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LASER TIMING AND SYNCHRONIZATION MEASUREMENTS

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Abstract

In this note we summarize the measurements of the temporal jitter between the laser system and the RF apparatus in the SPARC photoinjector. Synchronization between laser and the accelerating wave is critical to control the electron beam charge, the energy spread, the matching conditions in the accelerator and the electron beam emittance.
According to the beam dynamic simulations the maximum acceptable jitter must be limited within 2-3 ps_{RMS} for SPARC phase 1. The set of measurements presented is finalized to demonstrate the compensation of the phase drift on the scale of few seconds.

1 INTRODUCTION

In the SPARC photoinjector [1, 2], a precise synchronization between the photocathode drive laser and the accelerating wave is necessary to have a fixed and stable time-of-arrival of the photons on the cathode with respect of the phase of the 2856 MHz RF field frequency. This condition is very important to guarantee the stability and the shot-to-shot reproducibility of crucial beam parameters as the beam charge, energy, emittance and energy spread and to ensure a proper matching condition in the accelerator. From beam dynamics simulations [3], summarized in Fig. 1, a variation over ±4 degrees of RF (about 8 ps) of the laser-to-gun phase, in ideal conditions, increases the output rms projected normalized emittance of about 20%. From these results it has been concluded that a tolerance of ±2 ps around the optimal phase is acceptable in order to limit the emittance growth to less than 10%.

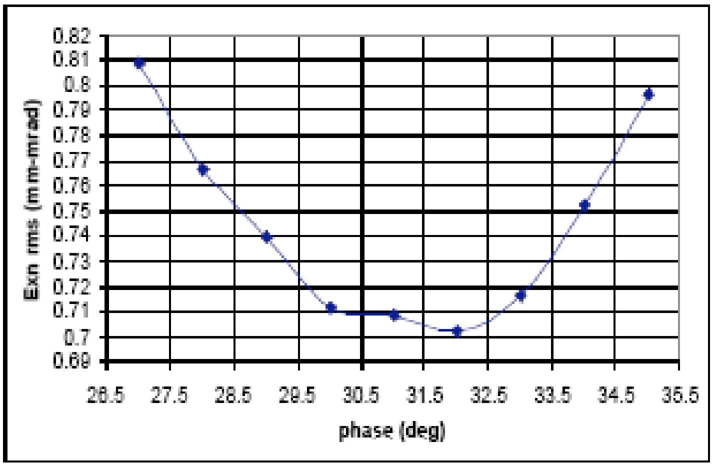

FIG. 1: Effect of a phase change on the normalized projected emittance.

This synchronization is achieved at two different levels: a) by controlling that the laser emission happens at the time when the high power rf fills the accelerating cavities for first-order timing; b) by phase-locking the laser optical oscillator with a low level reference signal which is a subharmonic of the S-band master clock for the real subps-synchronization.

The issue of timing jitter becomes even more critical when the future experiments planned at the SPARC facility are considered. In particular utilization of compressed electron beams in conjunction with an external laser beam (even if it is the photocathode driver laser), as foreseen for example in FEL seeding experiments[4], Inverse Compton Scattering (ICS) experiments, or laser acceleration experiments [5], requires the jitter between the rf clock and the laser to be maintained under tighter specifications than the ones tolerable for normal SASE operation. These specifications depend clearly on the case considered and go down to rms jitter below 100 fs in extreme cases, like the ICS X-source.

2 LASER TIMING DESCRIPTION

The photoinjector driver laser system has been purchased by Coherent and it is based on Ti:Sa active medium. The laser consists of a CW passive mode-locked oscillator pumped by 5W frequency doubled Nd:YVO_4. The oscillator delivers 130 fs, 10 nJ energy per pulse with a spectrum centered at 800 nm. The repetition rate of the oscillator is equal at c/2L, where c is the speed of the light and L is the optical length of the cavity. In our case L is 1.89m that gives a frequency of 79.333 MHz, 36^{th} subharmonic of the master rf frequency.

