T&S) scheme is based on a hybrid system utilising both “pulsed” and continuous wave (CW) timing techniques.

The “pulsed” technique has been originally developed at MIT [1]: an ultra-low phase noise pulsed laser, called optical master oscillator (OMO), is locked to the radiofrequency reference generator. Its pulses distributed over dispersion compensated fiber links (FO) give the time reference to all the “pulsed” timing clients, such as lasers and diagnostics devices

The “CW” timing technique, developed by LBNL at Berkeley [2] is based on a frequency stabilized CW laser amplitude modulated by the radio frequency (RF) of CW timing clients, such as low level RF systems. In this scheme, the FO links are stabilized using the optical mixing concept which fully exploits a carrier frequency 10^5 times higher than the repetition rate of the pulsed system.

The FERMI timing system is compatible with both the European ($f_{S\text{-band-EU}}$=2.998010 GHz) and U.S. ($f_{S\text{-band-US}}$ = 2.856 GHz) S-band frequencies, a necessary condition since the fourth harmonic (X-band) linearizer, that is part of the FEL design, will work at the US frequency. The greatest common divisor of these two frequencies is the coincidence frequency f_{COIN} (15.779 MHz) used to generate the "bunch clock" at the FEL repetition rate frequency f_{bunch}=10-50 Hz. At each period of the coincidence frequency waveform the rising slopes of the (EU) S-band and the (US) aX-band waveforms overlap, thus providing the required phase coincidence.

The reference oscillator for the whole timing system is a microwave sinusoidal oscillator, operating at the European X-band frequency of 11.992 GHZ, which provides the required, fs grade, ultra low phase noise and long term stability. The oscillator is housed in a temperature controlled "timing hutch" close to a set of ultra low phase noise dividers which generate the European S-band frequency (2,998.010 MHz), the optical master oscillator (OMO) reference frequency, $f_{REF\ OMO}$, and the greatest common divisor frequency, f_{COIN}, output signals.

The output signals are distributed to the OMO, to the CW timing and to the master time-base unit and finally, via dedicated stabilized optical channels, to the timing system end users.

FERMI's timing clients belong to two main classes: optical and electrical. Optical clients lock to the reference signal optically (by cross-correlation) or directly to the optical reference to measure phases or bunch arrival times. Electrical clients instead require electrical reference signals, provided by ultra-low phase noise optical to electrical (O/E) converters.

The timing system is completely integrated into the FERMI control system, thus allowing for remote control and monitoring of the performance and reliability of all key sub-systems.

9.1 Introduction

In its final configuration, FERMI is a two stage, harmonic generation seeded FEL providing coherent radiation at wavelengths ranging from 100 nm to 10 nm.

Being based on the seeded FEL scheme and aiming at routine operation in the "fresh bunch" configuration, FERMI requires state of art timing and synchronization systems.

Femto-second lasers, deeply integrated in the electron bunch and photon pulse generation systems, in diagnostic set-ups and in time resolved experiments require a timing stability and resolution at the level of 10% of the laser pulse duration.

Requirements on the stability of the accelerator RF system call for acceleration call for ultra-stable and ultra-low phase noise reference signals being distributed to the Low Level RF feedback loops. Such stringent requirements can only be met by optical and electro-optical (E/O) techniques.

9.2 System Requirements

The *timing system* must generate and distribute throughout the facility a timing reference signal to all sub-systems requiring it. The main function of the *synchronization system* is instead that of allowing to keep jitters and/or drifts of the relevant sub-systems (such as the electron bunch) with respect to the reference signal to within the specified tolerances (see Table 9.2.1). The *timing system* is therefore a critical machine sub-system in itself, whereas the *synchronization system*, distributed to many different sub-systems - including user experiments - is a critical function to be implemented. This conceptual distinction is mirrored in Table 9.2.1.

