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UPGRADE OF THE SPARC_LAB LOW LEVEL RADIOFREQUENCY SYSTEM

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Abstract

SPARC_LAB facility was born in 2004 as an R&D activity to develop a high brightness electron photo-injector dedicated to FEL experiments and exploration of advanced acceleration techniques. The electron source consists in a brazefree 1.6-cell S-band RF gun with a peak electric field of 120 MV/m and a metallic copper photocathode. The gun injects particles into two S-band sections, the initial section acting as an RF compressor using the velocity bunching technique, with built-in solenoid coils that enhance magnetic focusing and control emittance. A subsequent C-band acceleration section acts as a booster to achieve the desired kinetic energy. The Lazio Regional government recently funded the SABINA project for the consolidation of SPARC_LAB facility. The reference and the distribution systems and the Low Level radiofrequency (LLRF) system will also undergo a significant upgrade, involving the replacement of the original analogue S-band and digital C-band radiofrequency systems with commercial, temperature-stabilized, FPGA-controlled LLRF digital systems provided by Instrumentation Technologies in order to improve performance in terms of amplitude, phase resolution, and stability.

INTRODUCTION

SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Laser And Beam), a high brightness electron linac at LNF (Laboratori Nazionali di Frascati), is currently undergoing a major upgrade co-funded by the Lazio regional government (SABINA project [1]). This upgrade involves various aspects of the facility, including the Radio Frequency (RF) system, which encompasses the synchronization, reference and distribution systems and the Low Level Radio Frequency (LLRF) systems. In particular, the LLRF systems will be replaced by temperature-stabilized digital devices controlled by FPGAs. This upgrade aims to improve performance in terms of amplitude, phase resolution and stability. In this paper we will report the status of the upgrade, together with a detailed description of all the sub-systems involved.

SPARC_LAB FACILITY

SPARC_LAB, located at LNF, is a test facility providing electron bunches with energies up to 170 MeV feeding several experimental beamlines such as SASE and seeded FEL, Thomson backscattering, THz generation and plasma focusing and Particle WakeField Acceleration (PWFA). Established in 2004, it houses a high-brightness electron photoinjector and a 200 TW laser known as FLAME (Frascati Laser for Acceleration and Multidisciplinary Experiments). Key components include a BNL/UCLA/SLAC type S-band 1.6 cell RF-gun, providing a peak electric field of 120 MV/m and utilizing a copper photo-cathode. Electron extraction is achieved via UV laser pulses (266 nm, 4.66 eV), tailored for various experimental requirements. Electrons are accelerated up to 5.3 MeV within the gun before traversing two S-band sections, which act as RF compressors via velocity bunching. Magnetic focusing and emittance control are ensured by embedded solenoid coils. One C-band accelerating section serves as a booster stage to achieve nominal kinetic energies. Ongoing developments include research on high-gradient plasma acceleration, with a focus on the future EuPRAXIA@SPARC_LAB (European Plasma Research Accelerator with Excellence in Applications) project [2, 3]. This initiative aims to equip the LNF with a soft X-ray FEL driven by a compact X-band RF linac excited by a 0.5 PW class laser system.

SPARC_LAB LLRF SYSTEM

At SPARC_LAB, PFN modulators (from Puls-PlasmaTechnik - PPT) for the S-band and a solid-state modulator (from ScandiNova, Sweden) for the C-band are used to generate high voltage (HV) for the klystrons. The first S-band klystron drives the RF gun and deflection cavity for beam diagnostics. The second S-band klystron drives two SLAC traveling wave accelerating structures with a SLED pulse compressor. The C-band line is dedicated to the high gradient (35 MV/m) constant impedance structure for energy boosting. A block diagram of SPARC_LAB LLRF system is shown in Fig. 1. On each of the three lines, intra-pulse klystron feedback was implemented, a system capable of acting on klystron phase jitter within a single RF pulse and whose performance have been reviewed in [4].

The SABINA project, co-funded by the Lazio Region for 6.1 million euros, concerns the consolidation of the SPARC_LAB photoinjector (i.e. a new RF gun with braze-free technology and a renovated diagnostic station), the innovation of the photocathode laser, the replacement of the focusing solenoids of the two accelerating sections in S-band and also include the upgrade of some ancillary systems. In addition, the FLAME power laser will be upgraded and a THz line will be available using the THz radiation produced by the SPARC electron beam injected into a new high-tech undulator. As part of this initiative, the whole RF system