The laser pulse is then amplified by two 10 Hz amplification stages: a regenerative and two multipass amplifiers. The regenerative stage is pumped at 1 KHz by a frequency-doubled diode pumped Nd:YVO_4, the Evolution, and the second stage is excited by a high energy flash-pumped Continuum Nd:YAG. To extract photoelectrons from a metal photocathode the photon energy should be higher than the metal work function ~ 4 eV. For this reason, the fundamental laser frequency is tripled by two non linear crystals. An optical transfer line is used to image the laser on the cathode.

Fluctuations and drifts in the time of arrival of the laser on the cathode are mostly due to acoustic vibrations, thermal gradients and pump laser variations, leading to jitters and drifts of the laser oscillator frequency.

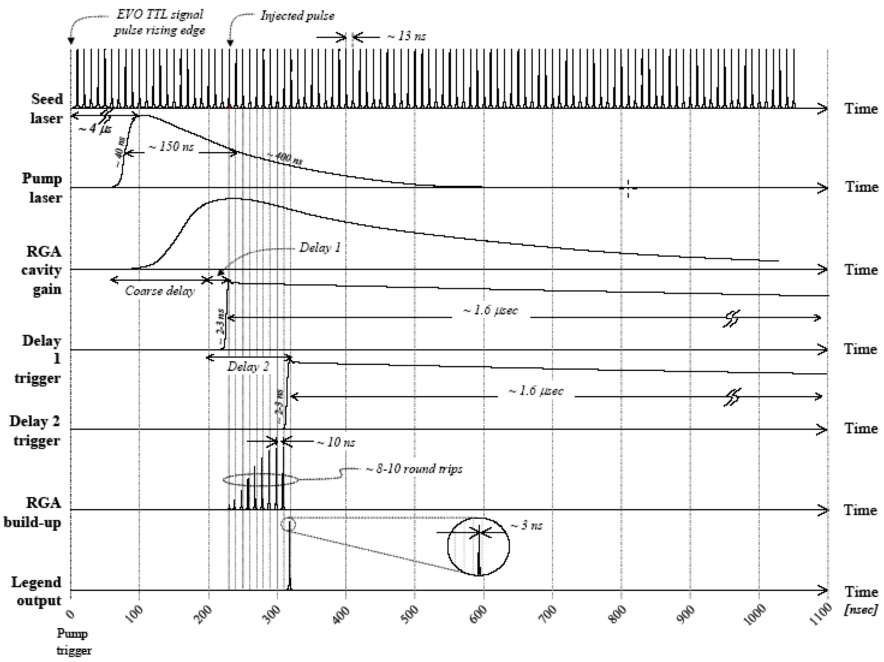

FIG. 2: Timing diagram of the laser system.

2.1 Repetition-rate timing

In Fig. 2 is reported the timing diagram of the laser system. From a quick analysis of this scheme it is readily understood that the 1 KHz Evolution trigger initiates the chain of events that leads to the amplified laser pulse output.

On the other hand, the laser amplifiers, as all of the other sub-systems of the SPARC photoinjector, are designed to work at 10 Hz. Two Pockels cells are used as optical switches inside the regenerative cavity to select and trap one incoming pulse to be amplified. The first Pockels cell selects the seed pulse when the gain in the regenerative amplifier is maximum, about 4 µs after the Evolution trigger. The Pockels cells are active for about 10 ns, with a rise time of 2-3 ns. This fast gate allows to discriminate only one pulse of the oscillator pulse train. The second Pockels cell is delayed to extract the pulse when it reaches the maximum of the amplification, after about 20 passes in the regenerative cavity which is equivalent to about 80 ns later.

A key consideration for the linac is the fact that the 10 Hz laser and henceforth accelerator repetition rate has to be locked with the 50 Hz line frequency to ensure that the beam arrives at the same phase in the ripple of voltage and current power supply. This is done to improve the stability of the RF power and beamline magnets field which affect important parameters as beam energy, beam position, beam sizes, etc.

As schematized in Fig. 3, the Pockels cells are driven by the Evolution trigger, through a frequency divider and by the multiple delay generator the SDG. The Coherent frequency divider can be used for laser stand alone operation and, in the normal operation mode, it is bypassed by a home-designed frequency divider that selects one pulse from the 1 KHz train, synchronized with the 50 Hz external power line. Using this home-designed board we measured that the laser shot is locked with the external line within 0.5 ms (1/40 of the 20 ms period). This implies that the beam fluctuations due to power supply ripples is reduced by more than one order of magnitude.

