GENERATION AND DISTRIBUTION OF STABLE TIMING SIGNALS TO SYNCHRONIZE RF AND LASERS AT THE FERMI FEL FACILITY

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Abstract

Fermi is the fourth generation Light Source that is currently being designed at ELETTRA, in the frame of a collaboration that includes LBL and MIT. The timing system will play a crucial role in achieving the expected performance in this and other Linac based FELs due to the sub-picosecond electron bunch length and to the expanded use of femtosecond lasers as key components in future light sources. Furthermore, the requirements of the timing system are also tightly linked to the applications of the generated ultra fast x-ray pulses. In this paper we present the requirements for the Fermi timing system, which is based on the optical timing distribution, currently seen to be the only technique that enables an RMS jitter at the 10fs level. The timing system, intended for a user facility operated on a 24-h, 7-d basis, must operate stable and reliable. The fundamental components of the system are analyzed, such as the optical reference oscillator, the fibre optic stabilized links and the local optical to electrical (O/E) converters, needed for the RF plant synchronization. Furthermore, solutions for the synchronization of the diagnostic tools for the Linac as well as user related synchronization issues are presented and discussed.

TIMING SYSTEM SPECIFICATIONS

Femtosecond x-ray light source test stands have already proven to generate sub-picosecond (10^{-14}s) x-ray pulses, at repetition rates of few Hertz (10^{-2}s), to be delivered during user shifts of many hours (10^{4}s). Therefore, the synchronization of a femto-second x-ray light source has to deal with 18 orders of magnitude, which calls for state of the art solutions. For a seeded FEL like FERMI@ELETTRA [1] the jitter between the electron bunch at the undulator entrance and the seeding laser pulse is a pre-requisite for proper operation.

The Timing system deals with:

- the generation of an ultra-low phase noise reference
- the distribution of the reference and trigger signals to all sub-systems

The achievement of a synchronization at the <200fs level calls for an ultra-low noise timing system, aiming at <10fs_{RMS} jitter, and for a very accurate machine design. As a consequence, synchronization has a broad impact on several machine sub systems.

Tolerance budget

For the Fermi normal conducting linac the total jitter of the electron bunch at the entrance of the undulator section at the final energy (E=1.2GeV), basically depends on:

- Photo-cathode laser to reference jitter
- Amplitude and phase stability of the accelerating voltages in the RF structures
- Stability of magnet power supplies in bunch compressor chicanes and vertical ramp / spreader
- Trajectory stability along the whole machine

To quantify the tolerance of RF parameters on the total jitter, a tolerance table has been produced [2] using the simulation code LiTrack. Considering a <10$\%_{RMS}$ peak current jitter variation, 0.1$\%_{RMS}$ on final electron energy and 200fs_{RMS} jitter of the electron bunch, the resulting stability of the RF plants is achievable upgrading the present linac.

Proposed seeding scheme

Fermi will generate coherent radiation either in a single harmonic cascade, FEL-I, or in a double cascade scheme, FEL-II, at different wavelengths: λ_{FEL-I}=100÷40nm and λ_{FEL-II}=40÷10nm. Furthermore, for FEL-II, both the whole-bunch (WB) and fresh-bunch (FB) seeding techniques have been adopted (see fig. 1). FEL pulse duration is driven by seed laser pulse if laser pulse is shorter than the core of the electron bunch; the operation may be critical as the bunch length is comparable to its jitter. Values are summarized in Table 1.

Table 1: values of Bunch and seed pulse durations

Mode	$L_{B\ core\ elec}$	$L_{B\ total\ elec}$	$L_{P\ seed\ laser}$	Units
FEL-I short	200	450	200	[fs]
FEL-I long	800	1.3	200	[fs]
FEL II, FB	200	450	100	[fs]

A modified initial set-up (longer laser/shorter bunch) relaxes jitter requirements. The seed laser average power has to be checked with a long laser pulse

Adopting the *longer bunch / shorter laser* option, the ranges of jitters ($t_{B\ JIT}$ and $t_{SLP\ JIT}$) are defined by the first part of the seeding process, the modulator. Assuming a seed laser jitter of <100fs_{RMS} and a bunch jitter of ≅200fs the operation becomes critical (see figure 1).

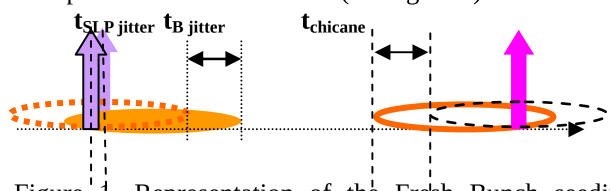

Figure 1. Representation of the Fresh Bunch seeding scheme, laser shorter/ bunch longer.