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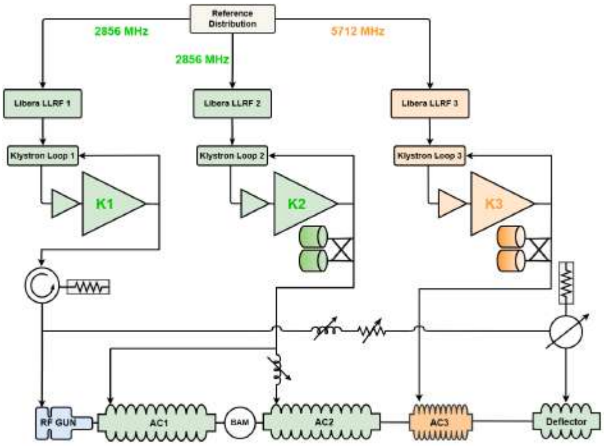

Figure 1: Block diagram of the SPARC_LAB LLRF system.

of the facility will be upgraded. In particular, a new Reference Master Oscillator (RMO) and a reference distribution system will be installed. In addition, the three LLRF systems (two for S-band and one for C-band lines) will be replaced with commercial, digital, temperature-stabilized, FPGA-controlled systems manufactured by Instrumentation Technologies (Libera LLRF [5]). The current analog S-band LLRF system, in operation at LNF since 2006, relies on direct conversion using custom 24-channel Pulsar Microwave I/Q mixers. It uses connectorized RF components, resulting in noise and offset limitations. In addition, digital signal acquisition is performed using general purpose National Instruments ADC cards (NI 5105), which have limited resolution and a non-negligible fault rate. Moreover, the front-end noise limits the minimum detectable RF phase jitter to a level of approximatively 50 fs when today's requirements demand <10 fs. Furthermore, with a fully analog system, the pulse shape cannot be arbitrarily set, and slow feedback against RF field amplitude and phase drifts must be provided via software by means of the control system. In contrast, the C-band LLRF system developed by PSI as part of the TIARA (Test Infrastructure and Accelerator Research Area) collaboration offers a digital solution with enhanced performance. It features a 16-channel front-end with high isolation (> 80 dB) and downconverts RF signals to an intermediate frequency (IF) of 39.667 MHz before digitization using a 16-bit ADC. In addition, the back-end integrates a differential I/Q vector modulator with over 40 MHz BW and less than <10 fs jitter. Although the current C-band LLRF system performance is adequate for the SPARC_LAB requirements, it will still be replaced. In fact, PSI has upgraded its systems over the years and spare parts are no longer available, and in any case it is preferable to bring all systems up to the same standard.

The Libera LLRF (shown in Fig. 2) offers a solution to overcome the main limitations of the systems currently installed at SPARC_LAB. It consists of two distinct units: an analog front-end and a digital processor. The analog front-end unit houses most of the analog signal processing components, including the LO & CLOCK generation and the analog front-end boards. These components are temperature stabilized to mitigate temperature drift, and 13 RF inputs are available. Using a down-conversion technique, the analog front-end converts RF signals to intermediate frequency (IF = 44.625 MHz) signals. The ADC application board then performs analog-to-digital conversion of the IF signals (14-bit, 119 MHz, 5 MHz BW), after which the digital signals are processed in the FPGA. The analog back-end manages the frequency up-conversion and generates the RF drive signal based on the IF and LO signals. The system is equipped to perform amplitude and phase feedback on two independent channels. The digital drive signal is generated in the VM FPGA. In addition, the user has control over the shape of the drive RF pulse through a 16-bit DAC with 15 MHz BW. Identical systems have already been purchased and successfully commissioned by the LNF RF group for both LNF and external projects, with measured amplitude and phase resolutions of <0.02 % and <0.01 deg, respectively [6–9]. As part of the project, the reference generation hardware and distribution system were also upgraded. The reference generation and distribution hardware was designed and manufactured by the RF LNF group. Commercial components, such as low noise amplifiers and power splitters from Mini Circuits, were utilized, and custom cavity filters were specifically designed to extract the desired harmonics from the Optical Master Oscillator (OMO) frequency. In Fig. 3 a photo of the reference generation chassis is shown.

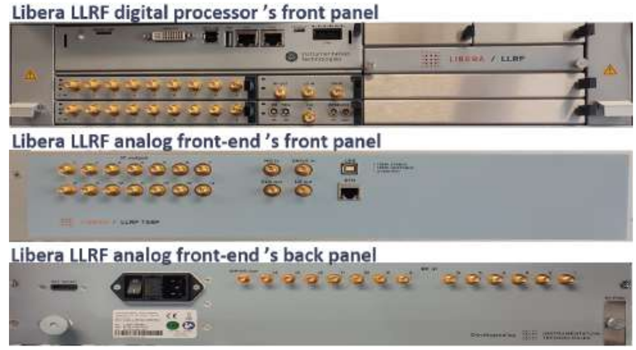

Figure 2: Libera LLRF system: digital processor's front panel (on top), analogue front-end's front panel (in the middle), analogue front-end's back panel (bottom).

