LASER AND RF SYNCHRONIZATION MEASUREMENTS AT SPARC

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Abstract

The SPARC* project consists in a 150 MeV S-band, high-brilliance linac followed by 6 undulators for FEL radiation production at 530 nm. The linac assembly has been recently completed. During year 2006 a first experimental phase aimed at characterizing the beam emittance in the first 2m drift downstream the RF gun has been carried out. The low level RF control electronics to monitor and synchronize the RF phase in the gun and the laser shot on the photocathode has been commissioned and extensively tested during the emittance measurement campaign. The laser synchronization has been monitored by measuring the phase of the free oscillation of an RF cavity impulsively excited by the signal of a fast photodiode illuminated by the laser shot. Phase stability measurements are reported, both with and without feed-back correction of the slow drifts. A fast intra-pulse phase feedback system to reduce the phase noise produced by the RF power station has been also positively tested.

INTRODUCTION

The SPARC project presently under commissioning at the Frascati Labs of INFN is a compact test facility aimed to generate FEL radiation in the visible spectrum (530 nm). The required nominal beam energy (150 MeV) is obtained from an S-band linac consisting in an RF gun followed by 3 TW accelerating sections (SLAC type), while an RF deflector dedicated to bunch longitudinal phase space diagnostics is placed at the linac end. As shown in Fig. 1, the linac total length is ≈ 15 m, while the whole machine is accommodated in a 36 m long experimental hall.

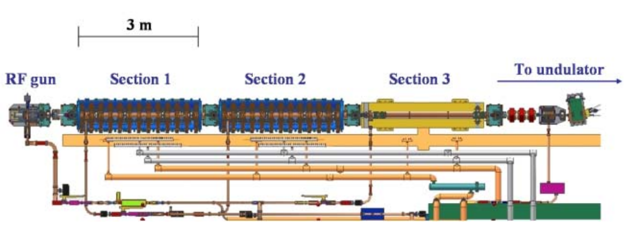

Figure 1: SPARC hall CAD top view.

The problem of keeping laser systems, RF systems and accelerator diagnostics extremely well synchronized is a crucial issue for the successful operation of the various FEL radiation sources presently in the construction or design phase [1]. For some projects the synchronization specifications are so tight that technological developments beyond the state-of-the-art are required to cope with them.

The general plant of synchronization systems consists in a distribution network to provide optical or electrical reference signals to the devices (lasers, RF stations, streak cameras, ...), and in a variety of equipments to measure and lock the device phase to the local reference.

Details on the architecture of the SPARC synchronization system and on the hardware used for this task have been already published [2].

The CW reference signal is generated by a commercial μ-wave frequency synthesizer (Rohde-Schwarz SMT) at the linac frequency (the SLAC standard 2856 MHz), then it is amplified by a solid state RF amplifier before being passively split in a number of reference signals distributed all over the machine.

Due to the limited linear dimensions of the machine, the commercial, coaxial, thermally compensated cable Andrew FSJ4-50B has been used for the reference distribution and RF signal transport to the central demodulation board. According to the producer specifications, the cable phase stability is better than 20fs/m/°C and the attenuation is ≈0.25dB/m @ 2856MHz. The SPARC hall is thermally stabilized within ±2°C.

The RF signal monitoring is performed by custom I&Q mixers followed by sampling boards of different types (ADLINK 9812 12-bit, 4-channels, 20 Ms/s; NI PXI 5105 12-bit, 8-channels, 60 Ms/s). A demodulation channel phase resolution of ≈ 10 fs for 4 μs flat RF pulses has been measured on the bench.