In order to provide the required synchronization, the Fermi timing system has to comply with the specifications listed in Table 2.

Table 2: Specifications of FERMI timing system

Parameter	symbol	Value	Units	Notes
Jitter frequency range	ΔF_{JIT}	$1 \div 10^7$	[Hz]	phase noise integration region
Jitter, OPT	$T_{JIT\ O}$	<10	[fs]	remote end
Jitter, ELE	$T_{JIT\ E}$	<100	[fs]	remote end
24-h drift	T_{DRIFT}	<350	[fs $_{pk-pk}$]	Long term stability
Max. distance	D_{MAX}	400	[m]	remote user from ref. osc.

FS TIMING: CONCEPTS AND RESULTS

A team has been set-up jointly with LBL and MIT to produce the Fermi Technical Optimization Study (TOS). As a result, for the timing system, two original proposals have been brought to attention by the Laboratories according to their skills and previous developments. The two proposals are here outlined.

Description of the MIT developments

A modular system is proposed that enables synchronization of various RF and optical sub-systems with fs precision over distances of a few kilometers [3]. For the Fermi facility fs precision timing will only be necessary over distances on the order of 300m. Here, we report on recent progress towards the realization of such a system. Successful optical transmission of the 2.856GHz microwave oscillator signal over 500m of fibre with an added timing jitter of less than 50fs is demonstrated.

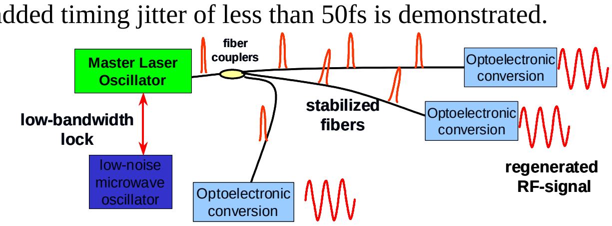

Figure 2. Conceptual schematic of the proposed MIT synchronization system.

The timing and synchronization system envisioned is sketched in Figure 2. An optical master oscillator (OMO) in the form of a mode-locked laser is tightly synchronized to the reference microwave oscillator (RMO). The phase noise of the distributed signal will be determined by the RMO phase noise for frequencies up to the locking bandwidth of the PLL (~1 kHz) and the superior phase noise of the OMO for higher frequencies. This makes improving the overall timing jitter over the full bandwidth (~mHz to ~10MHz) of the transmitted signal possible, compared to the jitter of the microwave oscillator alone.

The OMO generates a stream of very low jitter sub-ps pulses that are distributed to the individual sub-systems that need tight synchronization to the microwave reference of the facility. The optical pulse train has to fulfil two tasks. First, it serves as the means for achieving fs and, potentially, sub-fs point-to-point stability of the pulses travelling through the fibre link. Second, a fraction of the pulse train is coupled out from each end of the fibre links which can be used for synchronization of microwave or optical sub-systems to the OMO. The use of an optical pulse train for timing distribution has several advantages:

- The RF-signal is encoded in the pulse repetition rate and any harmonic can be recovered directly at the fibre end.
- The group delay of the fibre link is directly stabilized rather than the phase delay.
- Brillouin scattering and residual reflections at fibre discontinuities are strongly suppressed.
- Optical cross-correlation can be used both for link stabilization as well as local synchronization of additional optical sources.
- The pulse trains can be used to directly seed amplifiers at end stations.

The main sub-component of the timing distribution system is an ultra-low jitter OMO. Promising candidates for ultra-low jitter OMOs are: Er/Yb-based fibre and glass lasers [4]. The jitter of these lasers has been characterized in the electrical domain using an Agilent 5052 signal source analyzer after photo detection. It is important to note, that all these measurements where limited by the photo detector noise level and the dynamic range of the measurement rather than the actual noise of the OMO. The theoretically predicted fundamental limit on the jitter of these sources is on the order of 1fs. The free-running mode-locked erbium-doped fibre laser has a residual timing jitter of <10fs in the frequency range of 1kHz to 20MHz [5, 6]. Fig. 3 shows the schematic of the current low jitter OMO implementation based on a stretched pulse Er-doped fibre laser. The laser is also synchronized to a RMO with an in-loop fibre stretcher. Residual jitter between the RMO and the OMO is less than 35fs within 10Hz to 2kHz (PLL-bandwidth) [5, 6].

The fibre laser can easily be linked to a fibre distribution system. A crucial performance indicator for such a system is the timing jitter added by the distribution, integrated from frequencies equivalent to the roundtrip time of the specific fibre link to the Nyquist frequency of the laser, since a feedback system cannot compensate for this jitter. This jitter will set an inherent limitation to the precision with which the pulse train can be distributed in the facility. Using the Er-fibre based OMO we performed a proof of principle demonstration for RF signal transmission over a 500 m long fibre link at the MIT Bates Accelerator Centre during full operation of the facility. The schematic of the experimental setup is shown in Fig. 4. The pulse train of the Er-doped fibre laser, which is locked to the Bates RMO, is sent through a fibre coupler, generating a signal and a reference pulse stream. The signal pulses traverse a piezo electric (PZT) fiber stretcher before entering the fibre link.

