ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR01

RF POWER STATION STABILIZATION TECHNIQUES AND MEASUREMENTS AT LNF-INFN

L. Piersanti *, M. Bellaveglia, F. Cardelli, A. Gallo, G. Latini, R. Magnanimi, S. Pioli, S. Quaglia, M. Scampati, G. Scarselletta, B. Serenellini
INFN - Laboratori Nazionali di Frascati, Frascati, Italy

Abstract

In the framework of EuPRAXIA@SPARC_LAB project, we are studying possible solutions to upgrade and measure the amplitude and phase stability of the RF accelerating fields generated by a klystron. These studies concern the C- and X-band klystrons installed in the LNF infrastructures. In particular, we will present our work on a fast phase feedback around the C-band power station (50 MW klystron and solid state modulator) installed at SPARC_LAB. We are trying to push the timing jitter below the standard limit of such systems (few tens of fs RMS). A second topic is the study of the jitter of the X-band power station (50 MW klystron and solid state modulator) installed in the TEX facility. Precise measurements on amplitude and phase of this system will be reported at different positions both upstream (LLRF and pre-amp) and downstream (waveguides and prototype structure) the klystron.

INTRODUCTION

Free Electron Laser (FEL) and plasma accelerator facilities that use external injection require precise control over the amplitude and phase stability of radio-frequency (RF) accelerating fields, especially in their RF power systems. This is of crucial importance, for instance, whether magnetic or RF compression is employed, as the timing jitter of the beam at the linac end is tightly linked to phase noise in the RF fields, when the system operates off-crest [1, 2]. A significant role in the RF phase jitter in pulsed electron linacs is played by the high-voltage (HV) instability in the modulators that supply the klystrons, particularly in pulse forming network (PFN) modulators with phase variations in the order of hundreds of femtoseconds. Some facilities have improved their modulator designs to achieve HV stability levels around 30 ppm [3, 4]. However, solid-state modulators are generally more stable. State of the art HV pulse to pulse jitter can reach values as low as 10 ppm, but this is highly dependent on the actual modulator specimen under test. Thus, to achieve stability performance at or above the current state of the art level, it is necessary to implement an intra-pulse phase feedback capable of operating in a time frame of few hundreds of nanoseconds (i.e. well within the RF pulse). This fast-feedback system works by picking-up a portion of the klystron forward power through a directional coupler, comparing the phase of the sampled signal with the facility master reference using an RF mixer as phase detector. The resulting error signal is amplified and filtered, then used to adjust the phase of the klystron input within the RF pulse. This real-time correction is carried out by modulating the signal with a high-speed voltage-controlled phase shifter. In this context, this article provides an update on the fast intra-pulse feedback system, which has been in operation since 2008 at the SPARC_LAB facility of LNF-INFN for the S-band klystrons. The system has been redesigned, built, and experimentally tested on the solid-state C-band setup at SPARC_LAB. Moreover, a review of recent RF stability measurements performed in 2024 at TEX facility [5] at LNF on an X-band power plant driven by a solid state modulator will be presented as well. These results will be particularly important in view of the EuPRAXIA@SPARC_LAB project [6], that will equip LNF-INFN with a multi-disciplinary user-facility based on a soft X-ray FEL driven by a 1 GeV compact X-band RF linac with an S-band injector and a plasma acceleration stage.

* luca.piersanti@lnf.infn.it

INTRA-PULSE FEEDBACK UPGRADE AT SPARC_LAB

At SPARC_LAB the transition to seeded FEL experiments and RF compression scheme required a significant enhancement in RF stability. For this reason, a first version of a fast intra-pulse phase feedback system has been designed, implemented, and successfully tested in 2008 on the S-band power plant. This system works by picking up the klystron output through a waveguide directional coupler, then comparing its phase with that of the low-level RF (LLRF) drive to generate an error signal. This signal is fed into the loop error amplifier, and a fast phase shifter (Pulsar Microwave, ST-G9-411, with a bandwidth of approximately 50 MHz) provides the required phase correction. The error amplifier consists of two cascaded stages using current feedback operational amplifiers (CLC410).

The latest results of such system have been reviewed in [7] showing measurements from 200 consecutive shots using a low-noise receiver system. The phase jitter was reduced to 0.046 deg RMS, with an overall compression of more than a factor four.

However, the RF stability achieved with the first version of the klystron loop was not sufficient for the requirements of plasma acceleration. To ensure consistent and repeatable acceleration of the witness beam, especially for FEL radiation experiments planned at EuPRAXIA@SPARC_LAB, further improvements are in fact needed. Beam dynamics simulations at SPARC_LAB, using the velocity-bunching RF compression scheme, set a maximum limit for the RF

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR01

station jitter at 0.02 deg RMS for the S-band and 0.06 deg RMS for the X-band.

