EXPERIMENTS ON THE SYNCHRONIZATION OF AN ULTRAFAST CR:LISAF LASER WITH THE ELETTRA STORAGE RING AND FEL PULSES

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Abstract

The techniques for synchronizing ultra fast lasers to external radio frequency reference sources are well established and characterized in the literature. However, data lack on the minimum light-to-light jitter that can be achieved in different synchrotron operation modes when an external laser is locked to the storage ring master clock. Here we present first results for the synchronization of an ultra fast Cr:LiSAF laser with electromagnetic radiation coming from the Elettra storage ring in four bunch and multi-bunch mode. In addition, data on the synchronization of the same laser with the Elettra FEL pulses, both in free running and Q-switching regime, are reported. In our experiments, laser-to-RF locking was continuously monitored using a built-in phase detection. The laser light to storage ring light locking was characterized by simultaneous acquisition of two/three pulse trains by a streak camera. In addition, pulse jitter was determined by processing of the signal of fast photodiodes monitoring the different light beams.

INTRODUCTION

During the last decade, remarkable progress has been obtained in the establishment and full-potential operation of Third Generation Synchrotron light sources. At the same time, impressive peak powers (Terawatts) have been achieved by continuous advances in laser techniques; femto-second pulse duration is now available from commercial equipments. Current projects of fourth generation sources in the X-ray spectral range, X-ray Free Electron Lasers (X-FELs) integrate accelerator and laser based technologies [1]. This process has started also at the ELETTRA Laboratory, where the Storage Ring Free-Electron Laser SR-FEL [2] is in operation and the fourth generation light source [3] FERMI@ELETTRA is now ready to go.

As the synchronization of fs-lasers to the electron bunches is crucial for the optimum operation of these new sources, we performed some synchronization experiments using the currently available sources.

RADIATION SOURCES AT ELETTRA

Different radiation sources can be used simultaneously at ELETTRA for "time resolved" experiments. Beside the well-known Undulator and Bending magnet radiation, whose temporal structure directly reflects the Storage Ring filling pattern, the Storage Ring Free Electron Laser (SR-FEL) is now becoming available. Furthermore, table top laser oscillators can be used when the wavelength or the energy per pulse of a specific experiment is not fulfilled by the ELETTRA sources. In Table 1 the temporal structures of these sources are reported.

Table 1: Temporal structure of the radiation sources.

Source type	Pulse length t_{FWHM}	Repetition Frequency
Bending/ Undulator	50÷120ps 60ps	MB: 500MHz 4B: 4.26MHz
SR-FEL, free run	15ps	4.64MHz, pulsed
SR-FEL, Q-switch	15ps	10Hz
Table top fs laser Ti:Sa, Cr:LiSAF	≈110fs	≈100MHz

Synchrotron radiation

During user shifts the machine is operated in:

- multi bunch mode (MB), the standard user mode
- four-bunch mode (4-B), the SR-FEL mode

In MB mode, the 90% of the available buckets are filled consecutively, with 2ns spacing between bunches. This mode is used by those beam lines that rely on the average photon flux and do not exploit the time structure of the radiation. Typical electron energies are ranging from 2 to 2.4GeV, with a maximum average current of 330mA. Synchrotron radiation pulses have duration of typically $60ps_{FWHM}$ in MB operation; recently using the Third Harmonic super-conducting cavity, this value raised up to $120ps_{FWHM}$. The temporal structures of different sources are listed in Table 1.

The four bunch (4-B) mode is used by the SR-FEL, at 1GeV, and by the Users carrying out "time resolved" experiments, mostly at 2GeV as the photon beam is brighter. In this mode, four bunches are evenly distributed in four storage ring buckets and the interval between them results to be 216ns.

Storage Ring Free Electron Laser

In a SR-FEL, a relativistic electron beam interacts with an electromagnetic field as it passes through a periodic magnetic structure forcing particles to move along sin-like trajectories and, consequently, to emit radiation. The ELETTRA SR-FEL is the first and only one installed on a third-generation synchrotron light source. As a consequence, its performance profit from a relative low

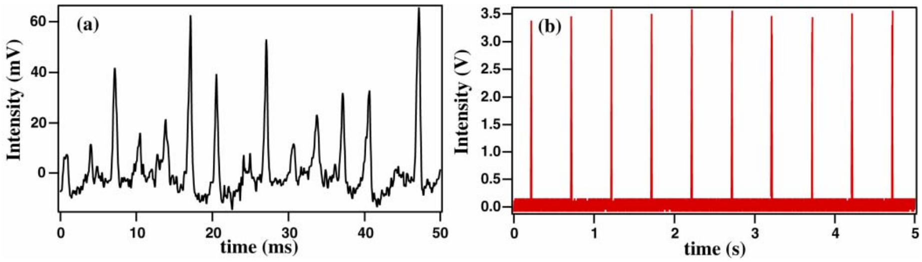

Figure 1: Example of the different macro-temporal structures displayed by the ELETTRA FEL when operated in standard (Figure 2a) or Q-switching (Figure 2b) mode.

