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Technical Note

Design and Test of a Klystron Intra-Pulse Phase Feedback System for Electron Linear Accelerators

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Abstract: Beam stability and timing jitter in modern linear accelerators are becoming increasingly important. In particular, if a magnetic or radio-frequency (RF) compression regime is employed, the beam time of arrival jitter at the end of the linac can be strictly correlated with the phase noise of the accelerating fields of the RF structure working off-crest. For this reason, since 2008, an RF fast-feedback technique, which acts within each RF pulse, has been successfully employed at LNF-INFN (Laboratori Nazionali di Frascati dell'Istituto Nazionale di Fisica Nucleare) in the SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Laser And Beam) facility on S-band (2856 MHz) klystrons powered by pulse-forming network (PFN) modulators, as reported in this paper. However, in order to meet the more stringent requirements of plasma wakefield acceleration schemes, some upgrades to this feedback system have been recently carried out. The first prototype has been experimentally tested on a C-band (5712 MHz) klystron, driven by a solid-state modulator, in order to investigate the possibility for additional improvement resulting from the inherently more stable power source. In this paper, the design, realization and the preliminary measurement results obtained at SPARC_LAB after such upgrades will be reviewed.

Keywords: low-level radio frequency; particle accelerator; feedback; free electron laser; fast electronics

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1. Introduction

The operational demands of Free Electron Laser (FEL) and plasma accelerator facilities with external injection impose stringent requirements for amplitude and phase stability of the radio-frequency (RF) accelerating fields, with particular attention to RF power plants. This becomes even more important when a magnetic or RF compression regime is employed, since the beam time of arrival jitter at the end of the linac can be strictly correlated with the phase noise of the accelerating fields of the RF structure working off-crest [1,2]. One of the main contributors to RF phase jitter in a pulsed electron linac is the high-voltage jitter of the modulator that feeds the klystron. High-voltage fluctuations are, in fact, directly converted to phase jitter by the klystron tube, and, especially for pulse forming network (PFN) modulators, this contribution can be up to hundreds of femtoseconds, even though some laboratories have optimized their design to reach a remarkable high-voltage (HV) stability of the order of 30 ppm [3,4]. Solid-state modulators, on the other hand, are inherently more stable. The state of the art of HV pulse to pulse jitter can be as low as 10 ppm, although this value is highly dependent on the particular "modulator specimen", as studied at the Paul Scherrer Institute (PSI) for the SwissFEL RF power plants [5]. However, typical applications rarely require further optimization. To contextualise our work, the state of the art for measured phase stability in pulsed RF plants worldwide is compared with the facilities at LNF-INFN (Laboratori Nazionali di Frascati dell'Istituto Nazionale di Fisica Nucleare) in Figure 1, collecting the information reported in [4–9]. The histogram is constructed exclusively from published or disseminated measurements of klystron phase jitter, considering RF plants of comparable size and peak power. The exception is the X-band, in which smaller-sized plants feeding deflecting cavities or linearizers have also been included. Although sometimes challenging to compare, due to different experimental conditions, data collection methods or post-processing, these results can guide new facilities in their RF plant design whether femtosecond-scale stability is required. The current benchmark for high-power pulsed modulators is represented by solid-state technology, which is known for its intrinsic stability compared to that of PFN modulators. However, the figure also shows results very close to the state of the art obtained with PFN modulators specifically optimized for high-voltage pulse-to-pulse stability. Such voltage variations generate a pulse-to-pulse phase change that cannot be rejected with conventional slow feedback loops, which typically counteract the environment-induced drifts of the plant on a time scale of tens of seconds. Then, if stability performance close to or even beyond the state of the art is required, fast-phase intra-pulse feedback, i.e., that which is capable of acting within a time window of about 1 µs or less, is therefore needed. The fast feedback system extracts a portion of the klystron forward power using a directional coupler. The phase of this signal is then compared to the system reference using an RF mixer. The resulting error signal is amplified, filtered, and used to directly correct the phase of the klystron seed within the same RF pulse. This correction is achieved by modulating the signal with a fast voltage-controlled phase shifter.