The main characteristics of the FERMI FEL scheme, which pose precise system requirements on the T&S system, are:

- shot to shot *energy* and *current stability* better than 0.1% and 10% respectively;

- *100s fs bunch length*, posing demanding tolerances on the timing signal fed to diagnostics components such as the "bunch arrival time" monitor;

- *extensive integration into the system of ps and fs lasers,* involved in the electron bunch generation (photo-cathode, laser heater) process, in the radiation production (seed laser) process and in the experiments. As an example, time resolved experiments call for a synchronisation precision at the level of better than 100 fs;

- *fresh bunch seeding scheme*, which requires the seed laser pulse timing with respect to the electron bunch arrival time to stay well within one half of the electron bunch duration, on a shot-to-shot basis. Since the flat, useful part of the bunch is ~ 500 fs_{FWHM} long, the electron bunch relative arrival time peak-to-peak jitter is specified to be ≤50 fs_{RMS}.

Table 9.2.1: Distribution throughout the machine of sub-systems requiring synchronization.

		accelerator sub-systems						
		LLRF	magnets & Power Supplies	undulator sections	diagnostics	timing	lasers	controls
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

9.2.1 Reference Oscillator Drift and Jitter Specifications

The time noise on the synchronization signals is divided into “drift” and “jitter” depending on the frequency band it belongs to, namely:

drift: DC to 10 Hz (FERMI initial repetition rate)

jitter: 10 Hz to one half the gun laser repetition frequency, $F_{\text{rep laser}}/2$.

At the sub-ps_{RMS} level, the phase noise of an oscillator is measured in the frequency domain and is quantified in dBc/Hz, indicating the strength per Hz of bandwidth of a jitter component at a given frequency offset from the carrier. The representation is very convenient as it allows to clearly identifying the *phase noise spectral components*, i.e. the frequencies, which contribute most to the overall drift and jitter of any given sub-system.

This classification leads us to the concept of *phase noise spectral components*. One must know the sensitivity to the various phase noise spectral components for each sub-system that needs to be synchronized to optimize its reference signal.

9.2.2 Reference Timing Distribution Lines

The various different lines distributing the timing reference signals are listed in Table 9.2.2.

For each timing client the following properties and parameters have been indicated:

type of reference signal continuous wave or pulsed

number of lines to be provided

physical layer electrical or optical, with duration of the pulse

frequency

maximum allowed jitter.

The latter is the sub-system total allowed jitter, defined on the basis of its net effect on the bunch.

9.2.3 Timing Jitter Budget

For each timing client, the net effect on the bunch jitter is computed as the quadratic sum of the timing line (phase reference) and the client (sub-system) contributions, since the two contributions are Gaussian and statistically independent. The resulting values for each line are listed in Table 9.2.2, under the heading "Max. allowed Jitter".

Table 9.2.2: Maximum jitter for each timing line.

Timing client	*Client jitter [fs_{RMS}]*	*Timing line jitter [fs_{RMS}]*	*Bandwidth of interest*
RF, S-band	167	118	DC-1kHz
RF, X-band	69	49	DC-1kHz
Photoinjector laser	200	141	DC - ≈1kHz
Seed laser	100	71	DC - ≈1kHz
Experiment laser	100	71	DC - ≈1kHz
Streak camera driver	500	354	DC - ≈1kHz
Streak camera fiducial	100	71	DC-50MHz
Bunch arrival monitor	100	71	DC-50MHz
E/O sampling station	100	71	DC-50MHz

Table 9.2.2 also lists, under "Bandwidth of interest", the bandwidth within which each timing client is most sensitive to jitter. The different sensitivities are explained by the intrinsic band characteristics of the sub-systems (RF accelerating structures) and the related stabilization loops (laser PLLs). This is an important issue that must be taken into consideration in the design of the timing lines to the different sub-systems.

The resulting overall client jitter specifications are listed in Table 9.2.3, for each line, under the heading "Max. allowed Jitter".

Table 9.2.3: FERMI client timing specifications.