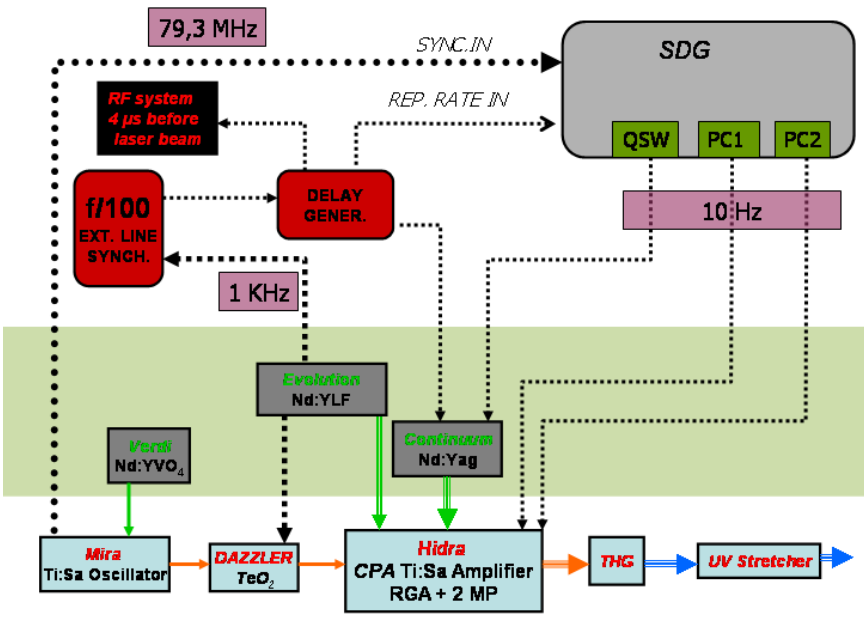

FIG. 3: Schematics of the timing units.

From the frequency divider, the trigger signals (at this point synchronized with the electron beam at the 10 ns level) are splitted through an adjustable delay generator for different uses. One trigger properly retarded is used for the modulators and the RF amplifiers (pre-amp + Klystron) chain which results synchronized to the laser shot timing.

A TTL level trigger is routed back to the SDG delay box in the laser room which controls the fast switches of the Hidra amplifier. The SDG delay box uses a signal from the laser oscillator at 79.333 MHz to increase the timing stability. A jitter of 0.3 ns between the SDG TTL output triggers and the amplified optical pulse has been measured using a streak camera. The signals from the SDG can be used to trigger the oscilloscopes and all the other fast diagnostics. The only shortcoming is that these signals are only few hundreds of ns before the effective time of the laser pulse and their use is then limited.

Another signal coming out from the home-designed divider 280 μs before the amplified pulse is used to discharge the capacitor bank which flashes the lamps of the Continuum laser. The other trigger, needed for the operation of the Continuum to Q-switch the cavity and release the laser pulse, comes from the SDG and can be adjusted on the scale of tens of ns to optimize the temporal overlap between the pump and the regenerative pulse, which strongly affects the Hidra output energy.

For pulse-shaping [6] an active acousto-optic crystal modulator, the DAZZLER, is inserted on the beam path after the laser oscillator before the regenerative amplifier. Since the Hidra bandwidth sensors should be always illuminated (a safety interlock to avoid that pulses too short and so too intense pass through the amplifier), the Evolution controller triggers the DAZZLER rf modulator, which works in continuous mode and applies the amplitude and phase spectral modulation all the time, even to pulses which will not be amplified.

2.2 Sub-ps synchronization

Since all the triggers described in the previous section control just the optical gates and the level of the amplifier gain and do not affect the optical path length traversed by the laser pulse, the fine synchronization has to be carried out at the level of the laser oscillator. The Mira synchronization unit, the Synchrolock [7], controls the laser frequency using three cavity length actuators in the laser head: a high frequency piezo-electric trasducer (PZT), a low frequency galvonometer driven delay line and a DC motor.

The output mirror coupler is mounted on the DC motor with 1 inch travel. The micrometer is positioned to minimize the frequency difference between the laser and the reference frequency with a coarse resolution of 100 Hz.