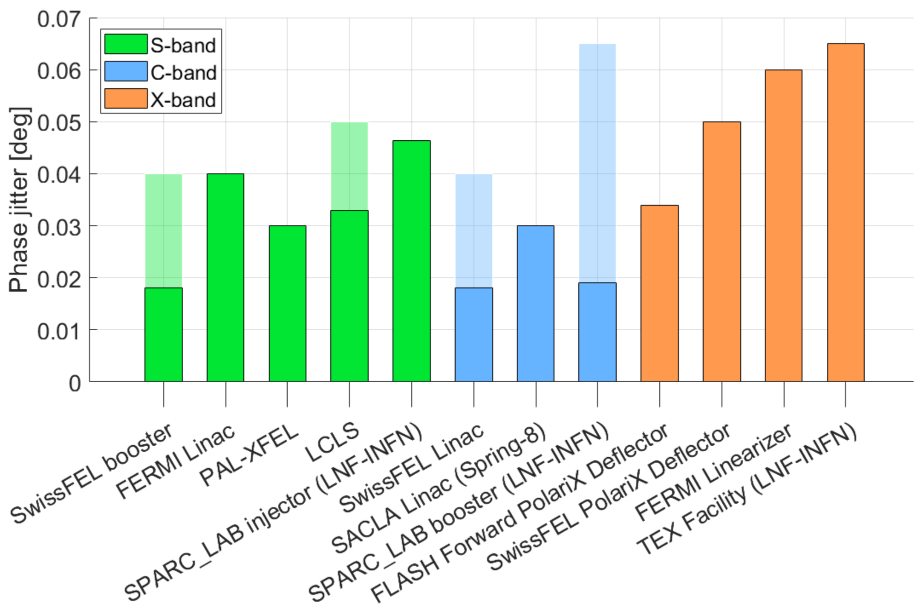


Figure 1. The state of the art for measured phase stability in pulsed RF plants worldwide is compared with the facilities at LNF-INFN. The solid fill color represents the best results published or disseminated by other laboratories, while the transparent fill color accounts for the spread between the worst- and best-case scenarios when multiple plants are available.

In view of the realization of the EuPRAXIA@SPARC_LAB (European Plasma Research Accelerator with Excellence in Applications) project [10], which, in its final configuration, 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, the call for stability of RF fields is becoming even more important. In this context, this article presents an update of the fast intra-pulse feedback system (already commissioned and in operation since 2008 at LNF-INFN for the S-band klystrons) designed, realized and experimentally tested on the solid-state C-band plant of SPARC_LAB. This choice has been made to investigate the possibility of additional stability improvement resulting from the solid-state-driven power source. If successful, the new feedback electronics will also be deployed to the S-band plants, aiming to enhance the overall RF stability of the facility. This work represents a fundamental step for both the EuPRAXIA@SPARC_LAB project, once the intra-pulse feedback design will be extended to X-band, and for any electron linac designed to utilize RF sources with very low phase noise.

The first implementation of such fast electronics, along with a presentation of the SPARC_LAB RF system, is reported in Section 2, while the system upgrade and the experimental results obtained with the first prototype are described in Sections 3 and 4, respectively. Finally, some discussions on future perspectives and system upgrades are reported in Section 5.

2. First Feedback Implementation at SPARC_LAB

2.1. SPARC_LAB Facility

The SPARC_LAB facility [11] was established in 2004 as an R&D activity aimed at producing a high-brightness e-beam for SASE-FEL (self-amplified spontaneous emission-FEL) experiments. It comprises a 150 MeV photo-injector that combines both S-band and C-band accelerating structures, an undulator for FEL radiation and a high-power (200 TW) laser FLAME (Frascati Laser for Acceleration and Multidisciplinary Experiments) for electron–photon and laser–matter interaction. Furthermore, ongoing installations include a new undulator for THz radiation and a new laser–plasma betatron radiation source. Over the last two decades, the R&D program has carried out many experiments, such as (i) conventional SASE and seeded FEL; (ii) Thomson back-scattering; (iii) THz generation; (iv) plasma wakefield acceleration (PWFA), focusing and FEL generation [12]; (v) laser interaction with matter.