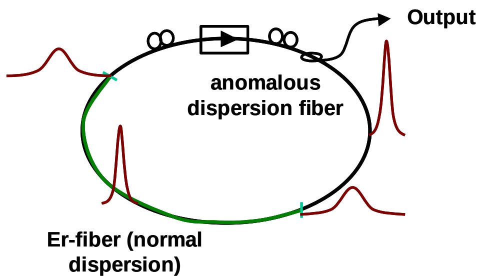

Figure 3. Schematic of the OMO, a mode-locked stretched pulse Er-fibre laser.

The fibre link made up of standard single mode telecom fibre, SMF 28, is passively temperature stabilized by a cooling water pipe running through the enclosure to about half its length. The signal pulse stream is back reflected into the same fibre via a Faraday rotator mirror. The returning signal pulse stream as well as the reference pulse stream is converted into electrical signals using photodiodes. The phases of the spectral components at 1GHz of both signals are compared in a mixer.

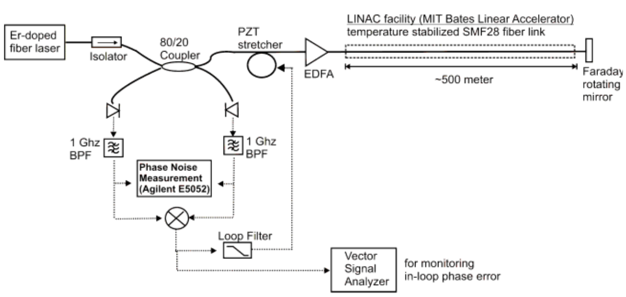

Figure 4. Schematic of the experimental setup for the synchronization experiment at the MIT-BATES facility.

The resulting error signal drives a feedback signal to the fibre stretcher. The fibre stretcher in turn adjusts the fibre length, thereby stabilizing the group delay in the fibre link. Measurements reveal that the additional jitter incurred by the transmission through the un-stabilized fibre in the frequency range of 0.1Hz to 22MHz is less than 20fs. In the long run, replacement of the microwave length stabilization by optical cross-correlation has the potential to reduce the jitter of the length stabilization to the sub-fs range [7]. The overall added jitter due to the fibre link stabilization and locking to a reference microwave oscillator is less than 50fs.

In summary, we have demonstrated RF-signal distribution over 500m over a standard fibre link in an accelerator environment with an overall added timing jitter of less than 50fs. For further technical details, see references [5, 6]. Based on the currently achieved results further development and deployment of a timing distribution system with less than 10fs added jitter from mHz to MHz seems feasible in the near future. Thus, the requirements of fourth generation light sources such as the XFEL at DESY, Germany, or the FERMI facility in Trieste, Italy can be met.

Description of the LBNL developments

An optical heterodyne technique using frequency offsets, used at the Atacama Radiotelescope Facility of NRAO [8], provides five orders of magnitude more sensitivity to phase differences in the reflected signal than an RF-based system. Phase differences at RF are optically down converted to 110MHz, where the phase detection is carried out. As phase information is preserved during the heterodyning process, phase differences at optical frequency is reflected at radio frequency, so conventional electronics may be used to detect the phase differences at RF rather than at optical frequencies. All operations at the 110 MHz radio frequency become non-critical, using inexpensive off-the-shelf components.

Figure 5 shows the application of the frequency-offset method in a practical fibre-based transmission system to carry precise timing signal from one point to another [9].

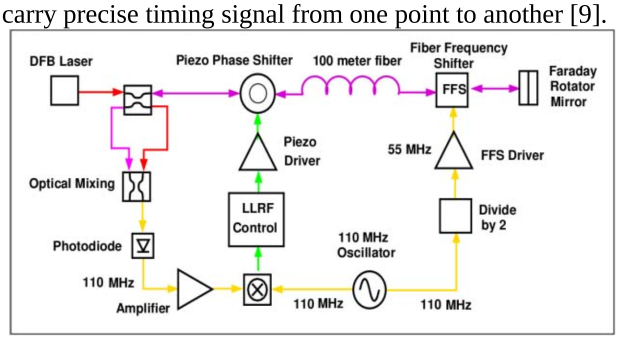

Figure 5. Scheme of the fibre stabilization set-up.

