MEASUREMENT DEVICES FOR THE SPARC SYNCHRONIZATION SYSTEM

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Abstract

The SPARC FEL facility is under commissioning at the Frascati National Laboratories of INFN. The synchronization system is working as expected and various devices are used to monitor its performances. In particular this paper is focused on a comparison between the results obtained using different methods and instruments to perform laser, RF and beam synchronization measurements. Both electro-optical and full electrical techniques are used to obtain information about the phase noise of the RF fields inside the accelerating structures, the phase noise of the IR laser oscillator, the time of arrival of the laser UV pulse on the cathode and the time of arrival of the accelerated electron bunch at a selected reference position along the linac.

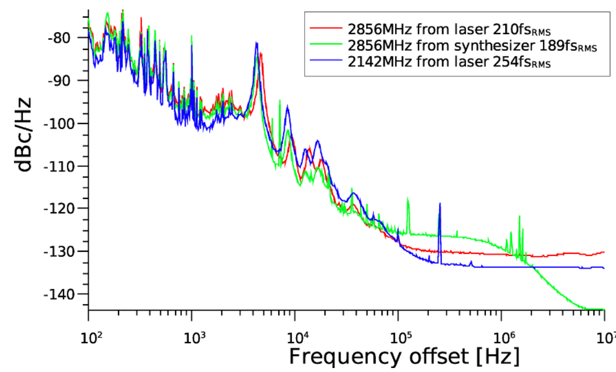


Figure 2: Phase noise spectra of the RF reference signals with integrated absolute jitter (from 100 Hz to 10 MHz).

INTRODUCTION

The SPARC project is now under its commissioning phase at the Frascati National Laboratories of INFN. First FEL lasing in the SASE regime has been observed and other experimental activities are on the way [1]. The synchronization system is working as expected. Its performance has been recently upgraded using a new scheme and also new diagnostic devices have been installed, as described later in this document.

System Layout

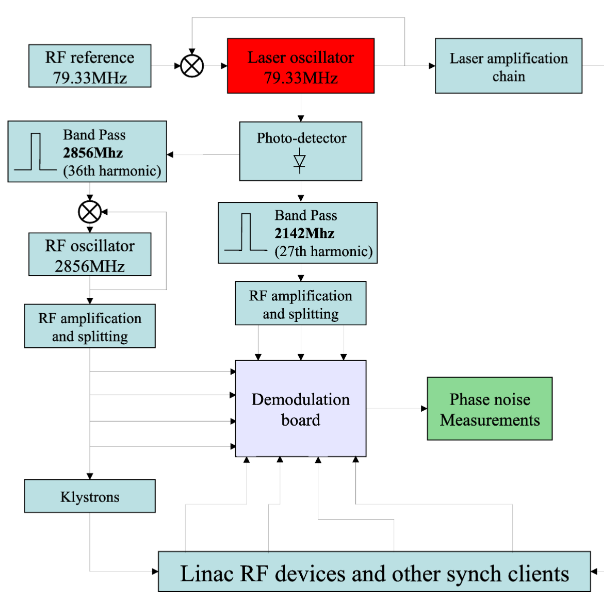


Figure 1: Layout of the synchronization system of SPARC.

The synchronization system has been modified and upgraded respect to the one operating during the last SPARC run [2]. We chose to use the Ti:Sa oscillator of the photocathode laser as optical master oscillator (OMO) instead of using a RF synthesizer. Doing this, we can bypass the electro-mechanical PLL used to synchronize the laser cavity oscillation to the RF reference. This loop has a bandwidth of ≈ 5 kHz and was the main limitation of the SPARC synchronization system. Using the new scheme and starting from the laser cavity frequency, we can lock the RF synthesizer to that, using a PLL with a larger bandwidth (≈ 1 MHz). Thus the RF-to-laser relative jitter results pretty much reduced, as reported later in this paper. The long term frequency stability of the laser cavity is granted by a $79.\overline{3}$ MHz signal coming from a RF synthesizer and squared by dedicated standard NIM electronics. The PLL around the oscillator cavity make use of both the fundamental and the 9th harmonic to lock the laser repetition rate.

Reference Generation

As described in Figure 1, the RF reference signals are obtained by the $79.\overline{3}$ MHz pulse train coming from a solid state 10 GHz bandwidth photodetector illuminated by the laser Ti:Sa oscillator. In particular we used two filters to isolate the 27th (2142 MHz) and the 36th (2856 MHz) harmonic of the laser repetition rate. The signal has been also pre-filtered after the photodetector to eliminate the fundamental frequency and the unwanted harmonics that could generate distortion in the RF amplification process. Actually a commercial RF synthesizer from Rhode&Schwarz is used to generate the reference sent to the RF power stations. We used its FM port to close a PLL to have a copy of the 2856 MHz laser reference that is distributed in the system. Due to the pretty large PLL bandwidth (about 1 MHz) the two SSB phase noise spectra are very similar at low frequencies as shown in Figure 2. We also report in the same figure the spectrum of the 2142 MHz signal coming from the photodetector and used for diagnostic purpose. The measurements have been performed using a Agilent E5052A Signal Source Analyzer.