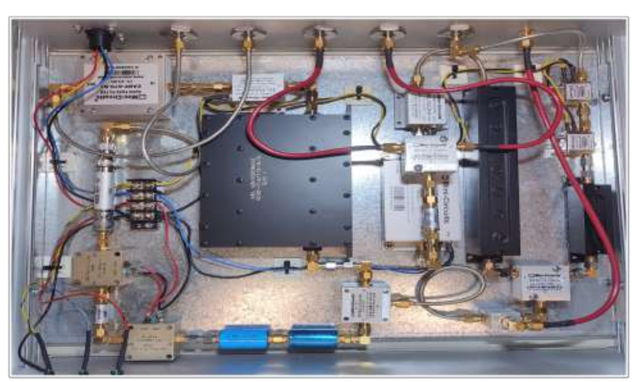

Figure 3: Detail of the reference generation chassis.

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SPARC_LAB SYNCHRONIZATION SYSTEM

The RMO in the SPARC_LAB synchronization system has been replaced with an ultra-low phase noise oscillator (Libera RMO) that generates four coherent 2856 MHz outputs. The phase jitter of the RMO was measured with the Rohde&Schwarz FSWP-26 phase noise analyzer, integrating between 10 Hz and 10 MHz from the carrier frequency, to be 20.5 fs, the noise power spectrum is shown in Fig. 4.

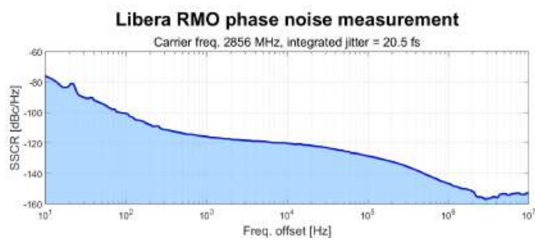

Figure 4: Integrated phase jitter of the RMO, measured with a Rohde&Schwarz FSWP-26 phase noise analyzer (between 10 Hz and 10 MHz from the carrier).

The RF reference is distributed by the synchronization system by means of an optical master oscillator that is phase-locked to the RMO. All the reference signals at 2856 MHz, 5712 MHz, and 714 MHz are generated from the electrical conversion of OMO pulses. The OMO also provides a 79.33 MHz signal that is essential for trigger generation. Both S-band and C-band references are amplified and distributed to various clients, including RF power supplies and LLRF systems. The 2856 MHz signal is also needed for phase-locking the photocathode laser. As for the 714 MHz signal, it allows the upconversion of signals from the 2142 MHz Beam Arrival Monitor (BAM) cavity used for beam timing measurements. A block diagram of the SPARC_LAB synchronization system is shown in the Fig. 5.

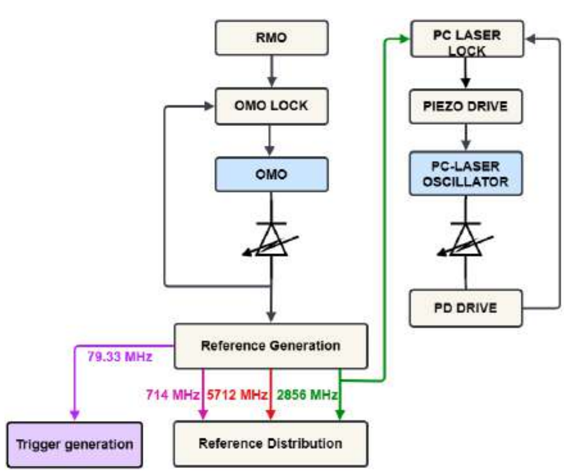

Figure 5: Block diagram of the synchronization system of SPARC_LAB.

CONCLUSION

The SPARC_LAB facility was presented with a focus on the synchronization system and the LLRF systems and their upgrade in the context of the SABINA project. This upgrade includes the replacement of analog LLRF systems with digital, temperature-stabilized, FPGA-controlled devices from Instrumentation Technologies. The transition to a digital solution is necessary to overcome the limitations of the existing analog systems. It will be able to significantly improve the RF amplitude and phase measurement resolution and meet the most stringent modern standards. Furthermore, complex amplitude and phase modulations, that might be needed to compensate unwanted non-linear effects of the beam, will be available. A new facility RMO synchronized with an OMO has been implemented. The OMO is used as a source of S-band and C-band references and to lock the photocathode laser. These enhancements to consolidate the SPARC_LAB research facility are focused on improving performance and increase the facility's operating time. The first machine commissioning activities after the upgrade are scheduled before summer 2024.

ACKNOWLEDGEMENTS

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