Timing client	*Time structure of reference signal needed by the client*	*Electrical or Optical /duration* $[fs_{FWHM}]$	*Frequency* *[Hz]*	*max. allowed jitter* $[fs_{RMS}]$	*Number of lines*
RF, S-band	quasi-CW	E (t_{RF}>2 μs)	$2.998010 \bullet 10^9$ (EU S-band)	167	12
RF, X-band	quasi-CW	E, (t_{RF}>2 μs)	$11.992040 \bullet 10^9$ (US X-band)	69	1
Photoinjector laser	CW pulsed cross-corr seeding	E O, O,	$F_{LASER\ OSC}$ 1 to 50 Hz $F_{LASER\ AMP}$	200	1
Seed laser	CW pulsed cross-corr seeding	E, O, O,	$F_{LASER\ OSC}$ 1 to 50 Hz $F_{LASER\ AMP}$	100	1
User laser	CW pulsed cross-corr seeding	E, O, O,	$F_{LASER\ OSC}$ 1 to 50Hz $F_{LASER\ AMP}$	100	2
Streak camera driver	pulsed, elec. trigger pulsed, opt. trigger	E, 100 ps O, 1 ps	$F_{LASER\ OSC}$ 1 to 50 Hz	500	2
Streak camera fiducial	pulsed	O, 500 fs	1 to 50 Hz	100	2
Bunch arrival monitor	pulsed	O, 1 ps	$F_{LASER\ OSC}$	100	6
E/O sampling station	pulsed	O, 100 fs	$F_{LASER\ OSC}$	100	2

9.2.4 Accelerator Related Frequencies

The FERMI reference frequencies are unambiguously determined by both the European (EU) S-band frequency (*2,998 010 GHz*) for the linear accelerator and the USA (US) X-band (4•2,855 999 GHz = *11,423 996 GHz*) for the fourth harmonic linearizer which must operate synchronously up to the 50Hz maximum bunch repetition frequency.

A unique, different from 1, greatest common divisor (GCD) of the two frequencies exists only for the two exact S-band values indicated above. The GCD is f_{COIN}=15.779 MHz with the division factors shown in Table 9.2.4.

Table 9.2.4: Table of the FERMI reference frequencies.

Signal name	*Symbol*	*Value*	*Notes / division factor*
μ-wave Master reference	f_{MASTER}	11.992 040 GHz	EU X-band
FERMI radio frequency	f_{RF}	2.998 010 GHz	EU S-band
American radio frequency	$f_{\text{US RF}}$	2.855 998 GHz	US S-band
American X-band	$f_{\text{US X-band}}$	11.423 996 GHz	US X-band
G.C.D.	f_{COIN}	15.779 000 MHz	EU S-band / 190 US S-band / 181

9.3 Description of the Timing System

A schematic layout of the FERMI T&S system is shown in Figure 9.3.1, in which the main sub-systems of the accelerator complex, the gun, the accelerating sections, the x-band structure, the undulator section and a generic beam-line (labelled “experiment”) are shown as blocks.

9.3.1 T&S System Diagram

A reference oscillator synchronizes the entire machine, ensuring the specified time stability and “low frequency” jitter level.

Two main units are directly linked to the reference oscillator: the reference frequencies generator and the master time base. The former generates the S-band and X-band frequencies, the laser repetition frequency and other needed intermediate frequencies. The latter generates the machine triggers, typically “digital” signals, such as the bunch repetition rate and various gates and triggers for the laser systems and the diagnostics.