emittance and short duration of the electron bunch and from a longer interacting region (this resulting in a higher gain with respect to similar devices). ELETTRA holds the world record of the shortest wavelength ever reached using an oscillator FEL (190 nm). The time duration of a single pulse from the SR-FEL can be as low as $15ps_{FWHM}$. The repetition rate of the SR-FEL pulses varies according to the operation mode of the SR-FEL: free running (fig. 1 left) and Q-switch (fig. 1 right), where the FEL power is "concentrated" into a series of giant pulses. In this case, the peak power is considerably enhanced (one to few orders of magnitude). The giant-pulse operation on a SR-FEL can be obtained by means of a radio frequency (RF) modulation, or using a gain-switching technique [4].

Table top fs laser oscillator

The laser system used for the experiments is a home-made femtosecond Cr:LiSAF laser. The laser construction has been optimized in order to decrease the intrinsic noise and increase stability. The active material is a 3% doped 3mm long Brewster cut Cr:LiSAF crystal (with temperature stabilization at 18^oC by a Peltier cooler), which is pumped at 670nm by a 350mW diode. The phase locking to an external reference is based on the well-established technique using a feedback loop acting on the cavity length [5]: we have used a commercially available instrument (CLX1100, Time Bandwidth Products) which implements this approach. The necessary laser frequency reference signal is provided by an avalanche photodiode illuminated by a small fraction of the laser output beam.

EXPERIMENT SET-UP

The objectives of the experiments were:

- to synchronize the fs laser to the machine RF
- to acquire in a single shot all three sources: synchrotron bending, SR-FEL and fs laser
- to measure the jitter between the sources
- to observe their stability on the long-term time scale, compared to the duration of the pulses

A pre-requisite for the experiment was to have all three sources available at the same location to allow their simultaneous acquisition. This configuration has been easily achieved in the Optical Laboratory of the Instrumentation Group where the synchrotron radiation (UV-VIS-NIR) generated by the storage ring bending magnet S12.2 is made available for diagnostic purposes. Furthermore, the back-end of the SR-FEL is conveniently located in the close vicinity of the same laboratory where the installed Streak Camera is routinely used for measuring both the synchrotron radiation pulses and the SR-FEL pulses. The accelerating voltage radio frequency (RF) has been routed to the Optical Laboratory to feed the streak camera timing system. Therefore, to perform the experiment it was sufficient to move the Cr:LiSAF fs laser to the Optical Laboratory and to synchronize it to the same RF signal by means of a low-jitter electronic module.

Electron beam operating conditions

The experiments have been carried out in both MB and 4-B modes. As the fs laser normally operates at a repetition frequency of 100MHz, to synchronize it to the MB beam it was sufficient to tune the length of its optical cavity to obtain f_{rep1}= 99.9308MHz. The reference signal at this frequency has been obtained by division modulo-5 of the RF, as indicated in Table 2.

Table 2: Different frequencies used for the experiments.

Symbol	div. modulo N	Frequency [MHz]	period [ns]
f_{RF}	1	499.654	2.0
f_{rep_1}	5	99.9308	10.0
f_{rep_2}	6	83.2756	12.0
$f_{4\text{-}BUNCH}$	108	4.626	216.1
108/6=18 ⇒ f_{rep_2}=18th harmonic (f_{4bunch})			

In 4-B mode, being the synchrotron radiation repetition rate equal to $f_{4\text{-}BUNCH}$=4.626MHz, to lock the fs laser pulses to the synchrotron radiation ones at each revolution, the fs laser repetition frequency has been changed to f_{rep_2}=83.2756MHz. In doing so, each synchrotron radiation pulse had a laser pulse locked to it, one out of 18 as f_{rep_2} has been selected to be the 18th harmonic of $f_{4\text{-}BUNCH}$.