One cavity mirror is mounted on the PZT for high resolution frequency control. It has a nominal range of 8 μm for a driver voltage between 0 and 140 V (usually it operates at 70±60 V) corresponding to ±170 Hz around the laser frequency. The PZT frequency feedback bandwidth extends up to 5-10 kHz.

For long term stability another laser frequency control is added. A DC-magnet driven Galvonometer slowly adjusts the position of the starter butterfly to vary the amount of glass in the optical path. This broadens the range of frequency correction of the PZT and allows to operate the piezo at its optimal DC voltage. The galvo guarantees the locking for temperature drifts of ±30 F in a frequency range of ± 6 kHz.

The Synchrolock controller monitors the laser pulse train by 2 GHz fiber-coupled photodiode. This signal is a comb of frequencies spaced by the value of the repetition rate or in other words its power spectrum contains the oscillator frequency and the its harmonics. The controller continuously measures the laser frequency or phase difference between the laser and the RF clock and makes the appropriate adjustment of the cavity length. It has to be stressed that the spectral power of the photodiode also contains the contribution of pulse-to-pulse amplitude noise limiting the resolution of phase lock mechanism. The amplitude jitter contribution decreases at higher frequencies [8]. Therefore to obtain better synchronous laser operation it is useful to mix the high harmonic frequency with the high harmonic of the reference clock. Unfortunately in the high harmonic correction signal the absolute phase with respect the external reference is lost. In fact the absolute phase is not defined because the lock can occur at any of the N relative positions between two laser pulses when the N^{th} harmonic used. The solution is to use the fundamental phase lock loop (PLL) to establish the absolute phase and in succession the harmonic PLL is employed to fine phase lock, see Fig. 4.

The photodiode spectrum is split into two parts and filtered with two band pass filters (BPF) centered at the 79+1/3 MHz and at the 9^{th} harmonic. The two signals are then amplified and sent to two separate mixers. The mixers are driven also by the reference frequency and the 9^{th} harmonic obtained thought a multiplier in the Synchrolock loop. The output signal of the mixers is amplified and used to control the cavity length actuators.

The fundamental PLL is activated, first, to drive the DC motor and to minimize the frequency difference. When the difference is small the control of the PZT is enabled. If the phase lock is achieved at the fundamental frequency, the high harmonic of the laser is compared with the same high harmonic of the external clock and a phase shifter is used. The laser company specifies a $jitter_{RMS}$ <250 fs when the Synchrolock is used to lock two laser oscillators. We did not have direct measurements of the oscillator phase noise when an external RF signal is used to drive the Synchrolock.

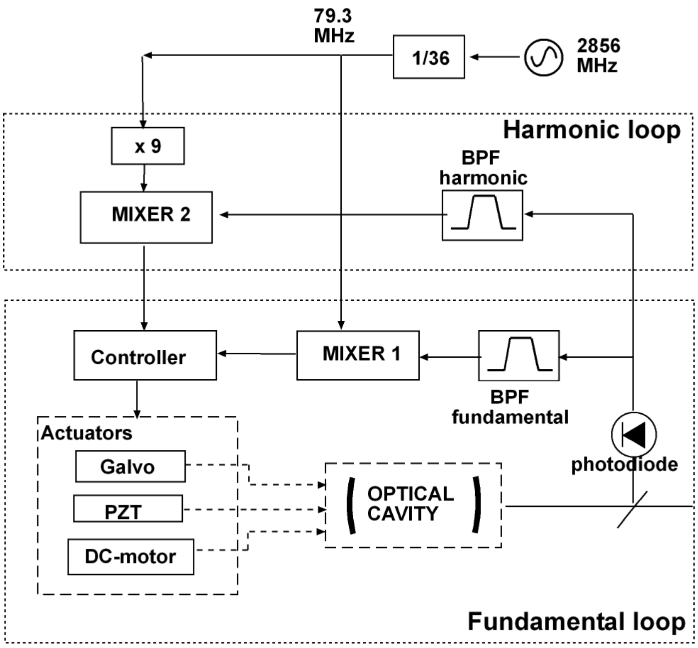

FIG. 4: Schematics of the Synchrolock operating principle.