SPARC_LAB RF System

The reference master oscillator (RMO) is a custom low-phase-noise oven-controlled crystal oscillator that provides coherent outputs at 2856 MHz (S-band reference), 5712 MHz (C-band reference) and 2142 MHz (for beam diagnostic signals down-conversion). Both the S-band and C-band references are amplified and distributed to the RF power plants and low-level RF (LLRF) systems. The 2856 MHz is also used to phase-lock the photocathode laser and the FLAME laser. The phase jitter of the RMO has been measured with a Rohde&Schwarz FSWP-26 phase-noise analyzer (between 10 Hz and 10 MHz from the carrier) and was found to be lower than 50 fs RMS.

The S-band RF power plants utilize PFN modulators (from Puls-PlasmaTechnik—PPT) and 45 MW pulsed klystrons from Thales (TH2128C). The C-band plant employs a solid-state modulator from ScandiNova and a 50 MW klystron from Canon (E37202). The first S-band klystron drives the RF gun and the deflecting cavity used for longitudinal beam diagnostics, while the second one feeds two SLAC-type traveling wave structures. The C-band plant serves the constant impedance high-gradient (35 MV/m) structure used as an energy booster.

The S-band LLRF system, designed and realized in 2006 by the RF group of the LNF, features a 24-channel direct conversion front-end based on custom Pulsar Microwave I/Q mixers. The base-band I/Q signals are subsequently sampled by commercial ADC cards (National Instruments, Austin, TX, USA, 5105, 60 MHz, 12 bit). The analog back-end employs connectorized RF components (trombone and electronic phase shifters for coarse and fine tuning, respectively, and variable attenuators and Binary Phase-Shift Keying for pulse compressor phase modulation). The noise floor of the front-end has been estimated to limit the phase readout to ≈50 fs. On the other hand, the C-band LLRF system, designed and realized by PSI in 2013 within the framework of the Test Infrastructure and Accelerator Research Area (TIARA) project collaboration, is a digital system. It consists of a 16-channel front-end (>80 dB isolation between channels) that down-converts the RF signals to an intermediate frequency of 39.667 MHz prior to digitization (16 bit ADC). The analog bandwidth of the front-end exceeds 30 MHz, and the system also has pulse-shaping capabilities. However, only signal detection is performed directly from the LLRF, with feedback implemented in the control system. The phase error is $<\pm 0.05$ deg and <0.1% for the amplitude. The back-end has a differential I/Q vector modulator with a bandwidth >40 MHz and an added jitter <10 fs.

Recently, the LNF was awarded regional funding of 6.1 M€ for the consolidation of SPARC_LAB facility (SABINA project [13]). The LLRF system will undergo a full upgrade with digital systems provided by Instrumentation Technologies, Solkan, Slovenia (Libera LLRF). These are temperature-stabilized, FPGA-based digital LLRF with a low noise front-end that demodulates the RF down to 44.625 MHz prior to digital conversion (14 bit, 119 MHz, 5 MHz bandwidth). The system has the ability to perform pulse-to-pulse amplitude and phase feedback on two independent channels, and the vector modulator can generate an arbitrary pulse shape from a user-defined mask (16 bit DAC, 15 MHz bandwidth). Similar systems have been realized and tested in other accelerator facilities [14]. This upgrade will overcome some of the known limitations of the actual system, primarily concerning the front-end noise floor, the temperature stabilization (to minimize drifts) and the possibility of an arbitrary pulse shape. Identical systems have already been purchased and successfully commissioned for both LNF and external projects by the LNF RF group; the measured amplitude and phase resolutions are <0.02% and <0.01 deg, respectively. These systems have also been used to perform precise measurements of the SPARC_LAB phase jitter of the S-band plants, as reported in the following paragraphs.

2.2. First Feedback Design and Implementation

The initial focus of the SPARC_LAB research line on emittance measurement, compensation, and SASE-FEL experiments allowed for a looser RF synchronization specification of less than 500 fs RMS. However, the transition to seeded FEL and RF compression scheme demanded a significant increase in RF stability requirements. Consequently, in 2008, to address this need, the first version of a fast intra-pulse phase feedback system was designed, implemented, and successfully tested at SPARC_LAB. The block diagram of the feedback system, also referred to as a "klystron loop", is illustrated in Figure 2 for the klystron number 2.