A narrow-band CW laser signal is launched through a directional coupler, used to provide a local sample, and into a piezo phase modulator and the 100 meter fibre to be stabilized. At the far end of the fibre, an acousto-optical frequency shifter shifts the optical carrier up by 55 MHz, which is then reflected by a Faraday rotator mirror, and again shifted up 55 MHz back through the frequency shifter, and sampled at the near end of the fibre. The resulting 110 MHz beat between the shifted and original laser frequency is phase compared with the 110 MHz reference and is used to correct transit time jitter with a piezo phase modulator. Since the heterodyning process preserves phase, phase shift of the 110 MHz reference frequency is equivalent to the phase shift at optical frequency. One degree error at 110 MHz corresponds to 1 degree at optical or 0.014fsec.

Both RF and optical signals may be sent over the stabilized fibre with zero-chirp Mach-Zehnder (MZ) amplitude modulators or with frequency-selective optical directional couplers.

Note that this is a linear system. Signals modulated onto the CW laser carrier at the fibre entrance do not inter-modulate with each other. The optical power level is significantly below any non-linear threshold in the fibre. Reflections along the fibre do not introduce error, as they have not been up converted by the 110MHz RF offset frequency necessary to produce a beat note in the photodiode. Performance measurements were performed on the configuration shown in Figure 6.

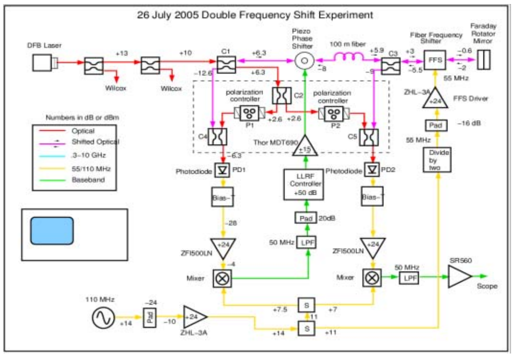

Figure 6: measurement set-up

A Koheras 15mw erbium-doped CW fibre laser with a 2 kHz line width (greater than 25km coherence length) provides the optical carrier. The laser itself is locked to a 1550nm absorption line in a 20milliTorr acetylene cell by a piezo actuator to provide an accurate frequency reference. To monitor the effectiveness of the fibre stabilization system, both an RF-based and an optical-based monitor system were used. The RF-based system modulates onto the optical carrier with a zero-chirp MZ fibre modulator signals ranging from 300 MHz to 18 GHz, which were then monitored at the far end with a fast photodiode. A clean 300MHz signal modulated onto and detected at the far end was showed no increase in noise floor above the -95 dBc of the spectrum analyzer. An 18GHz signal from a network analyzer showed phase modulation below the 0.5 degree noise floor of the analyzer. Neither of these measurements were sensitive enough to determine the ultimate performance of the stabilized fibre.

Therefore, a measurement at optical frequencies were performed by taking a sample of the reflected optical signal at the far end, reflected by the mirror and transformed up 110 MHz, and beating it with a sample of the CW signal out of the laser itself in a channel identical to the stabilization control channel. With an electronic chart recorder, the room temperature, the error signal fed to the phase modulator piezo and the monitor error signal were recorded over several day intervals. The lock-in range of the system is about 1.5ps, and the temperature variation in the room oscillates over a two-hour cycle by about 1 degree centigrade. Thus, over the temperature extreme, there will be four lock jumps, as the one-way transit time varies by 6psec. The present optical measurement of the corrected transit time drift, including the errors introduced by presently thermally uncontrolled directional coupler and Faraday mirror is 20fs. These components will be stabilized with small thermo-electric controlled chambers to 0.001^{o}C. Additional lock-in range will be provided by mating the piezo phase shifter to a thermal-electric cooler which will provide a 2ps/oC slow control along with the kilo Hertz bandwidth of the piezo itself within its 1.5ps lock range, extending the lock-in range to 10ps or more. The fast jitter of the transmitted CW laser signal, measured by observing the wideband (25MHz) signal from the 110MHz phase detector is 0.6fs (0.25fsecRMS). A major source of jitter was found to be white noise in the high-voltage piezo drivers was eliminated by high-level filtering.

THE FERMI TIMING SYSTEM

According to the today available technologies listed above, the FERMI timing system block diagram and the list of FERMI timing system users are here presented. The FERMI timing system relies on the optical clock scheme in combination with actively stabilized fibre optic links, in star topology. The basic building blocks are:

- a reference µ-wave oscillator, defining the stability
- an "optical oscillator" (fibre laser) phase locked to the µ-wave oscillator, providing <10fs jitter
- a star of stabilized fibre optic links
- a direct optical-to-optical lock scheme for laser synchronization to reference (preserving <10fs jitter level)
- ultra low noise O/E converter to recover the RF reference at remote stations

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