3 PHASE NOISE MEASUREMENT

3.1 Standard measurement equipment layout and resolution

As we know from the theory [9], the time jitter of any oscillator is strictly related to its phase noise spectrum, therefore, to remain inside the SPARC requirement of ±2ps, we are implementing a synchronization system capable to continuously monitor phase and amplitude of the signals coming from the RF structures placed along the accelerator. If you want to descent in more details about RF distribution and synchronization system, you can see the reference [10].

The core of the cited system is a 20 channels demodulation board and the digitizers that form a sort of virtual oscilloscope able to display the signals coming from the SPARC RF accelerating devices on the control room console screens. Each demodulation channel has the layout presented in fig. 5, where the two essential devices are the quadrature IF mixer and the data acquisition (DAQ) card. The mixer is a custom device from ©Pulsar Microwave Corporation able to demodulate the signal and to provide its in-phase and in-quadrature components from which we can simply calculate amplitude (absolute) and phase (relative to a reference), applying a mathematical algorithm implemented in a LabVIEW™ software. The standard channel data acquisition (DAQ) cards PCI9812 from ©ADLINK are A/D converters with sampling rate of 20 Msamples/s and resolution of 12 bit; for laser time jitter measurement we used the more precise DAQ card PCI9820 (60 Msamples/s, 14 bit).

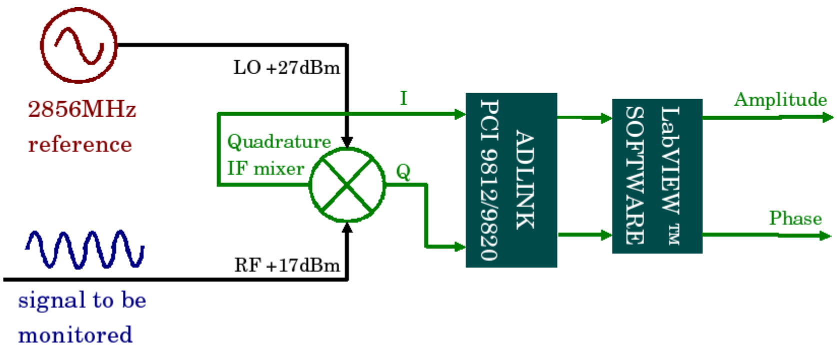

FIG. 5: Single demodulation channel equipment.

We measured the resolution of the instrument relative to the phase noise measurement sending two identical signals at the mixer inputs. We analyzed two different cases:

- CW waveform: the minimum phase noise observed in this case is 20 fs_{RMS}
- RF 5 µs pulse: this simulates the standard klystron amplified signal. Averaging the phase values acquired during a single pulse, we can achieve about 10 fs_{RMS} resolution. Some samples of acquired and analyzed pulse are plotted in fig. 6.

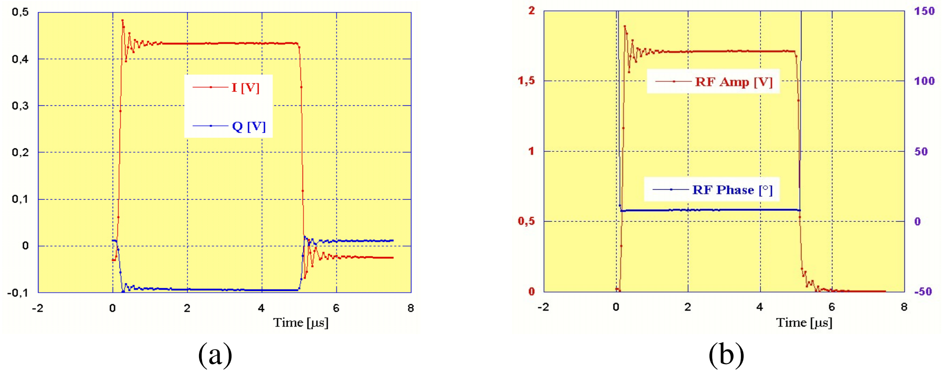

FIG. 6: Acquired information of a single RF pulse: (a) raw I and Q values; (b) calculated amplitude and phase pulses.