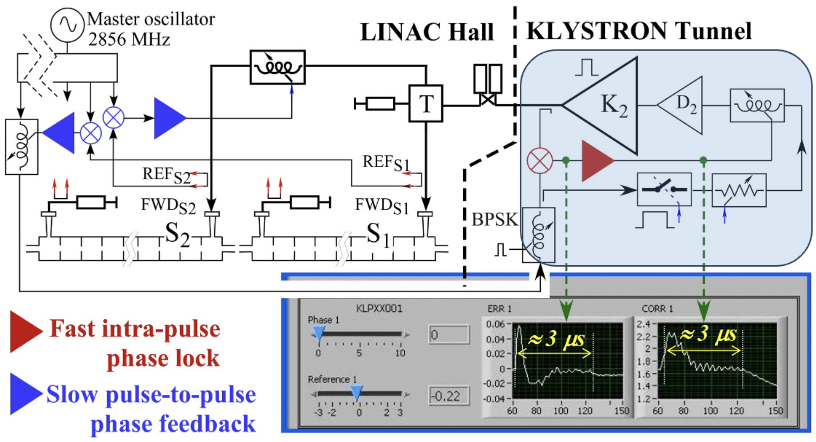


Figure 2. SPARC_LAB klystron n.2 (K2) RF system. Highlighted block diagram of the fast intra-pulse feedback that includes the solid state driver amplifier (D2) and the Binary Phase Shift Keying (BPSK), which realizes the phase jump for the pulse compressor that feeds the two accelerating sections (S1 and S2). Moreover, a screenshot of its control system with the typical phase detector and error amplifier output signals is reported at the bottom.

The klystron output, picked up by a waveguide directional coupler, is phase-compared with the LLRF drive generating an error signal fed into the loop error amplifier (depicted as a red triangle in Figure 2). Then, a fast phase-shifter (Pulsar Microwave, Clifton, NJ, USA, ST-G9-411, bandwidth ≈ 50 MHz) performs the necessary phase correction. The error amplifier comprises two cascaded current feedback operational amplifier (CLC410) stages. The bottom of Figure 2 depicts the typical error and correction signals. The feedback effectively stabilizes the phase to the nominal value in approximately 1 µs. Following comprehensive laboratory characterization, the system was successfully tested at SPARC_LAB, and the latest measurements, obtained with a low-noise receiver system, are presented in Figure 3 for 200 consecutive shots. A jitter reduction down to 0.046 deg RMS was achieved, with an overall compression of a factor exceeding four.

