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**SPARC photo-injector  
synchronization system  
and time jitter measurements**

September 2007 report

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## **Abstract**

During the installation of the SPARC photo-injector at the Frascati National Laboratories of INFN, we improved the synchronization systems for both the UV laser phase pulses and the RF power stations. This document is presented as an update of the previous EuroFEL report, delivered on February 2006, so we only briefly report about the general architecture of the machine since we want to focus on the new achievements in the RF-to-reference and laser-to-reference synchronization. In particular we report about: (i) the installation and the first tests on the intra-pulse feedback system around the klystrons; (ii) the improvement on the time arrival monitor of an individual UV laser pulse on the cathode; (iii) a new designed scheme to be implemented to improve the laser to RF system phase stability, starting from an optical instead of an electronic main reference signal.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	A SPARC project overview . . . . .	1
1.2	Photo-injector parameters and phase noise specifications . . . . .	1
1.3	Timing system . . . . .	2
1.4	Synchronization system . . . . .	3
1.4.1	Phase monitor system . . . . .	4
1.4.2	Feedback system . . . . .	5
<b>2</b>	<b>Laser time jitter measurements</b>	<b>5</b>
<b>3</b>	<b>Klystron intra-pulse feedback</b>	<b>10</b>
<b>4</b>	<b>Alternative synchronization layout</b>	<b>11</b>
<b>5</b>	<b>Conclusions</b>	<b>14</b>

# 1 Introduction

## 1.1 A SPARC project overview

The SPARC project, funded by the Italian Government in 2003 with a 3 year time schedule, is an R&D activity aimed to develop a high brightness photo-injector for self-amplified spontaneous emission free-electron laser (SASE-FEL) experiments. The installation of the machine at LNF started on September 2004 and the first RF gun tests and beam parameters measurements has started in february 2006. The SPARC [1] final configuration is composed by an RF gun driven by a Ti:Sa laser producing  $10ps$  flat top pulses that hit a photocathode, followed by three SLAC accelerating sections that bring the beam to an energy of  $150MeV$  to feed a  $14m$  long undulator. The main goals of the project are:

1. the generation of a high brightness electron beam to drive a SASE-FEL experiment in the green visible light and higher harmonics generation;
2. the development of an ultra-brilliant beam photoinjector needed for the future SASE-FEL based X-ray sources.

## 1.2 Photo-injector parameters and phase noise specifications

One of the major goals of the SPARC project is to experimentally explore the stability and reliability of the ultra-high brightness beam/SASE FEL systems. In order to appreciate how the performances of the systems are degraded by standard laboratory errors, jitters and uncertainties, a statistical study of sensitivity to combined errors was performed. Main task is to meet the requirements on transverse emittance (probability to get  $\epsilon \geq 1mrad$  less than 10%), on energy spread and on beam matching at the entrance of the undulator. The maximum acceptable variation of the main parameters, together with their nominal values are reported in Table 1. For a more detailed discussion see [2]. The quantity we will take into account in the next paragraphs is the gun RF phase relative to the laser time arrival. The maximum phase noise has to be limited to  $1.5ps_{RMS}$  for the fist SPARC operating phase.

The timing jitter becomes even more critical when the future experiments planned at the SPARC facility are considered. In particular utilization of compressed elec-

Table 1: Results of combined tolerance study of errors in SPARC injector

Parameter	Average value	RMS
Gun phase	31.5°	1.74°
Charge	1.15nC	0.032nC
Gun magnetic field amplitude	2733Gauss	5.8Gauss
Gun electric field amplitude	119.9MV/m	0.32MV/m
Spot radius	1.132mm	0.068mm
Ellipticity	1	0.02

tron beams in conjunction with an external laser beam (even if it is derived from the photocathode laser system), as foreseen for example in FEL seeding experiments [3], Inverse Compton Scattering (ICS) experiments, or plasma acceleration experiments [4], requires the jitter between the RF clock and the laser to be maintained under tighter specifications with respect to the normal SASE operation. These specifications depend clearly on the case considered and may go down to rms jitter below 100fs in extreme cases, as in the case of electron bunches injected in a plasma for acceleration.

