PERFORMANCES OF THE SPARC LASER AND RF SYNCHRONIZATION SYSTEMS

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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 completed and the SPARC scientific program is presently in progress.

The low level RF control electronics to monitor and synchronize the RF phase of the accelerating structures along the linac and the laser shot on the photocathode has been commissioned and it is now fully operative. The laser synchronization is routinely 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, and slow drifts are automatically corrected by a dedicated shot-to-shot feedback system. A similar slow automatic regulation is implemented on each linac accelerating section acting either on low level or high power sliding lines. The phase noise in the 2 RF power stations is counteracted by fast intra-pulse phase feedback systems that have been developed and put in operation. Phase stability measurements taken over the whole synchronization system are reported, and performances of different synchronization architectures, μ-wave based or laser based, are compared.

INTRODUCTION

All the various projects of FEL radiation facilities [1] presently in operation, commissioning, construction or proposal phases share a common technical issue since they require an unprecedented level of synchronization [2] among RF systems, laser systems and beam diagnostics. The required beam quality in terms of emittance, energy spread, peak current and shot-to-shot reproducibility can only be met provided that a global synchronization at level of 50÷500 fs (depending on the application) can be maintained over long time scales (hours or days).

The SPARC project [3], situated at the INFN Frascati National Labs, is a test facility consisting in a 150 MeV injector followed by 6 permanent magnet ondulators to produce 530 nm SASE FEL radiation in saturation regime. The linac RF is the standard SLAC S-band (f_{RF} =2856 MHz) and the beam generated in an RF gun is accelerated up to the final energy by three travelling wave (TW) accelerating sections (constant gradient, 3 m long each). Two klystrons (45 MW peak, 4.5 μs pulse duration, 10 Hz rep rate) are used. The first one powers the RF gun, the 3rd TW section and an RF deflector located between the linac and the undulators for beam diagnostic, while the second one, equipped with a pulse compressor (SLED), drives the 1st and 2nd TW sections.

The basic architecture and the performances of the SPARC RF reference distribution and synchronization system are reported in [4,5]. In this paper we report the operational experience with the SPARC synchronization system and recent results of experimental measurements aimed at improving its performances. We also describe the system upgrades proposed to cope with the synchronization requirements of the whole SPARC scientific program of beam experiments.

SPARC SYNCHRONIZATION: OPERATIONAL EXPERIENCE

The SPARC operation has started in 2006, with the characterization of the beam emittance at the RF gun exit, and has continued in 2007 and 2008 with the whole linac installed. During this period the laser synchronization and low-level RF systems have been operated and upgraded, showing good performances and reliability.

Photoinjector Laser Synchronization

The frequency of the optical cavity of the SPARC photoinjector laser oscillator is locked to the RF reference in a PLL configuration (Synchrolock™) [4,5]. Motorized and piezo-controlled mirrors are used to tune the optical cavity and close the loop.

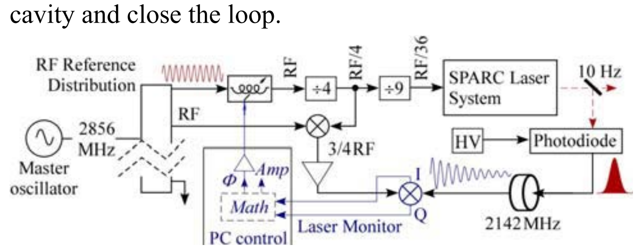

Figure 1: Laser synchronization monitoring and feedback.

The repetition rate of the laser pulses is reduced along the amplification chain from 79.33 MHz (RF/36, the frequency of the oscillator optical cavity) down to 10 Hz. The time of arrival of the laser shots after amplification is monitored using a resonant pulse stretching method, as sketched in Fig. 1. This technique, developed and implemented at SPARC, is based on a HV photodiode generating a narrow electric pulse synchronous with the laser which excites free oscillations of a resonant cavity tuned exactly at the frequency of the reference. The time of arrival is encoded in the phase of the free oscillations with respect to the reference, and is recovered by mixing the two signals. At SPARC we use the 3/4 RF = 2142 MHz signal as the reference for this measurement to reject the large environmental noise at the linac frequency appearing when the high power klystrons are in operation. The laser time of arrival is measured and acquired every shot, and the information is available in the SPARC computer control system for statistical analysis and slow feedback implementation.

The slow feedback keeps the phase of the laser arrival at a constant selectable value correcting the fluctuations by moving a motorized sliding delay line placed along the path of the laser reference signal. The phase jitter, i.e. the random shot-to-shot fluctuations, can not be corrected by the slow feedback loop but can be monitored in real time to qualify and tag the beam measurements. A typical sample of a short term acquisition is shown in Fig. 2, corresponding to a laser jitter of ≈ 400 fs.