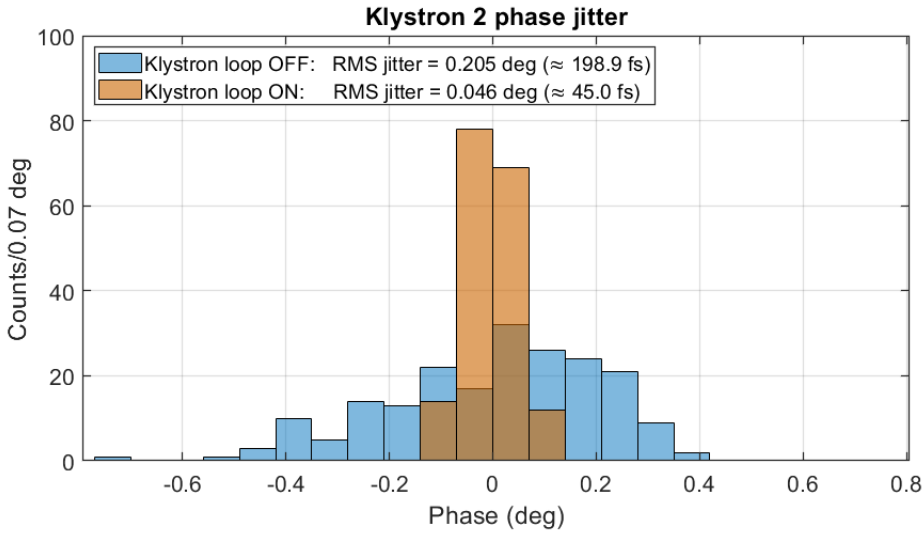


Figure 3. Recent measurement at SPARC_LAB of the S-band fast intra-pulse feedback capability with Libera LLRF front-end. The klystron phase measured with feedback off is shown in blue, whereas that with feedback on is shown in orange. There are approximatively 200 shots at 10 Hz repetition rate. A jitter reduction down to 0.046 deg RMS has been obtained, with an overall compression of a factor >4.

3. Intra-Pulse Phase Feedback Upgrade

The very good RF stability reached with the first version of the klystron loop is still not enough to meet the plasma acceleration requirements. Specifically, to achieve stable and reproducible acceleration of the witness beam, especially for experiments involving FEL radiation as planned for EuPRAXIA@SPARC_LAB, further advancements are necessary. Beam dynamics simulations utilizing the velocity-bunching RF compression scheme developed at SPARC_LAB set an upper limit on the maximum jitter of the RF stations at 0.02 deg RMS for the S-band and 0.06 deg RMS for the X-band stations. One potential solution involves replacing the old PFN modulators with new solid-state ones, significantly reducing the initial amount of jitter. However, this approach has practical drawbacks, including high cost and a significant time requirement from tender to component installation. Consequently, an upgrade of the existing plants' feedback electronics has been planned. This upgrade will specifically be implemented on the C-band station, allowing testing on the solid-state modulator available at SPARC_LAB. This testing approach, which was conducted during the experimental run with minimal interference, will provide useful insights into the achievable jitter limit with such a feedback system.

The upgrade includes modifications to (i) the phase shifter used as an actuator, which, in the first version, had insertion loss dependent on the control voltage and now operates at 5712 MHz; (ii) the operational amplifiers used in the error amp circuit, selected with a constant gain-bandwidth product of ≈200 MHz; (iii) the presence of an internal slow feedback ($G_{slow}/G_{fast} \approx 10^{-3}$) designed to maintain the phase value close to the desired one even when the RF pulse is off, reducing transients and the required phase modulation at the beginning of the RF pulse to correct the klystron phase; and finally (iv) placing the loop electronics as close to the klystron as possible. This choice minimizes the group delay introduced by coaxial cables, and has allowed us to increase the loop gain without reaching loop instability. Additionally, the remaining physical delay of the signal at the RF port of the phase detector, relative to the reference at the LO (Local Oscillator) port, has been finely compensated with a custom cable.

The objective of the klystron loop upgrade is to achieve a steady state within 100 ns. This value has been chosen to comply with the constraints imposed by the X-band accelerating structures in the EuPRAXIA@SPARC_LAB facility, which will require a much shorter RF pulse (approximatively 150 ns) from the klystron. A photograph of the new error amplifier board, its enclosure, and the entire RF chassis that was realized is presented in Figure 4. Unfortunately, the C-band phase shifter we had available in the laboratory has a 3 dB bandwidth of 2.5 MHz, so in the error amplifier transfer function, a zero at the same frequency has been added for compensation, in order to extend the overall bandwidth of the system. It is important to note that this is only a temporary measure, as the zero-pole compensation offers only a limited effect. In a future upgrade, a phase shifter with wider bandwidth could be chosen instead, to fully exploit the operational amplifiers' ability with the aim of minimizing the settling time of the loop.