### 1.3 Timing system

The SPARC timing system aims to generate and distribute the triggers to any machine apparatus like laser, modulators, cameras, BPM and so on. The main 10Hz trigger is spilled from the laser system (that is in turn synchronized with the radiofrequency reference clock) synchronously with 50Hz mains. The scheme used at SPARC reported in figure 1 utilizes a custom frequency divider board that provides the 79.33MHz signal (RF/36) to synchronize the laser optical oscillator to the 2856MHz RF reference oscillator signal. To minimize the possible phase noise introduced by this 1/36 division we utilized two successive stages: a first high performance integrated 1/4 divider, that is used at the critical highest frequency of 2856MHz, followed a second 1/9 divider stage. We also utilize four digital delay generators (DG535<sup>TM</sup> from Stanford Research Systems) to send the signals with correct delays and to change the logical levels to satisfy the various device input requirements (in the system are used TTL, ECL and

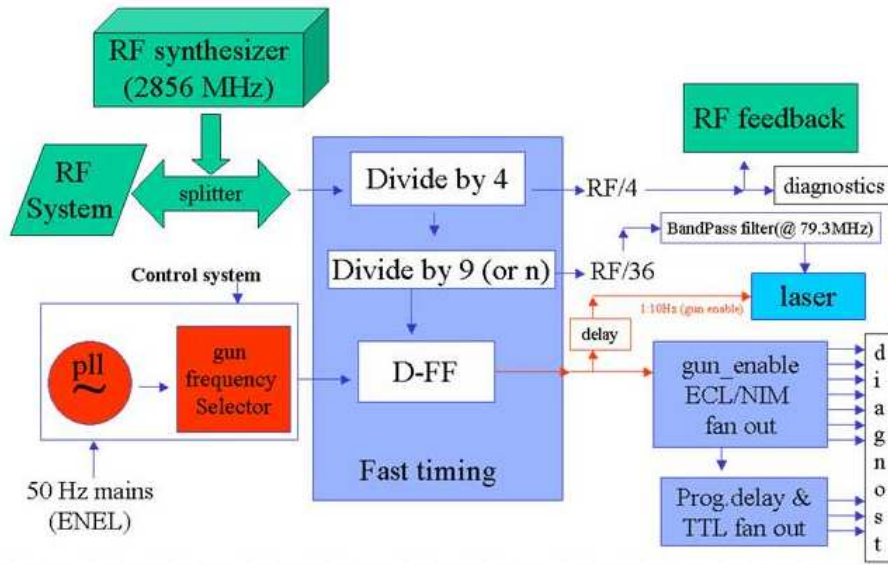


Figure 1: Timing scheme adopted at SPARC

NIM signals). The central part of the timing and synchronization system is embedded in the laser system. Thus in the next section we give an accurate description of the laser timing, analyzing the timing chain and its single components. We also briefly present the optical parameters of the SPARC laser to complete the system overview.

## 1.4 Synchronization system

The main systems involved in the synchronization task are the radio frequency and the laser systems. For a detailed description of these two parts of the machine and for a deeper discussion about the synchronization apparatus you can see [5, 6]. Here we only report about the main devices that permit to measure the phase stability of an apparatus respect to the main  $2856\text{MHz}$  RF clock reference. The SPARC RF system has been designed to meet the synchronization requirements. The main oscillator provides the signal to drive two klystrons and the laser system and to create the references to demodulate RF pulses coming from the devices of interest (i.e. waveguide lines, RF gun, accelerating sections, RF deflector and laser system). The phase stability requirements at SPARC pushed us to implement phase feedbacks in some location in the RF distribution chain. In particular the low power level phase is controlled by motorized phase shifters able to compensate slow drifts (mainly due to temperature

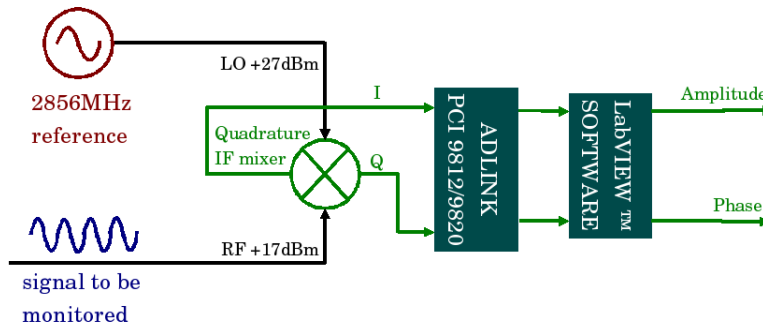


Figure 2: Single demodulation channel layout

changes), while the intra-pulse klystron high power phase is controlled using loops with fast electronic phase shifters as main component. Moreover, the amplitude and the phase of the field inside each device at the end of the distribution network is controlled by high power phase shifters.