Pulse-to-pulse phase variations can be monitored and corrected by slow feedback systems. Being 10 Hz the linac rep. rate, from Nyquist theorem follows that only phase noise in a band up to 5 Hz can be correct. We conventionally call "drift" the noise inside and "jitter" the noise outside this bandwidth. Pulse-to-pulse feedback systems can only correct the phase drift, which however includes all the thermal effects. The main synchronization goals for the various operational phases of the SPARC project are summarized in Table 1. The phase I goal is to drive the FEL process to saturation and an rms phase stability $\sigma_t < 1500$ fs is required, mainly between the UV laser shot and the accelerating field in the RF Gun.

The synchronization specifications will be tighter for phase II, where bunch RF compression will be tested, and for the SPARC next generation experiments, and will involve a larger number of the machine sub-systems.

Table 1: SPARC synchronization goals

	Goal	Critical sub-systems	RMS time jitter [fs]
SPARC Phase I	FEL radiation @ 530 nm	Laser, RF Gun	1500
SPARC Phase II	RF bunch compression	Laser, RF Gun, 1st TW section	500
SPARC next generation experiments	FEL seeding, Plasma accel. ...	Photocathode laser, seeding laser, RF power stations, ...	100 ÷ 300

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PHOTOCATHODE LASER SYNCHRONIZATION MEASUREMENTS

The SPARC photocathode laser system has been purchased by Coherent Inc. It consists in CW passive mode-locked IR oscillator (the MIRA 900 S) with 79.33 MHz pulse rep. rate, followed by a regenerative and 2 multi-pass amplifiers, UV conversion on a non-linear crystal, pulse stretcher and a transfer line to the photocathode. The final 10 ps flat-top pulse has a rep. rate of 10 Hz, with an energy per pulse of ≈ 100 µJ [3].

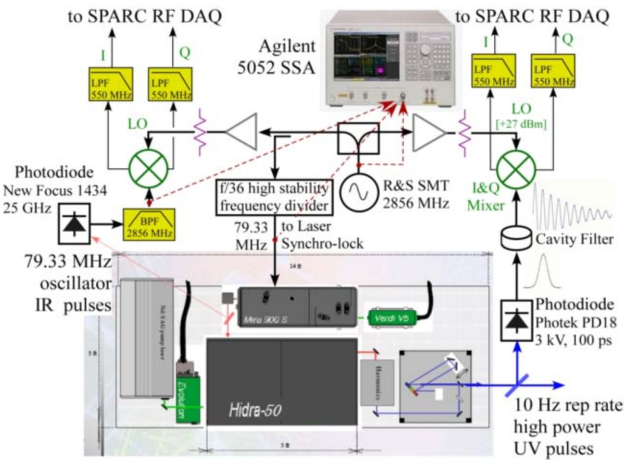

Figure 2: laser synchronization measurements.

The synchronization with the RF reference is obtained at the laser oscillator level. The frequency of the reference signal is reduced to RF/36 by means of a custom prescaler board based on fast and precise ECL technology [4]. The laser oscillator pulse repetition is locked to the RF/36 signal thanks to the Synchrolock system, which is a special PLL acting on the laser cavity mirrors through fast piezo-controllers. The fast mechanical control of the laser cavity length allows the Synchrolock bandwidth to extend typically up to ≈ 2 kHz.

Different kind of measurements on the laser-to-reference phase stability have been performed during the 2006 runs dedicated to the emittance experimental characterization in the 2 m drift downstream the RF gun. The complete schematic layout to measure the laser system phase stability is shown in Fig. 2.

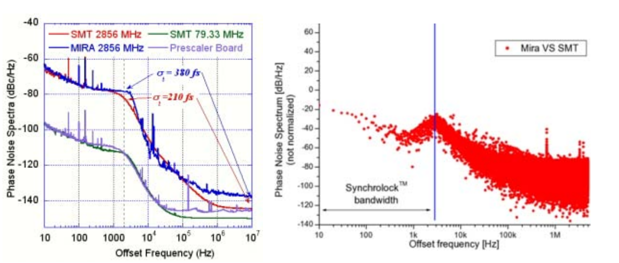

Figure 3: reference source and laser oscillator phase noise.