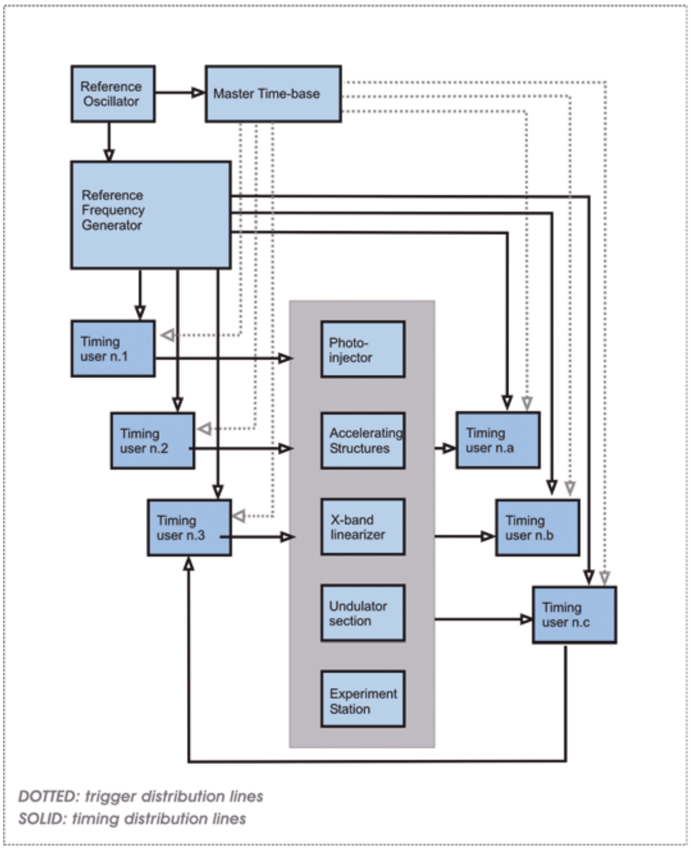

Figure 9.3.1:
Block diagram of the timing and synchronization system.

In the T&S system one distinguishes several classes of *timing clients*. A basic classification criterion is based on the physical layer of the reference signal they need be connected to: *optical* or *electrical*. Furthermore, one can also identify *timing clients* acting on accelerator sub-systems (labelled in Figure 9.3.1 as: 1, 2,...n), such as lasers, the RF system and the RF deflectors, and other *timing clients* (labelled in Figure 9.3.1 as: a, b, c) who may receive inputs from the accelerator under different forms (either electrically or optically) or who are closely interacting with the electron or photon beams. To this fourth class belong diagnostics clients such as 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 clients of the first (a) class, to implement a given "synchronization" task.

Two major R&D efforts are in progress related to the development of optical clock systems allowing to "synchronize" a large-scale accelerator facility, by generating the reference signal (clock) and distributing it typically over distances of several hundred meters.

Two synchronization schemes for such most demanding timing clients have in fact been recently proposed and are being developed:

- in MIT, work is in progress, in collaboration with DESY, on a pulsed optical clock whose in principle feasibility has already been demonstrated,
- a CW optical clock system is under development in LBNL.

While both schemes are expected to meet the kind of performance required of a complete femto-second, large scale timing system, each is best suited for "synching" specific classes of sub systems: the MIT/ DESY "time domain" one for "pulsed" clients such as laser diagnostics ones, the LBNL "frequency domain" one to provide the reference signal to the Low Level RF "quasi CW" clients.

The FERMI timing and synchronization systems will therefore exploit the best of both schemes (sharing the Reference Oscillator) by closely integrating them into the final FERMI timing design.

9.3.2 The Reference Oscillator

The Reference oscillator provides the phase noise floor for the facility; it ensures the required ultra low phase noise at the lower end of the phase noise spectrum, and therefore stable, precise timing throughout the facility.

Single frequency off the shelf reference oscillators can be found on the market, in the (factory selectable) range of 8 to 12 GHz, with output power levels of 13 dBm ± 3 dB and phase noise values as low as:

- 108 dBc/Hz @ 100 Hz
- 138 dBc/Hz @ 1 kHz
- 156 dBc/Hz @ 10 kHz
- 166 dBc/Hz @ 100 kHz

Compatible ultra low phase noise frequency dividers can also be purchased so that, starting from the EU X-band frequency ($f_{X\text{-band}}$= 11.991 GHz), the S-band and the Master Oscillator (OMO) repetition rates can be obtained by subsequent divisions, without spoiling the reference ultra low phase noise level.

9.3.3 Pulsed Timing Section

The pulsed section of the FERMI timing system relies on the Optical Master Oscillator. The OMO is a fibre laser, typically, passively mode locked to the reference oscillator; it generates a *comb* of discrete optical pulses at λ=1550 nm which are used as synchronizing events. The duration of the optical pulse is: 100 fs< $t_{\text{PULSE OMO}}$< 1 ps.

The OMO provides excellent jitter performance in the upper region of the jitter spectrum (f_{OFFSET}>10 kHz). To improve the natural phase noise performance of the OMO in the lower part of the phase noise spectrum, it is phase locked to the ultra low phase noise reference frequency, $f_{\text{REF OMO}}$.