#### 1.4.1 Phase monitor system

The phase signal monitor is made by a custom dedicated instrument consisting in a demodulation board installed in the SPARC hall together with some high frequency sampling boards that work as interface with an industrial PC, where data analysis is accomplished. This apparatus has been conceived as a custom multi-channel (about 30) digital scope, able to real time display all the demodulated signals in the control room. The layout of the single demodulation channel is shown in fig. 2. The quadrature IF mixer from Pulsar Microwave Corporation is a special device that provide the demodulated in-phase (I) and in-quadrature (Q) components of the signal under measurement. This is very useful to monitor the phase and amplitude of a signal because we can obtain these quantities directly from I and Q raw values applying a simple mathematical algorithm. The waveform is digitized using data acquisition (DAQ) cards: ADLINK PCI 9812/9820 and NI PXI-5105 that are respectively 12 – bit 20Msamples/s/14 – bit 60Msamples/s and 12 – bit 60Msamples/s A/D converters. The measured resolution of the instrument, intended as the minimum detectable time jitter, is about 100fs and it can be reduced to  $10 \div 20fs$  if we average inside a  $5\mu s$  RF pulse.

### 1.4.2 Feedback system

Some feedback systems have been designed to remain inside the SPARC synchronization specifications. They are used to lock the RF reference distributed along the machine to the main RF oscillator signal. They are:

- low power feedback: this is implemented in the RF distribution board that provides the RF reference signals to the two klystrons and to the laser system. The system will detect the phase from the various RF devices and from the laser (see section 1.4.1) and it will correct the long term phase shifts due to temperature drifts. The operating frequency bandwidth of the loop is about  $0.1Hz$  and this is well below the Nyquist frequency, since the repetition rate of the machine is  $10Hz$ . This system use motorized phase shifters, controlled by a PWM power driver. The tests during the first SPARC run have given satisfying results as reported in [5, 6];
- intra-pulse klystron feedback: this is an optional system able to correct phase shifts within a single klystron pulse, mainly due to the fluctuations of the modulator high voltage on the cathode. We simulated this event introducing a high frequency noise inside a RF pulse generated in laboratory and we adjusted the bandwidth of an electronic PLL to cut off the undesired frequency components of the signal. Further details are presented in section 3;
- high power feedback: the third and last system we designed is a feedback acting inside the waveguide distribution line. This feedback acts using some high power waveguide phase shifters that will correct the phase drifts due to temperature change in the SPARC bunker. This system is now under development and will be tested during the next machine operation.

## 2 Laser time jitter measurements

To characterize laser time jitter relative to a reference waveform, we used the setup of figure 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  $2856MHz$  RF oscillator. The first setup (on the left part of fig. 3)

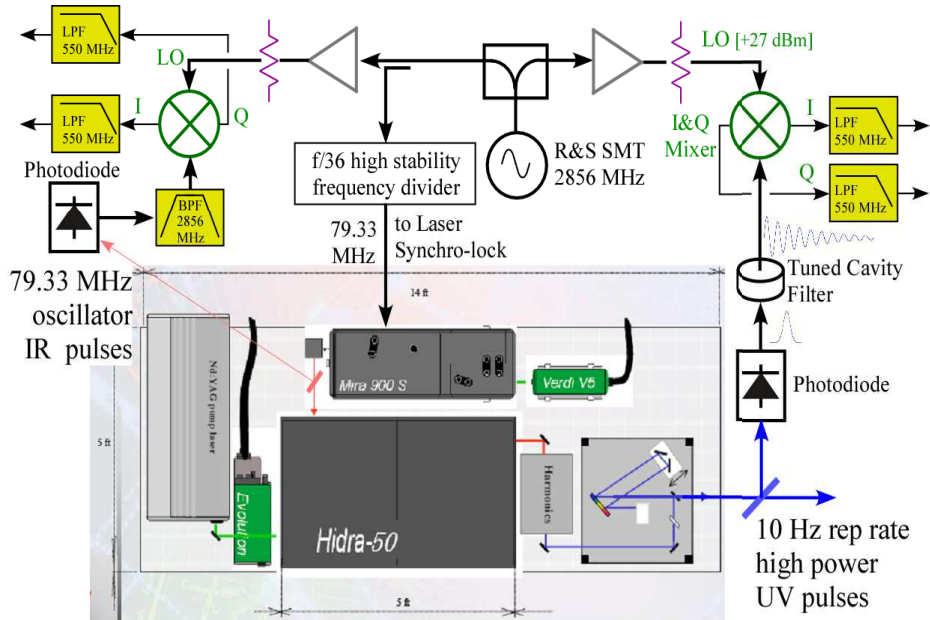


Figure 3: Measurement setup of the laser relative to RF phase noise characterization