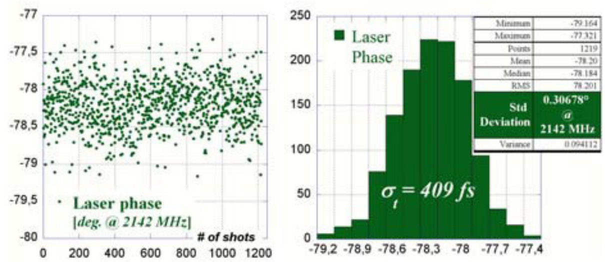

Figure 2: SPARC Laser measured phase jitter.

This is essentially the value already measured at the oscillator level [5], which means that laser amplification do not relevantly contribute to the jitter budget.

RF synchronization

The signal driving the two high power klystrons operating at SPARC is directly derived from the main RF distribution. The phase control implemented around each SPARC RF stations is sketched in Fig. 3 and consists of two main blocks: the fast intra-pulse phase lock, which encompasses the klystron and its driver amplifier, and the slow pulse-to-pulse feedback loops which includes the long coaxial and waveguide connections between the machine hall and the klystron tunnel.

The fast intra-pulse phase lock is a system developed and implemented at SPARC to reduce the contribution of the RF power stations to the total phase jitter of the RF fields interacting with the beam. To overcome the Nyquist limit associated to the 10 Hz pulse-to-pulse feedback loops, we have developed an analog system to measure the klystron output phase deviation with respect to the drive signal, and correct it along a fraction of the time duration of a single pulse. The required bandwidth of such a system is ≈ 1 MHz, which is obtained by using fast electronic phase shifters, while the loop error signal is processed by current-feedback operational amplifiers. The group delay of the klystron and the physical length of the signal path contribute with ≈ 100 ns and ≈ 50 ns to the total group delay of the loop, which has to be little enough to preserve the loop bandwidth. As a consequence the path length of the loop can not exceed ≈ 10 m. Under these conditions the transient regime of the loop error and correction signals lasts ≈ 1 μs over the ≈ 3 μs of the RF pulse duration, as shown in Fig. 3. The phase noise is thus reduced from ≈ 600 fs to < 80 fs.

Most of the coaxial and waveguide connections carrying the reference signal from the RF distribution rack (in the linac hall) to the klystrons (in the klystron tunnel) and the RF klystron power back to the linac cavities and accelerating sections are out of the fast intra-pulse loop. A slower feedback loop monitors the RF input power or directly the fields inside the RF devices connected to the klystron and acts on either low-level or high-power variable phase shifters to compensate the drifts that are mainly induced by thermal elongations. In this way the good phase stability of the stations equipped with the intra-pulse feedback loop is maintained across the RF devices over long time scales.

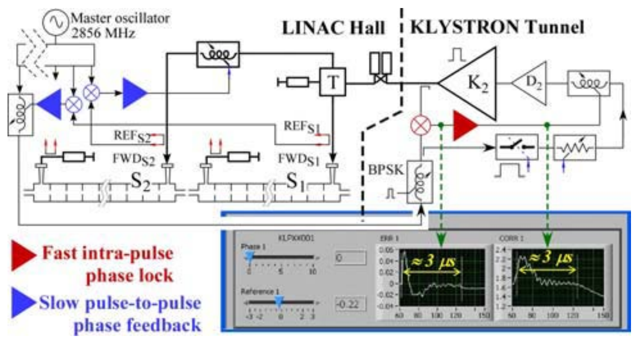

Figure 3: SPARC RF synchronization.

SPARC SYNCHRONIZATION DEVELOPMENTS

Tests of a laser-driven synchronization system

The previous presented data shows that presently the RF is a factor of ≈ 5 more accurately synchronized than the photoinjector laser. This is because the RF synchronization is a pure electronic process, and also because the RF pulse duration is long enough to allow for real time corrections. A possible way to increase the global synchronization of the machine is to eliminate the μ-wave master oscillator and use the signal coming from the laser oscillator as the machine reference.

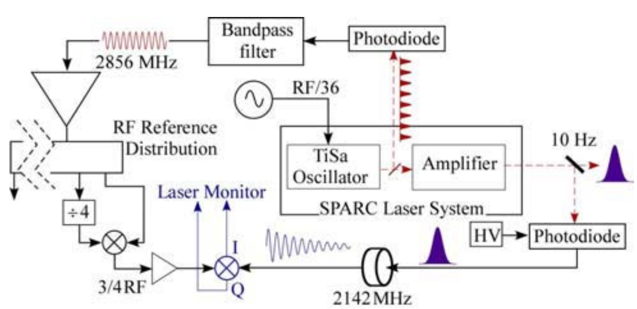

Figure 4: Laser driven synchronization set-up.

This will in principle make the laser high-power pulses intrinsically synchronous, while the conformity of the RF signals to the new reference should remain at the sub 100 fs level.