The fibre laser repetition rate, f_{OMO}, must be a sub-multiple, with dividing factor N, of the accelerator S-band frequency (2.997 GHz). Possible values are listed in Table 9.4.1.

N=1 is currently under investigation for an actively mode locked fibre laser. This specific case is shown in Figure 9.3.2. The stream of optical pulses generated by the OMO is distributed to the end clients by means of individually stabilized FO links, the group velocity being stabilized by an active loop. When required, optical pulses can be provided at a lower repetition rate.

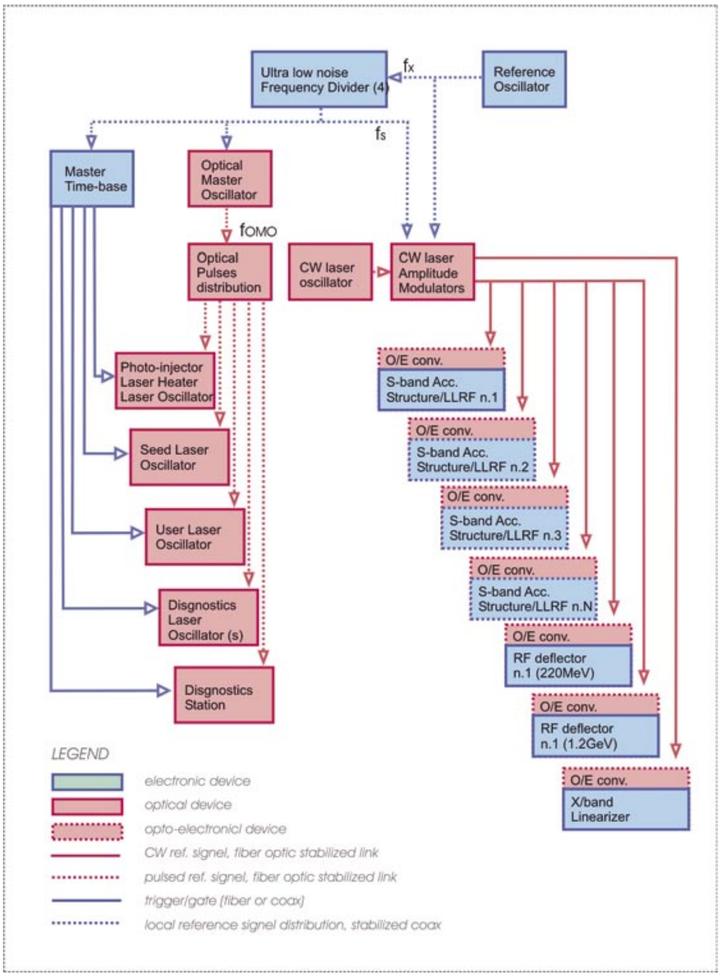

Figure 9.3.2:
Block diagram of the FERMI timing system, with f_{REF}=$f_{X\text{-}band}$ and f_{OMO}=$f_{S\text{-}band}$.

9.3.4 Continuous Wave Timing Section

In the CW timing section, an optical carrier signal is generated by a long coherence length, CW laser, at λ=1530 nm. The optical carrier is amplitude modulated by a radio frequency signal using an electro-optical modulator and transmitted over a "phase velocity" stabilized fiber optics link. On the transmitter side a fiber amplifier and a splitter create multiple lines, one for each client. The signal carried by the fiber is detected by a photodiode at the receiver side and the radio frequency signal extracted. All fiber paths not part of a stabilization loop are housed in temperature controlled racks, in order not to generate additional phase noise.

9.3.5 Reference and Triggers

Two classes of signals can be identified, *reference frequencies* and *triggers*, that can be distributed using different techniques since they have different requirements in terms of tolerable jitter:

- the Reference Distribution System distributes the reference frequencies around the machine keeping their phase noise at the level of the reference oscillator (i.e. $< 20\ \mathrm{fs_{RMS}}$);
- a less performing (less expensive) distribution system can be adopted for triggers and gates on which a $\leq 10\ \mathrm{ps_{RMS}}$ jitter is tolerated.