One possible solution to minimize the S-band stations jitter is to replace the old PFN modulators with newer solid-state versions. However, this approach has significant downsides, such as: high costs and long implementation times. An upgrade to the feedback electronics of the existing plants has been performed instead. The upgrade involved the C-band station, this in fact allowed to test the performance of the electronics with minimal impact on machine operations, and provided useful insights into achievable jitter limits with the new system applied to a solid state modulator.

The upgrade involved in particular: (i) the phase shifter: selected to operate at 5712 MHz with an almost constant insertion loss with respect of control voltage; (ii) the operational amplifiers: featuring a constant gain-bandwidth product of approximately 200 MHz; (iii) an internal slow feedback: designed to keep the phase stable even when the RF pulse is off, reducing transients and minimizing phase modulation required at the beginning of the RF pulse; (iv) the loop electronics location: placed as close to the klystron as possible to minimize group delay, allowing higher loop gain without risking loop instability. Additionally, the physical delay between the RF port of the phase detector and the reference at the local oscillator (LO) port has been adjusted with a custom cable to ensure precise compensation.

The final goal is to achieve a steady-state response within 100 ns, a target chosen to meet the constraints of the X-band accelerating structures at EuPRAXIA@SPARC_LAB, which require an RF pulse of approximately 150 ns from the klystron. Although a temporary solution involving zero-pole compensation has been used to extend the limited bandwidth of the available phase shifter, future upgrades will include a wider bandwidth phase shifter to fully exploit the operational amplifier capabilities and minimize loop settling time.

Experimental Setup and First Measurement Results

To evaluate the performance of the new klystron loop, comprehensive laboratory tests were conducted. Figure 1 reports the feedback laboratory setup and Fig. 2 shows the concept of the slow feedback mechanism. After completing these initial tests, the new feedback system prototype was installed at SPARC_LAB, where RF measurements were taken to test its effectiveness. The experimental setup used for these tests closely resembles the one shown in Fig. 1, with the C-band klystron located after the driver amplifier.

The measurement campaign with the prototype yielded the results reported in [7]. A significant reduction in the C-band klystron phase jitter was achieved, with a decrease of over 3 times from 0.065 deg to 0.019 deg, equivalent to a residual phase jitter of 9.2 fs.

RF MEASUREMENTS AT TEX FACILITY

TEX is a test facility established at LNF-INFN in 2021 (in collaboration with CERN) for R&D on X-band RF components, LLRF systems, beam diagnostics, vacuum technologies and control system in view of INFN future accelerator EuPRAXIA@SPARC_LAB [6, 8] that will be built at LNF.

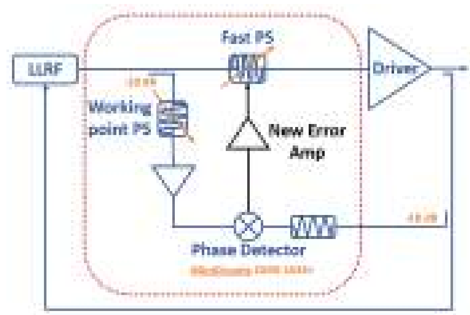

Figure 1: Experimental setup of klystron loop laboratory and high-power measurements.

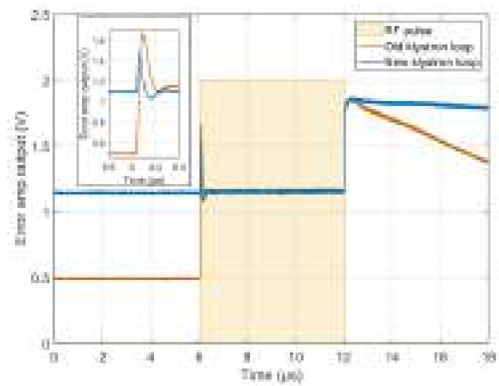
Figure 2: Oscilloscope capture of the functionality of the slow feedback. The error amplifier output without slow feedback is shown in orange; the same output with slow feedback in operation is shown in blue.