3.2 Locked oscillator measurement

To better understand next paragraph, we can now cite some time jitter measurements we did on locked oscillators. The simple setup of fig. 7 is very similar to that of the laser system locked to the RF reference oscillator by the Synchrolock system.

The locking system is made up of a PLL with variable operation bandwidth and the oscillator adopted as reference has better phase noise specifications than the other one under test. Measurement results are shown in table 1. We want to emphasize that the R&S SMT oscillator provides the SPARC RF 2856MHz wave reference.

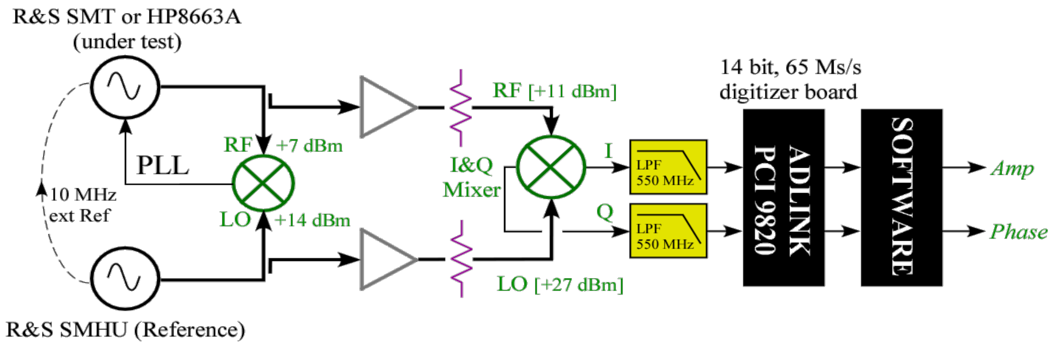

FIG. 7: Time jitter measurement setup for a locked oscillator.

TAB. 1: Locked oscillator measurements.

	Rhode&Schwarz SMT	HP8663A
2.5 GHz	130fs (PLL BW = 5kHz) 65 fs (PLL BW = 75kHz)	85 fs (PLL BW = 5kHz) 72 fs (PLL BW = 75kHz)
2.856 GHz	183 fs (PLL BW = 5kHz) 92 fs (PLL BW = 75kHz)	