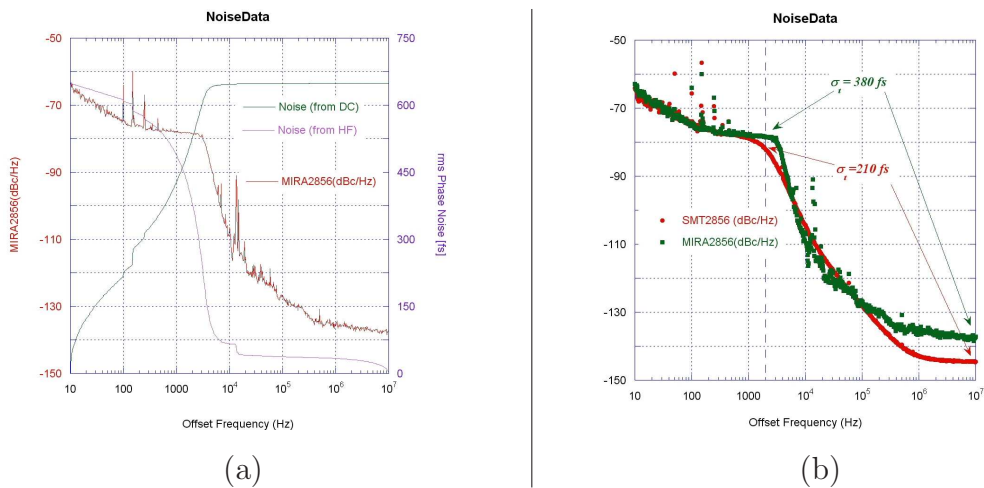


Figure 4: MIRA laser oscillator absolute phase noise measurement (a) and comparison with SMT RF oscillator (b)

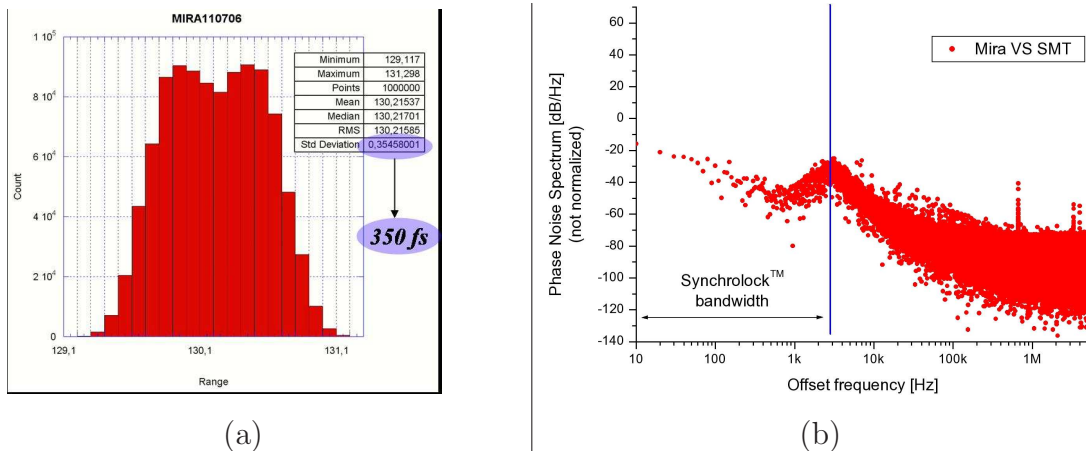


Figure 5: MIRA laser oscillator vs R&S SMT main oscillator: (a) phase histogram and (b) frequency components

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 [7], illuminated by the IR laser beam at the exit of the oscillator, with a repetition rate of  $79.33MHz$ . The out-coming sinusoidal waveform has been analyzed by the Agilent E5052A and the results are shown in figure 4 together with a comparison with the R&S main SPARC oscillator. From figure 4(b), it is clear that the Synchrolock unit is able to follow an input signal up to the frequency of some  $kHz$ . This is consistent with Synchrolock specifications and it is due to the fact that piezoelectric actuators are employed to adjust the length of the laser oscillating cavity. To have a better estimation of the Synchrolock bandwidth and to qualify our phase noise measurement system, we performed a measurement of the laser oscillator phase noise, relative to the main driving RF oscillator. Results reported in figure 5 give a clear indication of the laser synchronization system bandwidth, obtained by performing an FFT of the acquired data sample (figure 5(b)). Measurements give encouraging results and are in perfect agreement with the absolute measurements performed with the E5052A on the single devices. Furthermore, the measurements taken confirm the oscillator specifications given by the manufacturer.