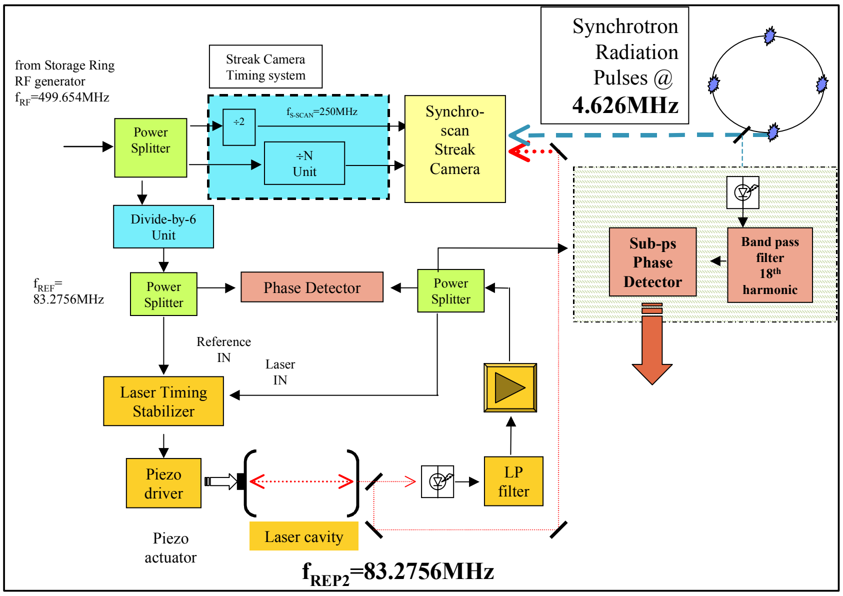

Figure 2: Block diagram of the Synchronization experiment

Description of the block diagram

The block diagram is reported in figure 2. In the upper left part, the low –jitter division-by-6 module can be seen. In the lower part, the Cr:LiSAF fs laser is visible with the lock-in equipment. Finally, in the right hand part of the block diagram, the light-to-light jitter measurement device is shown.

Before acquiring these different sources with the streak camera, they had to be precisely aligned onto the streak camera input pinhole (D=50÷200μm) and separately attenuated, using Neutral Density filters, due to their rather different intensities.

JITTER MEASUREMENTS

With the term jitter, here we intend the amplitude of the short-term time fluctuations of a signal with respect to its reference. When dealing with signals of the same frequency (i.e. frequency locked) the jitter turns out to be the phase noise of a signal to its reference.

The fs laser is equipped with its Timing Stabilizer unit that locks the repetition frequency of the laser to a reference by controlling the length of the optical cavity using a piezoelectric actuator. The Timing Stabilizer unit outputs the phase noise instantaneous values on a front panel display that is very useful for the fs laser set-up.

As the phase noise is a key parameter to know in our experiment, we implemented a redundant phase noise measurement beside the Timing Stabilizer unit. We adopted the Amplitude and Phase Detector AD8302 from Analog Devices [6] that performs amplitude ratio and phase difference measurements on two signals, from DC up to 2.7GHz and with a bandwidth of 30MHz. The two measurements have been cross-checked in both the time and frequency domain. In figure 3, the phase oscillations of the fs laser with respect to its reference, and due to a kick applied to the laser table, are shown. The upper trace shows the AD8302 output, the lower one the Timing Stabilizer output: there is a very good agreement with a higher sensitivity on the AD8302. Same results have been obtained with spectral observations in the range 10Hz to 1MHz, showing no major laser phase noise components above 1kHz.

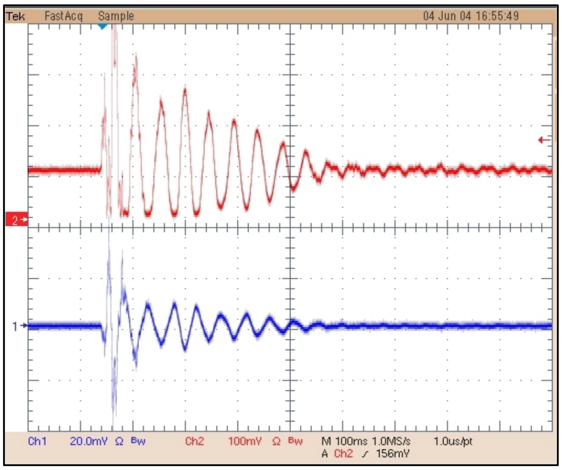

Figure 3: Phase oscillations of fs laser to reference after applying an external kick to the laser table. Upper trace: AD8302 phase output, 100mV/div. Lower trace: Timing Stabilizer output, 20mV/div. Hor. Scale 100ms/div.