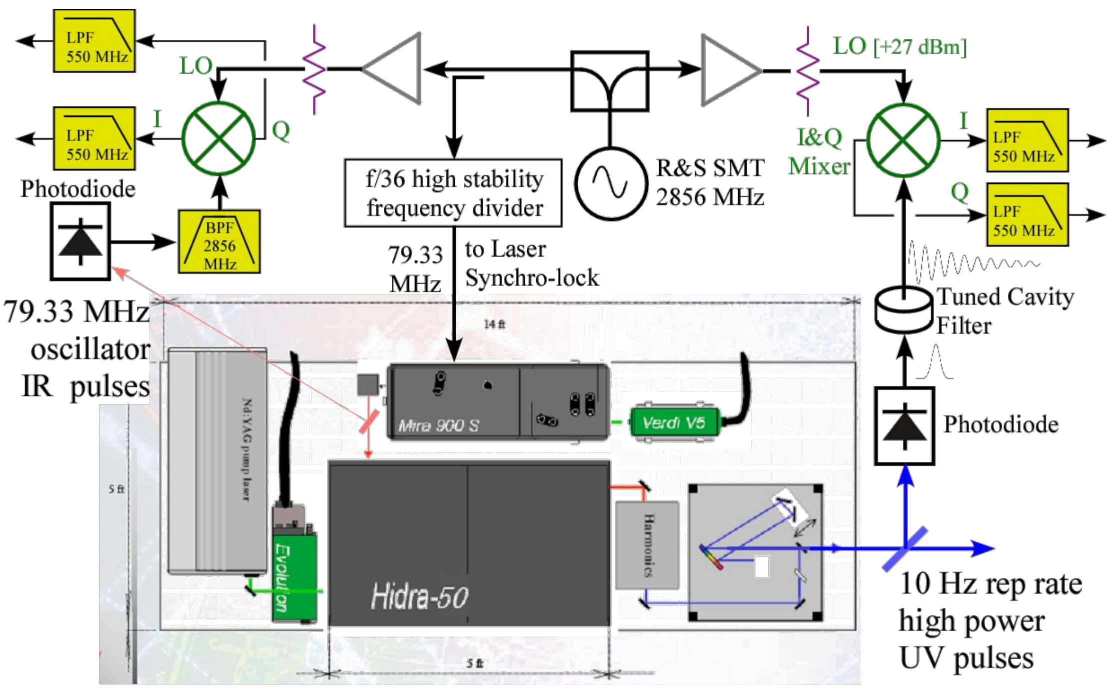

FIG. 8: Laser time jitter measurement setup

4 LASER TIME JITTER EXPERIMENTAL SET UP AND RESULTS

To characterize laser time jitter relative to a reference waveform, we used the setup of fig. 8 where you can identify the laser phase lock system described in section 2 and the main items for phase noise measurement introduced in section 3.

Two kinds of measurement has been performed to have information in different points of the laser chain. The reference signal comes in both cases directly from the driving 2856 MHz oscillator. The first setup (on the left part of fig. 8) employs the standard phase noise detection technique and the signal in input to the mixer is a continuous waveform originated by the filtered output of a fiber-coupled fast solid state photodiode with a bandwidth of 25GHz, model 1434 from New Focus, illuminated by the IR laser beam at the exit of the oscillator, with a repetition rate of 79+1/3 MHz. This type of measurement is very common and quite simple to be performed, but the idea for SPARC is to have also information on the single laser UV pulse near the cathode at 10 Hz, using it to build a pulse-to-pulse phase lock feedback. To do this we implemented the setup measurement shown in the right part of fig. 8. The measured signal comes from a cavity tuned at 2856MHz, fed by a high voltage electric pulse (with a peak of about 100V) formed by a fast photodiode illuminated by the laser UV 10ps pulse, with a repetition rate of 10Hz. This photodetector is a biplanar vacuum photodiode with a rise time of 100 ps operating at 1.5 kV bias voltage. The cavity grants an exponential decaying RF pulse that has a duration of about 1.5 μ s and allows to perform a consistent measurement using the PCI9820 DAQ card (see the end of par. 3.1) with sampling rate of 60Msamples/s.

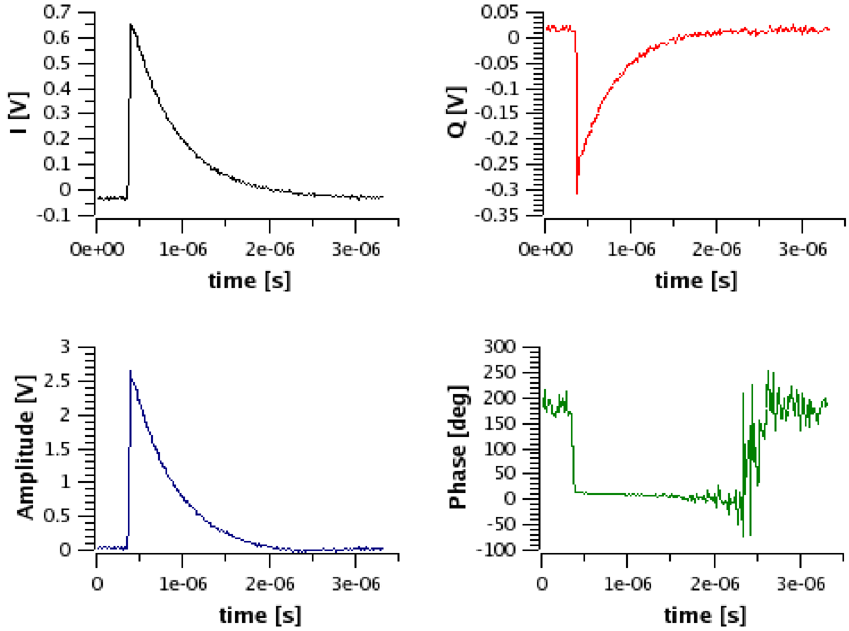

FIG. 9: Acquired and analyzed laser pulse.