The characterization of a laser phase stability usually ends with the measurements described above, but 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  $10Hz$  of repetition rate is almost impossible to extract this information. Thus we thought to use our system to detect the relative jitter of a single pulse relative to the SPARC RF main oscillator. To do this, we implemented the setup measurement shown in the right part of figure 3. The measured signal comes from a cavity tuned at  $2856MHz$ , fed by a high voltage electric pulse (with a peak of  $70 \div 100V$ ) 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  $100ps$  operating at  $2kV$  bias voltage. A new cavity shown in figure 6(a) has been designed and built to accomplish these measurement. It works with a solenoidal  $TE_{011}$  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  $3\mu s$  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  $2142MHz$ , equal to the  $3/4$  RF SPARC frequency. It is very simple to obtain this frequency from the main RF oscillator because we can just mix the RF reference signal at  $2856MHz$  with the  $RF/4$  output of the SPARC divider card and make some filtering. This device is also equipped with a motorized tuner that can be remotely controlled.

After the signal sampling, performed using the NI-5105 DAQ card with sampling rate of  $60Msamples/s$  and 12 bits of resolution, we obtain the data shown in figure 6(b), where the acquired I and Q raw data are reported in red and green lines and the calculated amplitude and phase are reported in white and orange lines, respectively. Due to a non perfect tuning of the cavity, a slope can be present in the phase pulse. Consequently, to extract a single phase value associated to each laser shot we needed to implement a more complicated algorithm respect to the case of a flat top pulse. We perform a linear fit on the initial part on the phase pulse and the calculated intercept is the phase value associated to the pulse. This is well shown inside the green square of figure 6(b). The software for the data analysis is completely developed in LabVIEW<sup>TM</sup> and integrated in the control system.

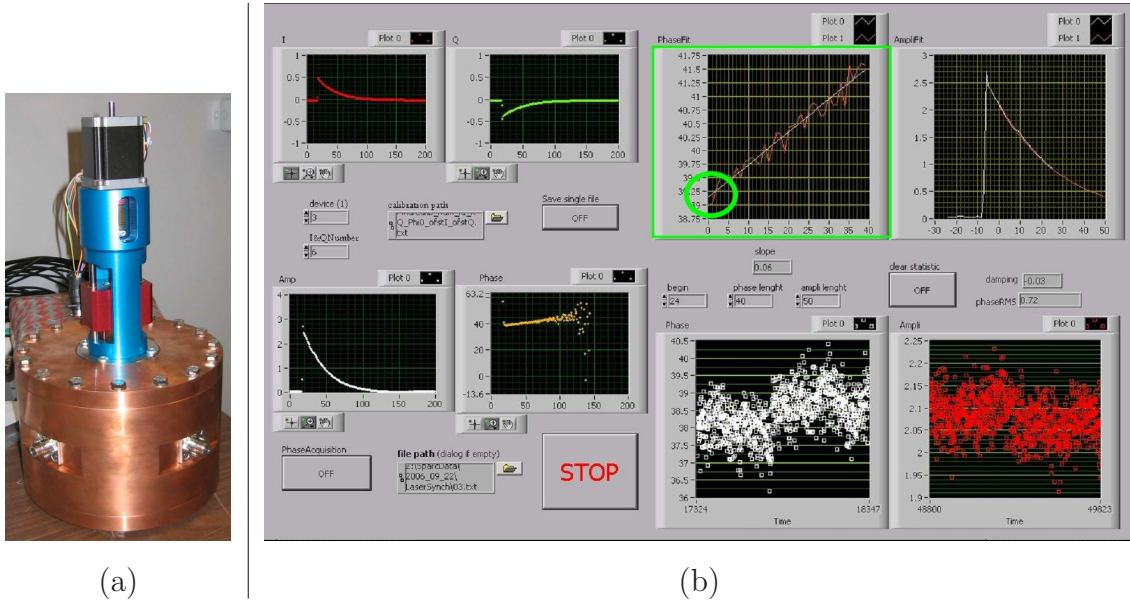


Figure 6: UV single shot measurement: (a) new designed cavity and (b) snapshot of the control application

As the intercept of the linear fit is used to select a phase value, the slope present in the linear phase behavior is a measurement of the cavity detuning respect to the nominal RF frequency. The information on the detuning will be used, in the SPARC final phase, to remotely control the cavity tuner. This feedback will flatten the linear behavior of the phase, forcing the slope to be zero, and this will allow an accurate phase noise measurement, also in presence of temperature drifts. The data displayed in figure 7 were acquired in a time interval of about 2 minutes, but we performed also measurements relative to a time interval of 30 minutes. The difference between the two cases is that the phase acquired during 30 minutes obviously shows low frequency structures due to temperature drifts. This is not a problem because, as discussed before, the drifts can be corrected during the machine operations by dedicated stabilization feedback loops.