The facility has been successfully commissioned in 2021 and is in operation since 2022, the latest results have been reviewed in [10–12]. The LLRF system of the facility has been designed adapting a commercial S-band Libera LLRF produced by Intrumentation Technologies (Slovenia), and whose performance has been already summarized in [13, 14] for a similar architecture, with a custom up/down converter and reference generation system designed at LNF [15, 16]. The RF block diagram of the facility is shown in Fig. 3 where all the directional coupler, where the RF signals are sampled by the LLRF system, are highlighted. In the experimental run of February 2024, a dedicated RF stability measurement campaign was conducted to assess system performance. Initially, the RF driver amplifier was disconnected from the klystron and connected to an RF load to measure amplitude and phase jitter as functions of output power. This configuration allowed to deeply saturate the driver amplifier, a condition which does not occur during normal operation because the klystron becomes fully saturated with less than 800 W. Additionally, a scan to examine the impact of RF pulse repetition rate on RF jitter has been conducted, which showed no noticeable effect. Figure 4 summarizes the RF

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR01

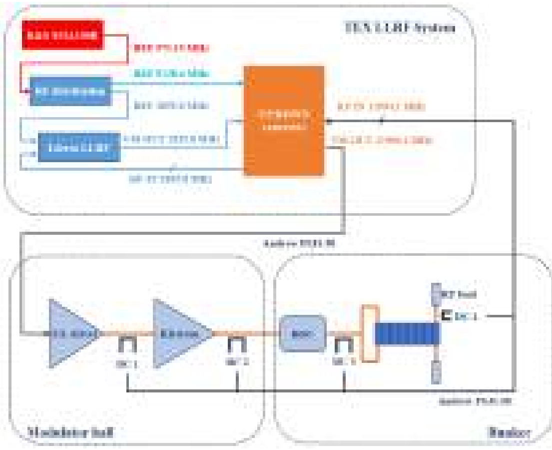

Figure 3: TEX facility RF block diagram.

driver jitter performance with 500 ns and 1 µs RF pulses. The best stability was achieved under deep saturation conditions, i.e. where the output power exceeded 1 kW. However, the amplifier reached a plateau in phase jitter already at 200 W, albeit with a value 50 % larger than the optimal one. The

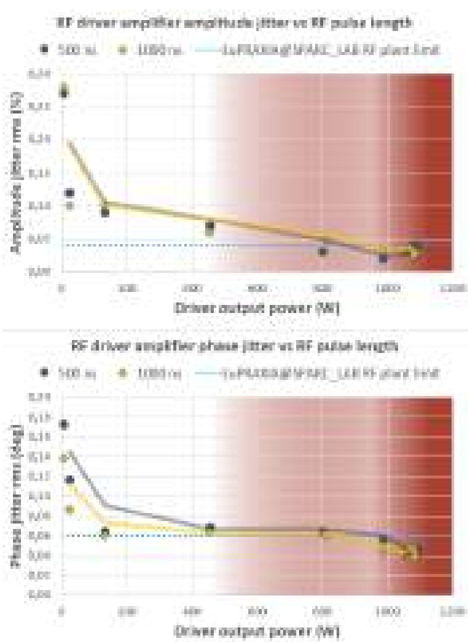

Figure 4: RF driver amplifier stability measurements for a 500 ns (blue) and 1000 ns (yellow) RF pulse. The requirement of EuPRAXIA@SPARC_LAB is shown in dashed cyan, while the saturation of the amplifier is shown in the plot background (1 dB compression at 450 W).

RF power plant was extensively tested under various conditions, including changing the high-voltage setting of the modulator to explore different saturation conditions of the klystron tube, as well as varying the RF pulse length and the klystron output power. All tests yielded consistent results, aligning with the driver amplifier analysis shown in Figure 4, and that have been summarized in Table 1.

Figure 5 shows a plot of the jitter measured with a high-voltage setpoint of 1300 V (corresponding to a video pulse of 400 kV and 290 A) and an RF pulse length of 1 µs for the three signals of interest (vector modulator output, RF driver amplifier forward power, and klystron forward power, picked up from DC1, DC2, and DC3 as indicated in Fig. 3). The figure also highlights the EuPRAXIA@SPARC_LAB limit for the RF plant stability.

Table 1: RF Phase Stability of TEX Facility

Signal	Phase jitter	Time jitter
VM OUT	0.051 ± 0.006 deg	11.9 ± 1.4 fs
Driver FWD	0.068 ± 0.008 deg	15.8 ± 1.8 fs
Klystron FWD	0.087 ± 0.014 deg	20.1 ± 3.3 fs

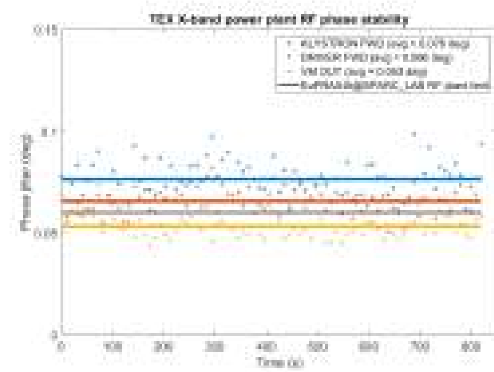

Figure 5: Phase jitter measurement at TEX facility for HV setpoint of 1300 V, 1 µs RF pulse and 16 MW klystron output power. The solid lines represent the average values, while in black the requirement of EuPRAXIA@SPARC_LAB has been reported for reference.