Laser Oscillator Phase Noise Measurements

The phase noise spectra of the reference source and of the synchro-locked laser oscillator converted with a fast photodiode have been measured. The measurement has been made with the Source Signal Analyzer Agilent 5052A SSA, which is a standard instrument for characterize source phase noise. Measurement results are summarized in the Fig. 3 left plots, showing that laser oscillator and reference are well locked in a frequency range up to 1 kHz. The residual integrated phase noise outside the Synchrolock bandwidth is ≈ 210 fs for the source and ≈ 380 fs for the laser oscillator.

The residual phase jitter outside the Synchrolock bandwidth results in a relative jitter between the two sources. A time-domain sample of relative jitter has been measured with the standard mixing technique and acquired, and then converted in frequency-domain by applying FFT. The result, reported in the right plot of Fig. 3, is a noise spectrum peaking at ≈ 3 kHz, showing that the Synchrolock loop gain is properly set close to the limit. The standard deviation of the data sample is ≈ 350 fs, in good agreement with SSA measurements.

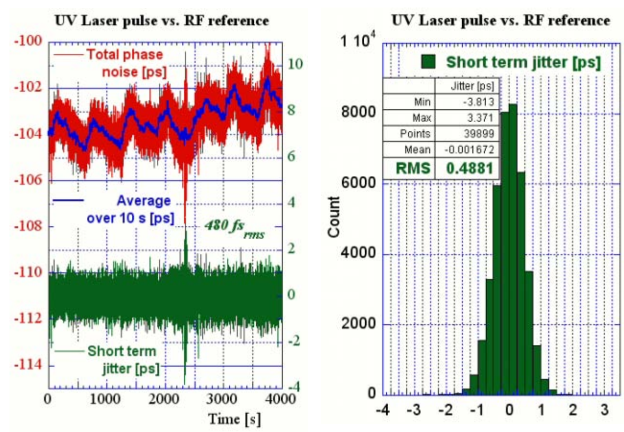

Figure 4: Phase jitter of the UV laser pulses.

UV Laser Pulse Phase Jitter Measured at 10 Hz

The laser rep. rate is reduced first to 1 kHz and finally to 10 Hz along the amplification chain. In order to measure the phase stability of the laser output pulses, we make use of a high-voltage photodiode and of a dedicated RF cavity filter to convert the laser pulse in a long-lasting, decaying sine-wave voltage. The cavity free oscillations are "triggered" by the laser pulse arrival, so that the information on the pulse synchronism is encoded in the RF phase of the cavity oscillations which is measurable with the standard mixing technique. The demodulated amplitude and phase of the cavity free oscillations have respectively exponential and linear profiles. The laser shot arrival phase is given by the intercept of the linear fit on the RF phase data, while the slope of the fit is a measure of the detune of the cavity with respect to the frequency of the reference source. This allows tuning the cavity by means of a remotely controlled mechanical plunger in order to maintain its natural frequency as close as possible to the reference frequency.

Measurement results are reported in Fig. 4. The phase of the UV laser shots has been acquired at 10 Hz for about 4000 s. Data vs. time are plot in the left, showing a slow time-varying structure (in blue). The short-term jitter, i.e. the difference between the phase data and the low frequency structure is plot in green. The measured standard deviation on this data sample is $\sigma_t \approx 490$ fs. The lowest time jitter measured on the SPARC laser UV beam is $\sigma_t \approx 400$ fs, obtained on a data record of ≈ 120 s. Being this figure very similar to the relative phase noise measured on the laser oscillator, we may conclude that the laser amplification chain contributes very little to the total jitter of the laser beam

Recently, the cavity filter has been rebuilt to resonate at 3/4 RF = 2142 MHz to reject the large environmental noise at 2856 MHz that affects the measurement when the RF power stations are working. The new cavity has been designed to work on the TE011 solenoidal mode, which provides a large Q-value improving the quality of the phase linear fit. The upgraded measurement set-up has shown excellent performances.