Figure 7(b) shows that the RMS time jitter of the UV laser is about  $400fs$  that is in good agreement with the measurements taken at the IR low power level. This point needs some more elucidation. Previous results reported in [5, 6] did not completely agree with the measurement taken on the MIRA IR laser oscillator because we obtained a time jitter of the order of  $700fs$  at the UV exit. After some investigation we discovered

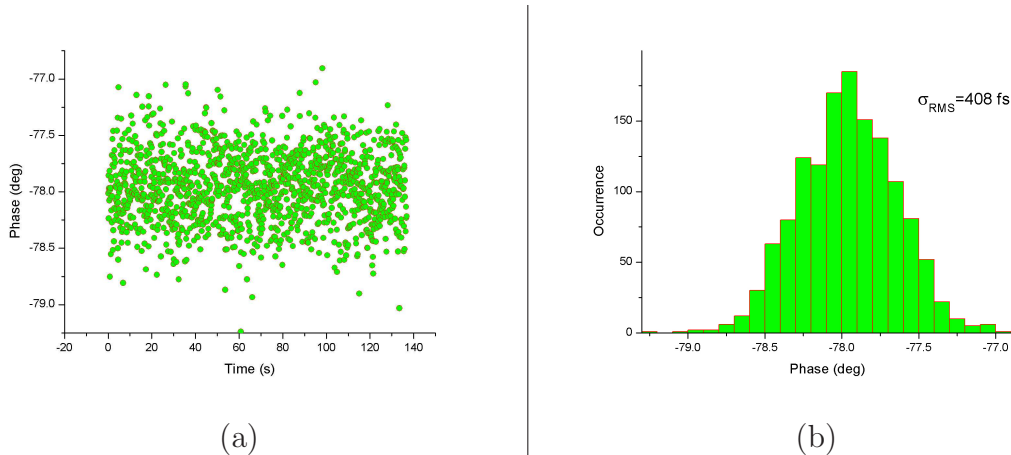


Figure 7: Acquired phase values with slow drifts behavior (a) and histogram of the short time phase evolution (b)

that the reason of the problem was a saturation effect occurring in the high voltage photo-diode. In fact the polarization voltage applied to the diode ( $1.5kV$ ) was not large enough to produce an efficient electron extraction from the cathode. We increased the bias voltage up to about  $2kV$  and the problem vanished. We can now say that the laser time jitter performances are limited by the Synchrolock<sup>TM</sup> bandwidth, while the optical amplification chain does not significantly affect the laser synchronism.

### 3 Klystron intra-pulse feedback

To increase the phase stability of the amplified RF pulse at the output of the klystron, we implemented and installed a fast intra-pulse feedback. This loop is made by fast electronic components and it is able to stabilize the phase inside a single  $4.5\mu s$  RF pulse, having a transient time of about  $1\mu s$ , due to the large loop bandwidth of about  $1MHz$ . Recently first tests has been made during the klystron n.2 operations and they gave positive results. The electronic scheme used to develop the phase stabilization loop, is reported in figure 8. To be sure that the loop can achieve the desired phase stability, we compared data acquired with feedback loop open or closed. The phase value relative to one RF pulse is obtained according with our standard procedure, i.e. by averaging the phase values sampled in the last part of the pulse (after about  $1\mu s$  transient). Due to temperature drifts, the cables change their length and the phase long

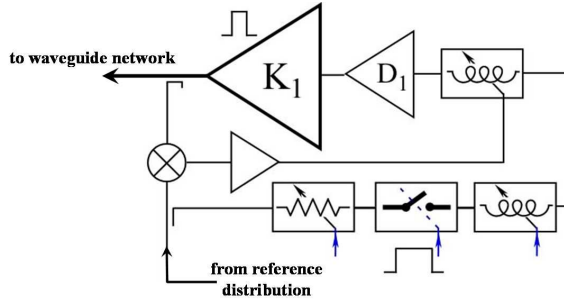


Figure 8: Fast klystron feedback scheme

time behavior presents a slope. The acquired values have been analyzed to suppress these drifts, highlighting and measuring the short time jitter. Slow drifts of the phase will be suppressed during the machine operation by the combined use of this phase stabilization loop and a slow feedback described in [5, 6]. Figure 9 shows the acquired raw data and the filtered data in the case of open and closed feedback loop. Figure 10 is a comparison of the fast time jitter obtained in the two different cases. It is important to note that the fast jitter is suppressed by a factor ten by the phase locking system and in the case of closed loop it results to be  $0.023^{\circ}_{RMS}$  of radio frequency that corresponds to a time jitter of about  $23f_{sRMS}$ . This system is now completely integrated in the SPARC control system, thus one can real time monitor the error signal and tune some feedback parameters directly from the control room consoles.