CONCLUSION

This paper reviews recent advancements in RF phase stabilization techniques at SPARC_LAB facility at LNF-INFN. The upgrade of the fast intra-pulse phase feedback, tested on a C-band power plant driven with a solid state modulator, achieved results at the level of the state of the art already with the first prototype. Moreover, extensive RF measurements on a X-band power plant have been carried out at TEX facility during February 2024. The results are consistent for several working points, but not yet compliant with EuPRAXIA@SPARC_LAB requirements. This could be due both to the LLRF system stability (as discussed in detail in [15, 16]) and to the non-optimal working point of the RF driver amplifier. In addition, further benefit could be gained by applying the intra-pulse feedback to the X-band power plant as well, that is foreseen for the next future.

ACKNOWLEDGEMENTS

LATINO is a project co-funded by Regione Lazio within POR-FESR 2014-2020 program.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR01

REFERENCES

[1] R. Pompili *et al.*, "Femtosecond timing-jitter between photocathode laser and ultra-short electron bunches by means of hybrid compression ", *New J. Phys*. vol. 18, p. 083033, Aug. 2016. doi:10.1088/1367-2630/18/8/083033

[2] G. Giannetti *et al.*, "Experimental and numerical characterization of timing jitter for short electron beams in a linear photo-injector", *Meas. Sci. Technol.*, vol. 35, p. 02501, Nov. 2023. doi:10.1088/1361-6501/ad099c

[3] A. Fabris, P. Delgiusto, F. Pribaz, N. Sodomaco, R. Umer, and L. Veljak, "Experience and Developments on the S-band RF Power System of the FERMI Linac", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 2856–2858. doi:10.18429/JACoW-IPAC2015-WEPMA042

[4] C. Kim *et al.*, "Review of technical achievements in PAL-XFEL", *AAPPS Bull.*, vol. 32, n. 15, 2022. doi:10.1007/s43673-022-00045-4

[5] S. Pioli *et al.*, "TEX - an X-Band Test Facility at INFN-LNF", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3406–3409. doi:10.18429/JACoW-IPAC2021-WEPAB314

[6] M. Ferrario *et al.*, "EuPRAXIA@SPARC_LAB Design study towards a compact FEL facility at LNF" *Nucl. Instrum. Meth. A*, vol. 909, pp. 134-138, 2018. doi:10.1016/j.nima.2018.01.094.

[7] L. Piersanti *et al.*, "Design and Test of a Klystron Intra-Pulse Phase Feedback System for Electron Linear Accelerators", *Photonics*, vol. 11, n. 5, p. 413, Apr. 2024. doi:10.3390/photonics11050413

[8] D. Alesini *et al.*, "EuPRAXIA@SPARC_LAB Conceptual Design Report", LNF, Frascati, Italy, Rep. INFN-18-03/LNF, May 2018.

[9] L. Sabbatini *et al.*, "The LATINO Project - An Italian Perspective on Connecting SMEs with Research Infrastructures", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2277–2279. doi:10.18429/JACoW-IPAC2019-WEZPLM1

[10] F. Cardelli *et al.*, "Status and Commissioning of the First X-Band RF Source of the TEX Facility", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 1148–1151. doi:10.18429/JACoW-IPAC2022-TUPOPT061

[11] S. Pioli *et al.*, "Control and Functional Safety Systems Design for Real-Time Conditioning of RF Structures at TEX", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 751–753. doi:10.18429/JACoW-IPAC2022-MOPOMS047

[12] F. Cardelli *et al.*, "Advancements in X-band technology at the TEX facility at INFN-LNF", presented at the IPAC'24, Nashville, TN, USA, May 2024, paper TUPR02, this conference.

[13] L. Piersanti *et al.*, "The RF System of the ELI-NP Gamma Beam Source", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 407–410. doi:10.18429/JACoW-IPAC2016-MOPMW006

[14] L. Piersanti *et al.*, "Review of the ELI-NP-GBS Low Level RF and Synchronization Systems", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2162–2165. doi:10.18429/JACoW-IPAC2018-WEPAL010

[15] L. Piersanti *et al.*, "Design of an X-Band LLRF System for TEX Test Facility at LNF-INFN", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3371–3374. doi:10.18429/JACoW-IPAC2021-WEPAB301

[16] L. Piersanti *et al.*, "Commissioning and First Results of an X-Band LLRF System for TEX Test Facility at LNF-INFN", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 876–879. doi:10.18429/JACoW-IPAC2022-TUPOST015