Fig. 9 reports the plots of the acquired I and Q raw data (black and red lines) and the calculated amplitude and phase (blue and green lines). As you can see in fig. 10 (that shows a magnified plot of fig. 9), due to a non perfect tuning of the cavity, a slope is present in the phase plot. Consequently, to extract a single value for each laser shot we needed to implement a more complicated algorithm than the case of a flat top pulse. We decided to perform a linear fit on the part with the linear behavior (the initial one) and to choose the calculated intercept as the phase value representing the pulse.

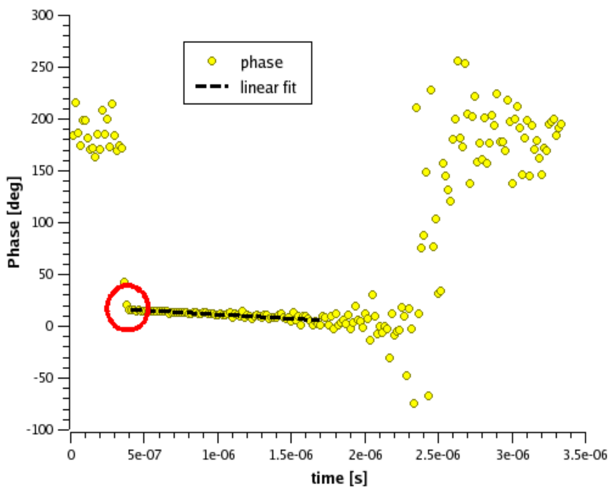

FIG. 10: Laser phase pulse analysis with emphasis on the chosen phase value.

Histograms on measurements performed over 5-10 minutes are depicted in fig. 11 and the results we got are listed below:

- laser IR pulses (repetition rate 79MHz): we observed a time jitter that varied from $650fs_{RMS}$ to $750fs_{RMS}$;

- laser UV pulses (repetition rate 10Hz): detected time jitter varied from $630fs_{RMS}$ to $1ps_{RMS}$.

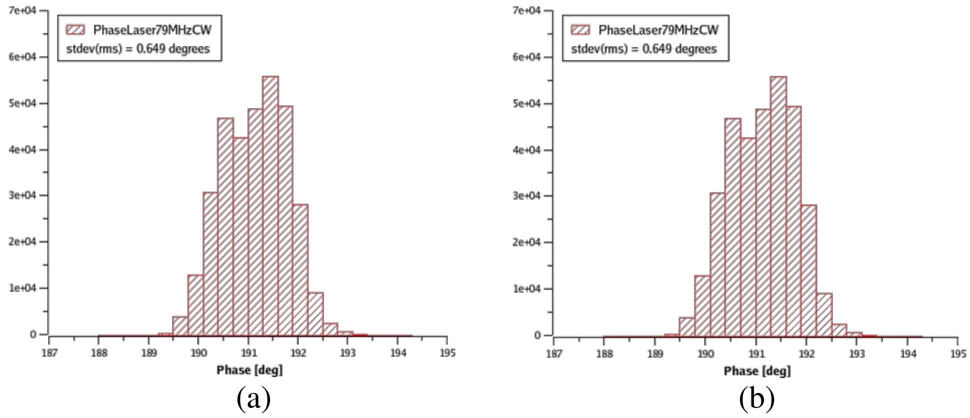

FIG. 11: Histograms representing acquired phase values for: (a) IR laser and (b) UV laser pulse measurements.

5 CONCLUSIONS

The laser time jitter measurements reported in this paper shows a minimum observed phase noise of 630fs: this is a very satisfying preliminary results because the synchronization system appears already inside the basic SPARC specifications. We want to point out that the detected phase noise includes the contribution of many elements present in the chain: frequency down-conversion board, laser Synchrolock system and photodiodes. More experimental activities are necessary to understand how each of the cited components modifies the phase noise spectrum of the signal. Moreover we observed that the measured time jitter is sensitive to the laser system setup (Synchrolock parameters), power level, mechanical vibrations and temperature drifts.

Some alternative measurement schemes are yet under study to comprehend which way could be undertaken to reduce the total phase noise. Good hypothesis are acquiring devices with better performance or completely changing the phase lock chain of SPARC RF-laser synchronization system starting from a reference derived from the laser pulse.

8 REFERENCES

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