RF STATION PHASE NOISE CURES

The RF power stations introduce a non-negligible amount of phase noise that has to be limited or cured to improve the machine global synchronization. The RF phase of each station can be measured pulse-by-pulse, and corrected by a slow feedback loop in a band extending up to 5 Hz. To correct also the high-frequency jitter introduced by the station (mainly due to its high-voltage supply) we have designed and built a fast, intra-pulse feedback loop capable of correcting the station phase deviation within the 4.5 μs time duration of the RF pulse.

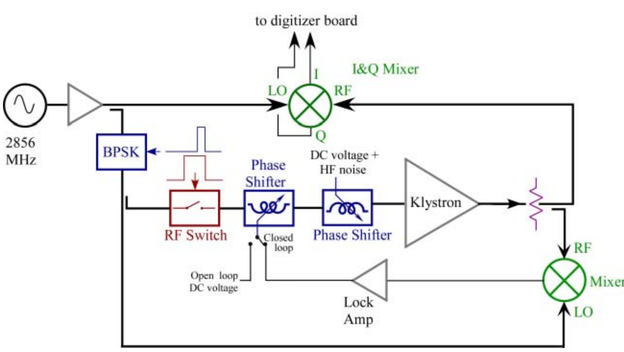

Figure 5: Intra-pulse phase lock schematics.

The schematics of the intra-pulse phase lock feedback loop is shown in Fig. 5. This kind of feedback loop requires a fast, analog controlled phase shifter and a broadband lock amplifier, together with short connections to limit the total open loop group delay. The lock amp is a real integrator circuit based on broadband current-feedback operational amplifiers.

The RF station phase noise has been measured in open and closed loop condition, and results are reported in Fig. 6. Again the phase noise jitter appears to be superimposed to a slow, low frequency structure that can be corrected by pulse-to-pulse feedback loop. The phase jitter is noticeably reduced by one order of magnitude from ≈ 230 fs to ≈ 23 fs. Also the low-frequency structure of the global phase noise sample is strongly reduced by the intra-pulse feedback loop, being mainly generated by temperature drift of the klystron cooling water.

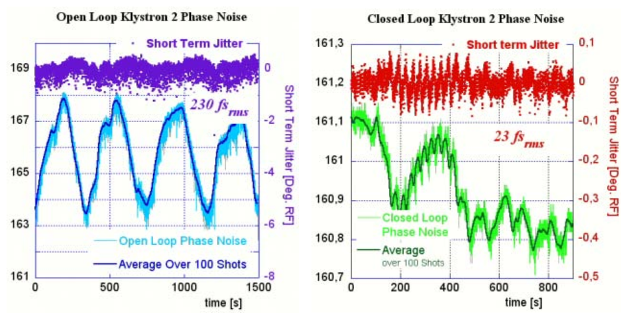

Figure 6: Open and closed loop RF station phase noise.

CONCLUSIONS

The SPARC synchronization and low-level RF system has been extensively tested during the 2006 run dedicated to the emittance characterization downstream the RF gun.

Results show that the 10 Hz UV laser pulses sent to the photocathode are synchronized to the RF reference within ≈ 400 fs rms, and that this jitter mainly comes from the synchronization of the laser oscillator to the reference accomplished by the Synchrolock servo-loop.

The inherent phase jitter of the RF station output is ≈ 230 fs rms and it is reduced to ≈ 23 fs rms by using a dedicated intra-pulse phase lock feedback loop. Therefore the contribution of the RF stations to total synchronization noise of the machine can be made negligible.

The reported results already comply with the specifications for the SPARC experimental phases I and II. SPARC next generation experiments may require improvements of the phase noise quality of the laser and μ-wave sources, and/or modification of the system architecture to reach global synchronization in the scale of ≈ 100 fs rms.

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