## 4 Alternative synchronization layout

Since we verified that the synchronization of the laser respect to the RF is limited to  $300 \div 400fs$  by the Synchrolock<sup>TM</sup> bandwidth ( $1 \div 5kHz$ ), we are considering the implementation of a new synchronization scheme that is not critical respect to the Synchrolock<sup>TM</sup> performances. The alternative layout is reported in figure 11 where it is shown how the main reference signal for the photo-injector comes no more from RF synthesizer tuned at  $2856MHz$ , but is derived from the output of the laser oscillator, with repetition rate equal to  $79.33MHz$ . In fact the very large bandwidth of the IR pulses coming out from the MIRA oscillator permits to easily select the higher harmonics of the fundamental frequency ( $79.33MHz$ ) in the same way we did for the time jitter measurement on the laser oscillator, reported in section 2. We can substitute

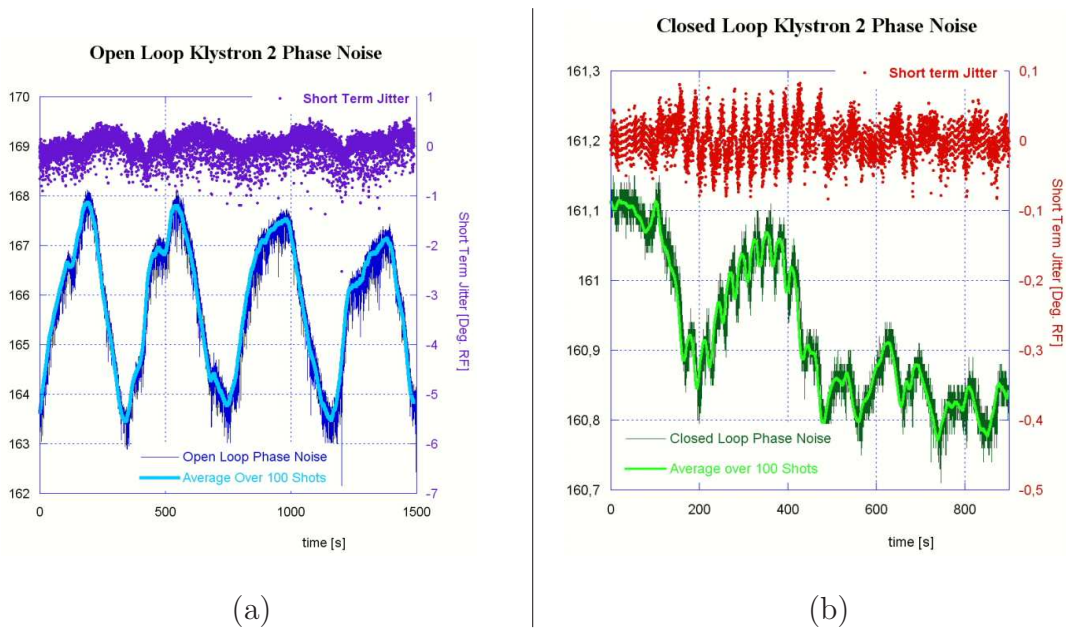


Figure 9: Fast phase feedback loop performance measurement: (a) open loop and (b) closed loop case

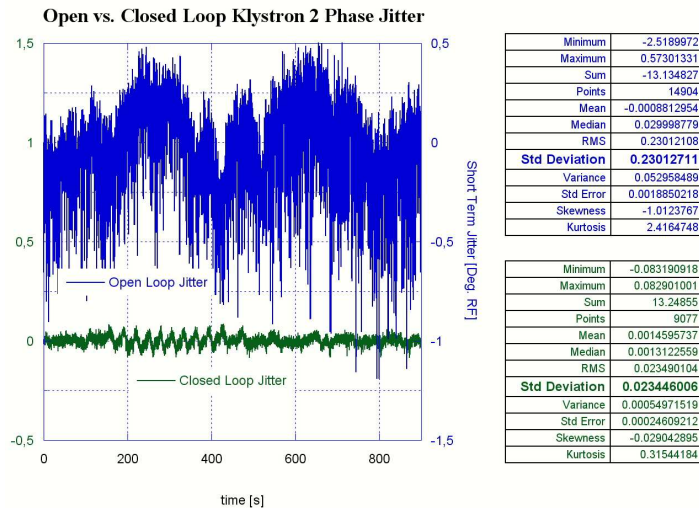


Figure 10: Comparison between the RMS fast jitters obtained with and without the phase stabilization around the klystron