STREAK CAMERA ACQUISITIONS

Several streak camera measurements have been carried out during the experiments. The aim was not the measurement of the fs laser pulse duration, well beyond streak camera resolution, but rather the characterization of the jitter and the long-term stability of the synchronized sources. The synchro-scan streak camera with its double sweep capability is well suited for this measurement as it can acquire up to 70ms of light pulses while keeping the resolution of few picoseconds. The synchro-scan acquisitions of the ELETTRA streak camera show the fast time axis horizontally and the slow one vertically, from the bottom to the top of the picture.

In the following figures, some examples of streak camera acquisitions are shown with simultaneous acquisitions of the fs laser pulses and synchrotron light pulses, even overlapping on the same fast sweep (duration 440ps or 880ps), like in figure 4. In this acquisition the fs laser pulse really “seats” on the synchrotron light pulse. The duration of the fs laser pulses is greatly increased by the limited streak camera resolution ($<2ps_{FWHM}$). Synchrotron pulses are 2ns apart

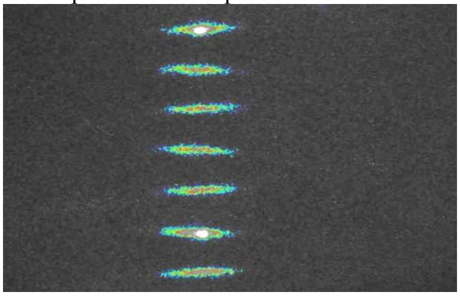

Figure 4: Fast synchro-scan acquisition (VERT=13ns, HOR=880ps) of seven synchrotron light pulses (MB beam) and two overlapping fs laser pulses at f_{rep1} (10ns apart).

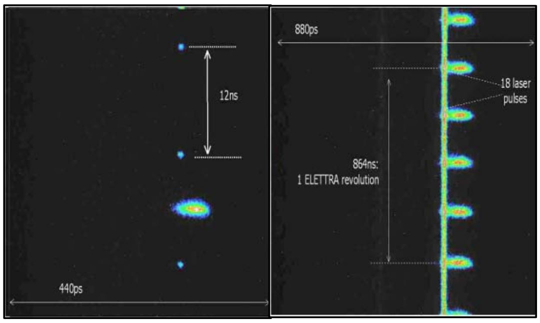

Figure 5, LEFT: fast synchro-scan acquisition (VERT=34ns, HOR=440ps) of one ELETTRA bunch (4-B mode) surrounded by three fs laser pulses. The laser now operates at f_{rep2} 12ns period). RIGHT, same beam but slower vertical axis (VERT=1380ns, HOR=880ps): six ELETTRA bunches captured with 18 laser pulses in between each pair, here shown as a solid line.

In figure 5 LEFT, one bunch of the ELETTRA beam in 4-B mode has been captured with three surrounding fs laser pulses. Now the light pulses have been “streaked” on different sweeps. In figure 5 RIGHT, a longer synchro scan acquisition is shown with the same 4-B beam as fig. 5 LEFT: the laser-to-synchrotron jitter has been estimated to be $\leq 1ps_{RMS}$. In figure 6, all three sources have been captured on a long-time scale (VERT=6.7ms; HOR=880ps) acquisition. The fs laser and the synchrotron pulses appear as solid lines, whereas the SR-FEL is operating free running (pulsed): the stability between the sources can be estimated.

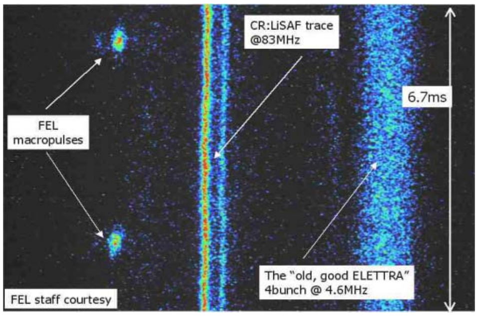

Figure 6: all three sources on a single synchro scan acquisition (VERT=6.7ms, HOR=880ps). The fs laser and synchrotron light pulses appear as continuous lines, the SR-FEL is in free running mode i.e. pulsed.

LIGHT TO LIGHT JITTER MONITOR

As previously shown (fig. 1), a direct light to light jitter monitor is proposed here based on the AD8302 phase detector. Relying on the integer multiplying factor (N=18) between the 4-B beam repetition frequency and the fs laser operating at f_{rep2} (83.2756MHz), a narrow-band band pass filter can be adopted to extract the 18^{th} harmonic from a beam signal (pick-up or photo-diode). The two sinusoidal signals (fs laser rep. rate and filtered beam signal) can be, then, phase-compared using an AD8302, in a 30MHz bandwidth and with a resolution better than 0.01deg. We call it light to light, real-time, on-line jitter monitor: reliminary measurements are encouraging.

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