9.4 Machine Frequencies and Trigger Generators

The machine frequencies and trigger generators are asked to:

- provide ultra-low phase noise references to all sub-systems to be synchronized
- provide the bunch repetition frequency
- generate the G. C. D. frequency

In the following paragraphs the solutions proposed for the different sub-systems are presented.

9.4.1 Machine Frequencies Generator

As previously said, a set of reference frequencies have to be generated and distributed to synchronize all the different FERMI sub-systems. The basic idea is to obtain all (but one) reference frequencies using low phase noise frequency dividers fed by an ultra low phase noise oscillator, the Reference oscillator (see Par. 9.3.2). The expected jitter from this configuration is at the $5\ \mathrm{fs_{RMS}}$ level.

The only exception is the US X-band frequency, obtained by up conversion of a frequency synthesizer.

9.4.2 Laser Frequencies

FERMI makes massive use of lasers, including both oscillators and amplifiers: in the following, “laser” refers to laser oscillators.

The adoption of an hybrid scheme for the optical timing allows, in principle, to operate the whole facility using a single laser (oscillator). This single laser could serve both as optical reference and as seed to the various amplifiers operating in the facility. This solution leads to an intrinsically synchronized facility, the only sources of jitter/drift being the stabilized fibre optics links for which sub-5 $\mathrm{fs_{RMS}}$ jitter has been already demonstrated.

On the day-zero though FERMI will start to operate in a multi laser configuration where the Optical Master Oscillator (OMO) synchronizes the remote lasers by providing them the ultra stable optical reference. The optical reference can either be converted into an electrical one to be used as reference input to the timing stabilizer units controlling the repetition rate of the remote lasers (jitter $\approx 100\ \mathrm{fs_{RMS}}$) or can be used directly in a cross correlator scheme for remote laser synchronization (jitter $\approx 5\ \mathrm{fs_{RMS}}$).

When dealing with pulsed laser synchronization two frequencies can be identified:

the reference frequency, $f_{\text{REF LASER}}$

the repetition rate of the laser pulses, f_{LASER}

These two signals need not to be necessarily the same: depending on the laser synchronization architecture; what is generally true is:

$f_{\text{LASER}} = m \bullet f_{\text{REF LASER}}$, m integer

For the OMO we define:

the OMO reference frequency, $f_{\text{REF OMO}}$

the OMO repetition rate, f_{OMO}

For the OMOs currently under evaluation, $f_{\text{REF OMO}} = f_{\text{OMO}}$.

The $f_{\text{REF OMO}}$ has to be an integer sub-multiple of the microwave master reference f_{MASTER}, since any relative jitter between these two signals is directly seen as jitter of the OMO output.

The available values of the reference frequencies for the Optical Master Oscillator and for the other facility lasers (photo-cathode laser, seeding laser and user's lasers) can be obtained from those listed in Table 9.2.4 and are shown in Table 9.4.1 with the respective microwave master frequency division factors.

Table 9.4.1: Table of the FERMI sub-multiple reference frequencies.

Signal name	*Symbol*	*Value [MHz]*	*Notes*
FERMI radio frequency	f_{RF}	2,998.010	EU S-band
OMO reference frequency	$f_{\text{REF OMO}}$	599.602	possible OMO ref
OMO reference frequency	$f_{\text{REF OMO}}$	299.801	possible OMO ref
OMO reference frequency	$f_{\text{REF OMO}}$	157.790	possible OMO ref
LASER ref. frequency	$f_{\text{REF LASER}}$	78.895	possible LASER ref
LASER ref. frequency	$f_{\text{REF LASER}}$	31.558	possible LASER ref
LASER ref. frequency	f_{COIN}	15.779	possible LASER ref

Note that the Master Time base frequency is 50 HZ.

9.5 Timing Channels

As shown in the block diagram (Figure 9.3.2) the FERMI timing system adopts two media for the generation and the distribution of the timing signals in the facility. Fiber optics and coaxial lines have been adopted to suit the physical layer of the different adopted device (μ-wave Reference generator, fiber laser or LLRF controller).

In the following paragraphs the characteristics of the different media are outlined.