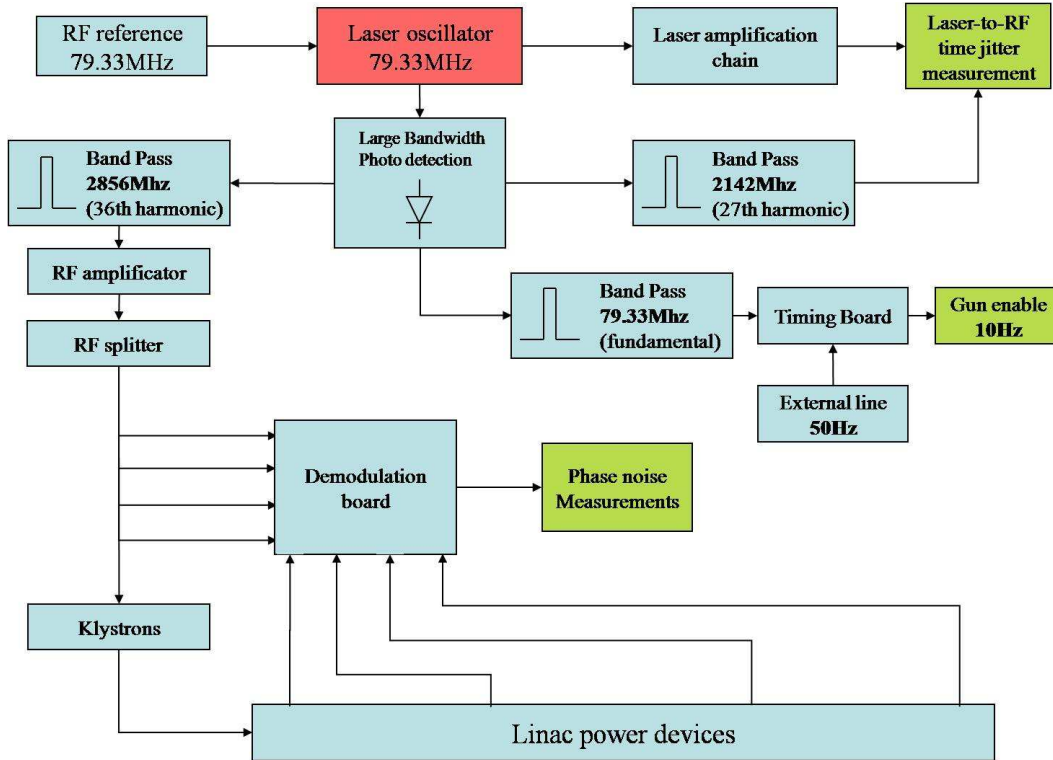


Figure 11: The new designed SPARC synchronization scheme

the previous electronic references at different frequencies with new ones obtained by band pass filtering the output of a fast photo-detector illuminated by the MIRA output. In this way, the Synchrolock<sup>TM</sup> is only used to stabilize the laser oscillator repetition rate. Starting from this, we can feed all the devices working at different frequencies present in our experiment: (i) the RF system and in particular the demodulation board and the klystrons ( $2856\text{MHz}$ ); (ii) the laser UV single pulse time jitter measurement system (presently  $2142\text{MHz}$ , but we are also considering to use higher harmonics to obtain a better resolution); (iii) the synchronization with the external line and the laser amplification stage ( $79.33\text{MHz}$ ). Since we own basically all the hardware needed to realize this new layout, we are confident that we will start the first tests very soon.

## 5 Conclusions

The work done on the SPARC synchronization system has brought some improvement in the phase detection of the UV laser pulses and on the phase noise compensation inside a single RF klystron pulse.

In particular in section 2 we reported about the system able to measure the arrival time of a single laser pulse on the cathode and how it was improved so that it detected a time jitter in good agreement with CW measured jitter at the level of the laser IR oscillator (see section 2). In fact we measured a time jitter of about  $400fs$  for the UV amplified pulses and a time jitter of about  $350fs$  at the exit of the IR oscillator.

Concerning the active phase noise reduction, based on feedback systems, new results have been achieved in the fast intra-pulse feedback around the klystrons. In fact this system has been installed and tested with very good results as we reported in section 3. An RMS phase noise of  $0.023^{\circ}_{RMS}$ , relative to the main RF oscillator, was measured in the RF inside a single pulse by averaging over the last  $3\mu s$  of the pulse duration.

We are ready to start tests on a new synchronization layout described in section 4 before the end of this year. We expect a significant improvement in the system relative synchronization, since we will use a single master oscillator (the MIRA laser oscillator) to generate all the reference signals needed to operate the linac.

## Acknowledgements

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