DEVICES AND MEASUREMENTS

All the signals coming from the RF devices and from other diagnostics elements of the synchronization system are gathered into the demodulation boards located in the SPARC tunnel. The phase detection relative to the RF references is accomplished by mixers and the information is digitalized and sent into the control system by a dedicated CPU. All the synchronization measurements are easily performed in the control room using custom applications.

RF Phase Noise

To reduce the phase noise of the RF power signals inside the accelerating structures relative to the RF reference, we implemented PLLs working around the two klystrons [3], that are the main noise sources in the RF network. The loop has a large bandwidth, so that its transient has a duration of about 1 µs and it can easily operate inside a single 4.5 µs RF pulse. This allowed us to compress the noise of a factor $\approx$ 10 resulting in a relative jitter less than 100 $\mathrm{fs_{RMS}}$ measured at various RF probes along the linac. The phase information for each RF square pulse is obtained sampling the RF demodulated signal with a 60 Msample/s-12bit digitizer card and averaging the data over about 200 samples. The long term phase stability is provided by slow feedback loops acting at RF low level. They use motorized delay lines to keep the phase stable, compensating possible temperature drifts [3].

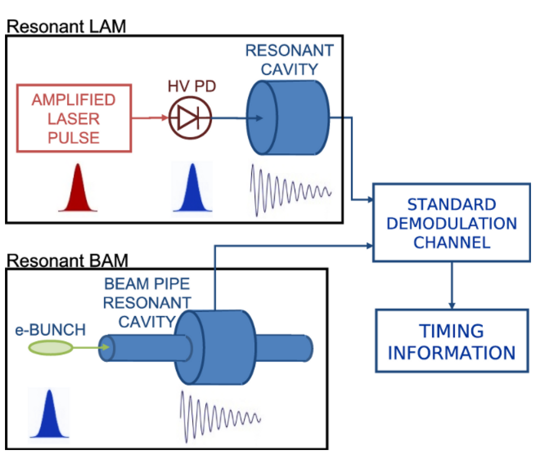
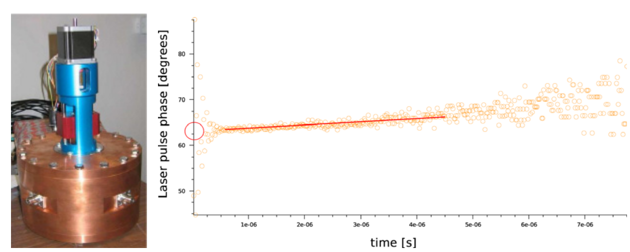


Figure 3: Block diagram of the BAM and LAM devices.

LASER Time of Arrival Monitor (LAM)

The innovative idea for SPARC is to have timing information on the single laser UV pulse at the end of the amplification chain and to use it to build a pulse-to-pulse phase lock feedback. Normally one needs a continuous sinusoidal waveform to analyze its spectrum and give an estimation of the phase stability of an oscillator. Unfortunately, in the case of a pulse train with 10 Hz of repetition rate it is almost impossible to extract this information. To overcome the problem, we implemented the experimental setup shown in Figure 3. The measured signal comes from a cavity tuned at 2142 MHz, fed by a high voltage electric pulse (with a peak of 70 ÷ 100 V) formed by a fast photodiode illuminated by the laser UV 10 ps pulse, with a repetition rate of 10 Hz. This photodetector is a biplanar vacuum photodiode with a rise time less than 100 ps operating at 5 kV bias voltage. A resonant cavity shown in Figure 4a has been designed and built to accomplish these measurement. It works with a solenoidal $TE011$ mode and has a high Q factor ($Q_0 = 60000$, $Q_L = 20000$). This grants an exponential decaying RF pulse with a duration of about 3 µs and allows to perform a consistent measurement. Due to the interference of the signals with the strong electric fields inside the accelerating structure, the cavity has been designed with a central frequency of 2142 MHz, equal to the 3/4 RF SPARC frequency. This device is also equipped with a motorized tuner that can be remotely controlled. The out-coming signal is then compared with the 2142 MHz RF reference obtained from the Ti:Sa oscillator.



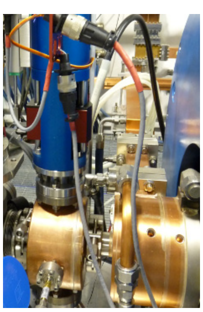
(a) (b)

Figure 4: (a) Picture of the resonant cavity for the LAM and (b) an acquired phase data for a single UV pulse with emphasis on the analysis algorithm.