This alternative configuration has been preliminary tested only on the laser system as sketched in Fig. 4. A standalone 79.33 MHz RF reference has been provided to the laser oscillator to ensure long term stability of the optical cavity. A portion of the IR radiation leaving the optical cavity is converted in a sequence of narrow electric pulses by a fast, high rep-rate photodiode, and the 36th harmonic of the signal (the 2856 MHz) is extracted by a tuned bandpass filter and used as the reference tone to drive all the RF distribution network.

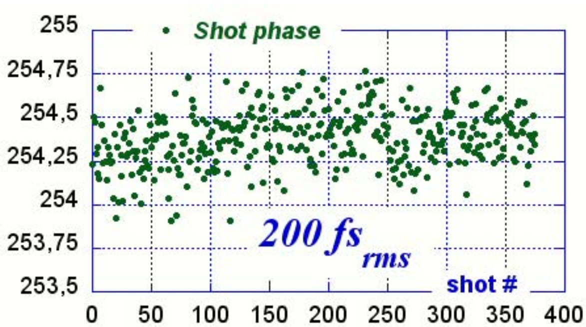

Figure 5: Jitter in the laser driven synchronization.

A measurement of the time of arrival stability of the laser pulses after amplification is reported in the Fig. 5 plot, showing a reduction of a factor ≈ 2 with respect to Fig. 2. We believe that most of the measured residual jitter (≈ 200 fs) can be attributed to the presence of the divider-by-4 prescaler board in the test set up, which could be in principle substitute by inserting a tuned 2142 MHz filter on a portion of the photodiode signal. We estimate that following this way a global synchronization at level of ≈ 100 fs is attainable.

Improvements of the time-of-arrival monitors

As an interesting by-product, the Fig. 5 measurement also shows that the resolution of our laser time of arrival monitor is < 200 fs. A more precise evaluation of the ultimate achievable resolution of arrival monitors based on resonant pulse stretching is of great interest for a comparison of this pure μ-wave method with high sensitivity, optical techniques based on cross correlation. Since no calibration sources with high stability (< 100 fs) and low repetition rate (< 100 kHz) are available for bench measurements, the resolution will be evaluated by duplicating the laser phase monitor of Fig. 1 to take the differential jitter between the two channels. A pair of equal HV photodiodes has been purchased for this task, while two resonant cavities have been designed and are going to be built. This part of the program is supported by the FAST (Femtosecond Active Synchronization and Timing) collaboration. FAST is an experiment approved by the INFN Committee for technological research to endorse the efforts aimed at improving the state-of-the-art in laser-to-RF and laser-to-laser synchronization.

The new photodiodes are rated for high saturation currents and are expected to deliver high peak voltages in the linear regime, where the photodiode AM-to-PM conversion is tolerable and do not significantly affect the phase jitter measurements. Large pulse voltages require less RF amplification after being filtered by the cavity, thus reducing the electronic noise.

Bunch arrival monitors based on the same principle are expected to be effective and much simpler with respect to laser ones, since a resonant idle cavity can be placed directly along the linac beam trajectory, and a decaying voltage oscillation synchronous with the bunch passage can be coupled out of the cavity and demodulated, with no need of photodiodes and RF amplifications. Two bunch arrival monitor cavities have been designed and will be installed after the 1st and the 3rd TW accelerating sections to study the bunch synchronization dependence on the laser arrival and on the amplitudes and phases of the RF fields for various working points and regimes (FEL seeding, bunch compression, ...). CAD 3D views of the SPARC bunch arrival monitor cavity equipped with two tuning plungers is shown in Fig. 6. A manual tuner will be used for coarse frequency regulation, while a motorized fine tuner will be remotely controlled to maintain the coherency between the cavity free oscillations and the reference frequency.

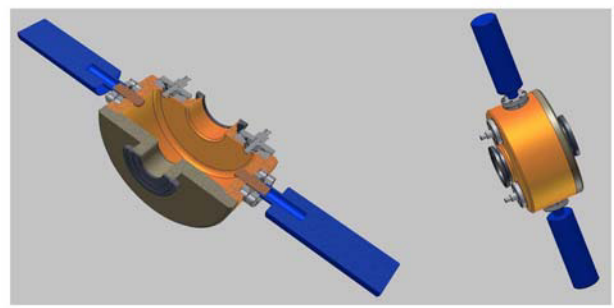

Figure 6: 3D views of the SPARC bunch arrival monitor.

CONCLUSIONS

Presently, the level of the synchronization obtained at SPARC (≈ 400 fs for the photoinjector laser and < 100 fs for the RF fields interacting with the beam) fully meets the machine requirements to have stable and reproducible beam conditions for SASE-FEL radiation production. It is also adequate for experiments of RF bunch compression and FEL seeding. Global synchronization at < 100 fs level requires improvements in the laser stabilization and/or implementation of different timing architecture. Laser and electron beams arrival monitors based on resonant pulse stretching are in operation and in preparation, respectively.

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