9.5.1 Local Reference Distribution Coaxial Channel

As shown in Figure 9.3.2, the Reference signal generated by the Reference oscillator (via the low noise divider) needs to be locally routed to the different devices users (OMO, CW laser amplitude modulators). The length of the links must preferably be shorter than 1m, so that units to be connected should be located in a same rack. Phase stable cables with low temperature coefficient (< 5 ppm/°C) will be used.

9.5.2 Optical Timing Channel

Optical reference signals will be distributed through single mode fibers (SMF28).

Depending to the type of signal transmitted (pulsed or CW) either "group velocity" or "phase velocity" stabilization schemes will been adopted, both solutions having showed jitter performances well below 10 fs_{RMS} during both laboratory and field tests.

Maximum attention has to be paid to short fiber links not within a stabilization loop: such these links will be housed in a temperature and vibration controlled ambient.

9.5.3 Coaxial Timing Channel

Coaxial, double shield wideband cables will be used for the various trigger and gate signals with more relaxed jitter specifications. The cables will be run in the machine tunnel on radiation safe cable trays, the expected temperature excursion being less than ±1°C.

9.6 Synchronization of Electrical Clients

Most of the FERMI sub-systems to be synchronized, the largest number of which are diagnostics LLRF controllers, need electrical reference signals, f_{REF}, at (RF) power levels to be defined item by item.

9.6.1 Low Level Radio Frequency

Because of the synchronization scheme selected for the Low Level RF controllers, the S-band reference signal has to be brought to each LLRF box. As of today, this reference signal is obtained by envelope detection of the CW, amplitude modulated optical signal at 1550nm wavelength. All the electronics located downstream from this E/O converter must be designed in such a way as to preserve the fs grade jitter at the end location.

The most appropriate configuration for the reference distribution is a “star” one, since it prevents jitters from adding up; the jitter is thus the same at all remote stations, independently from their distance.

On the contrary, spilling optical power from a single phase-stabilized optical link does not ensure the required fs-level jitter everywhere.

9.6.2 Diagnostics

Diagnostics equipment also requires both electrical and optical reference signals for synchronous operation.

There are two different equipment categories, requiring synchronization

- at the pick up level or
- at the level of the acquisition electronics

respectively.

Bunch Phase Monitors (BPhM), Electro Optical Sampling (EOS) stations and Streak Cameras belong to the first category whereas all other diagnostics belong to the second one which, because FERMI operates at low repetition rate, needs a bunch clock for acquisition.

Both the BPhM and the EOS scheme rely on the pulsed optical reference signal to output the measurement. The Streak Camera needs a low phase-noise trigger, which can even be a high energy optical pulse, to initiate the "streaking ramp".

A fiducial light pulse (the optical reference itself) may be provided as well to compensate for the residual jitter on the sweep start since, when the camera operates in the optical trigger mode, the ramp would still exhibit some jitter (at the few hundred fs level) even were the trigger ideally jitter-free.

9.7 Synchronization of Optical Clients

Other important optical timing clients are the lasers. Basically, lasers can be synchronized either electrically, to ~ 100 fs, or optically to achieve jitters below 10fs and even down to sub-fs performance in carrier envelope stabilization schemes.

On "day zero", the FERMI lasers (mainly the photo-cathode and the laser heater ones) will be synchronized electrically, by providing an electrical reference signal to the laser timing stabilizer box.

The scheme has been already successfully tested at ELETTRA in 2004 by locking the Storage Ring synchrotron radiation pulses to an external synchronized fs laser oscillator [ref]. The minimum achievable jitter has been measured to be in the 100s fs $_{\text{RMS}}$ range.

Eventually it is foreseen to synchronize the lasers electrically during coarse alignment and to switch to optical for fine adjustments.

Optical synchronization is based on cross-correlating the laser oscillator pulses to the reference optical clock ones; the jitter measured in the laboratory has been shown to be as low as 5 fs$_{\text{RMS}}$.

A further option, being considered for the longer term, is direct seeding of the remote laser amplifiers directly using the optical clock pulses, thus obtaining an intrinsically synchronized machine.

9.8 Integration of Synchronisation with Controls

Full integration into the accelerator and experiments control system is foreseen, to provide full remote control of all devices and equipment, including real-time monitoring of the sub-systems timing, to allow for efficient and fault free operation of the whole facility.

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