After the signal sampling, performed using a 60 Msample/s-12bit digitizer card, we obtain the phase data shown in Figure 4b. To extract a single phase value associated to each laser shot we had to overcome two problems: (i) due to a non perfect tuning of the cavity, a slope can be present in the phase signal and (ii) the initial part of the signal is distorted by the presence of some higher cavity mode excited by the short electric pulse. Thus we post-process the data performing a fit in the central part of the pulse using a linear model and we reconstruct the phase information at the pulse initial time. This tasks are performed at the machine repetition rate of 10 Hz and allow us to have a real time information of the laser time arrival. The best result we obtained after the synchronization system upgrade is a jitter of 220 fs_{RMS}.

e-bunch Time of Arrival Monitor (BAM)

Resonant Cavity BAM The principle used in the resonant cavity BAM [4] is identical to the one reported in the previous section about the LAM. The only difference is that the exciting electric pulse comes from the e.m. field of the electron bunch propagating inside the beam pipe, as shown in Figure 3. The consequent cavity free oscillations are carried outside by 2 antennas connected to vacuum coaxial feedthroughs and are sampled as described in the LAM section. Two pill-box like cavities have been designed and realized at LNF and a resonant frequency of 2142 MHz has been chosen to avoid interference coming from the 2856 MHz power signal present in the accelerating structures. The first cavity has been installed between the first two accelerating sections and the second one will be installed at the end of the linac. A picture and some of the main parameters of the first cavity are shown in Figure 5a and b. The BAM cavities are equipped with two tuning ports. The larger port accommodates a fixed tuning plunger to coarsely tune the cell, while the smaller port host a remotely controlled tuner plunger to finely correct the cavity natural resonant frequency of the fundamental mode to < 10 kHz respect to the reference 3/4 RF to limit the detected phase slippage during the measurement time slot. The coupling of the antennas is designed to produce large detectable signals (≈ 2 V for 1 nC bunch) which will eventually require no extra RF front-end amplification before being demodulated. The use of BAMs on the SPARC linac will allow to direct monitor the electron bunch synchronization and, by differentially comparing the measurements of 2 different BAMs, to finally qualify the ultimate resolution attainable by the pulse resonant stretching method which is fully based on electrical microwave techniques.



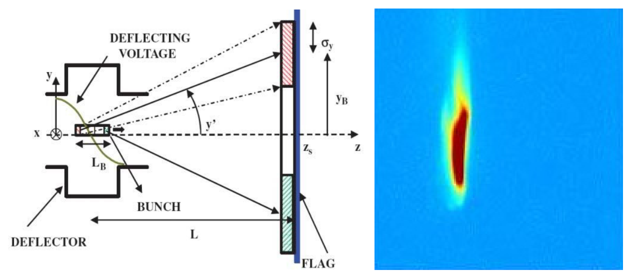
(a)

Operating mode	$TM010$
Frequency	f_0 = 2142 MHz
Unloaded Q factor	Q_0 = 16000
R/Q factor	R/Q = 40 Ω
Antenna ext. Q fact.	Q_{ext} = 30000
Loaded Q factor	Q_L = 7500
Decay time	τ_d = 1 µs
Output peak voltage @1 nC bunch charge	$V_{pk} \approx 2V$

(b)

Figure 5: (a) A picture of the BAM cavity and (b) some of its useful parameters.

RF deflector BAM This BAM technique uses the SPARC RF deflector developed at SPARC that is a 5-cell SW structure reaching a maximum transverse deflecting voltage of more than 3 MV with an input power of nearly 2 MW. This device has been designed for longitudinal profile and slice emittance measurements that have been already performed at SPARC [5]. A sketch of the deflector working principle and a sample of the measured longitudinal bunch shape are reported in Figure 6a and b. Due to the deflection, the longitudinal distribution of the bunch is projected into the vertical plane of a target placed after the RF deflector. After a necessary calibration, the BAM in this case works analyzing some tens of raw images acquired by a digital camera and extrapolating the information about the jitter of the beam centroid vertical position. Also the phase noise of the RF field inside the deflecting structure affects the measurement, changing the deflecting force that the beam centroid "feels". The contribution has been estimated measuring the phase noise from a deflector vacuum probe. Thus we could easily eliminate this systematic error that is of the order of 100 fs_{RMS}. The residual jitter of the bunch arrival time is finally estimated to be ≈ 140 fs_{RMS}.



(a) (b)

Figure 6: (a) Sketch of the RF deflector working principle and (b) an acquired image showing the longitudinal beam shape.

CONCLUSION

After implementing a synchronization system upgrade we measured the signals jitter observing a significant improvement on the performance respect to the previous configuration. The photocathode laser time arrival monitor measured a ≈ 200 fs_{RMS} jitter while the RF deflector bunch time of arrival monitor measured 140 fs_{RMS}. The resonant BAM will be tested as soon as possible during the next SPARC run. Also correlated measurements will be performed between BAM, LAM, gun launching phase and other other RF signals sampled along the linac to completely characterize the sources of noise in the system.

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