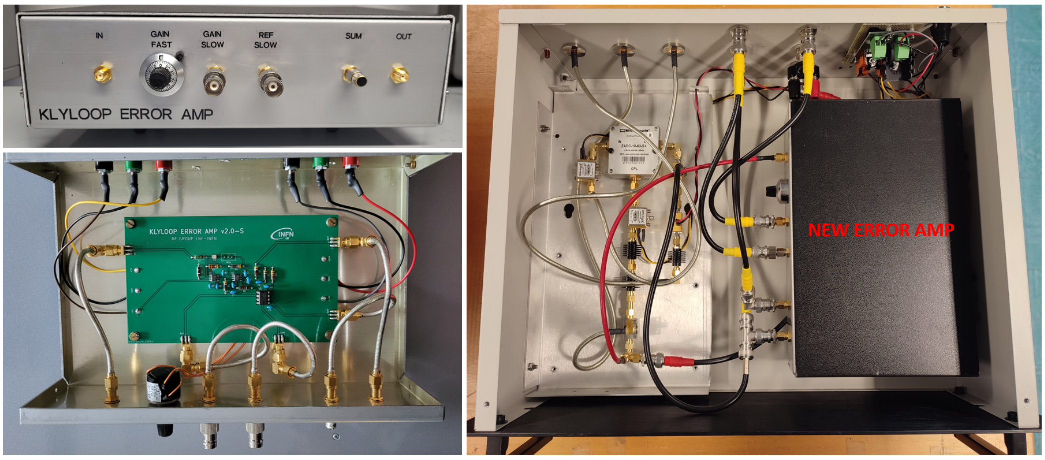


Figure 4. New error amplifier board (**left**) and the new RF chassis (**right**) realized at INFN-LNF laboratories for the klystron loop upgrade.

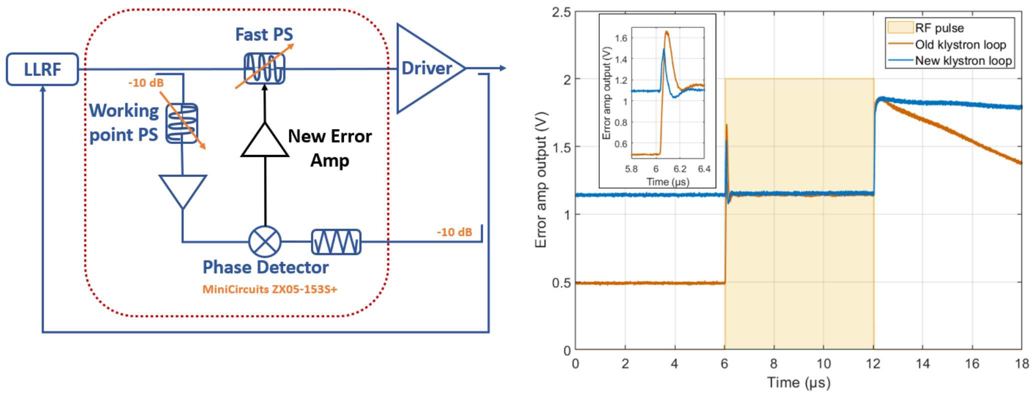
4. Preliminary Measurement Results

In order to verify the functionality of the new klystron loop, detailed laboratory tests have been conducted. A picture illustrating the laboratory experimental setup and the operational principle of the slow feedback is presented in Figure 5a,b. Following the successful completion of this preliminary phase, the new feedback system prototype was installed at SPARC_LAB. RF measurements were conducted to assess the feedback performance. The experimental setup essentially mirrors the one depicted in Figure 5a, with the C-band klystron positioned after the driver amplifier.

A measurement campaign has been carried out with such prototype and the results are reported in Table 1 and Figure 6. A remarkable reduction in the C-band klystron phase jitter of a factor exceeding 3 from 0.065 deg down to 0.019 deg (corresponding to 9.2 fs) has been observed.

Table 1. Preliminary measurement results obtained at SPARC_LAB on the C-band power plant with the new error amplifier prototype

Signal: Klystron 3 FWD	Jitter (deg)	Jitter (fs)
klystron loop OFF	0.065	31.6
klystron loop ON	0.019	9.2



(**a**) Klystron loop experimental setup (**b**) Slow feedback functionality

Figure 5. (**a**) Block diagram of the laboratory experimental setup for the klystron loop bench test, and (**b**) 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. It can be clearly seen that the loop also allows us to reach a phase value close to the desired one when the RF pulse is off. This minimizes the transient and the overall phase modulation required to reach the steady state, as shown in the waveform zoom.

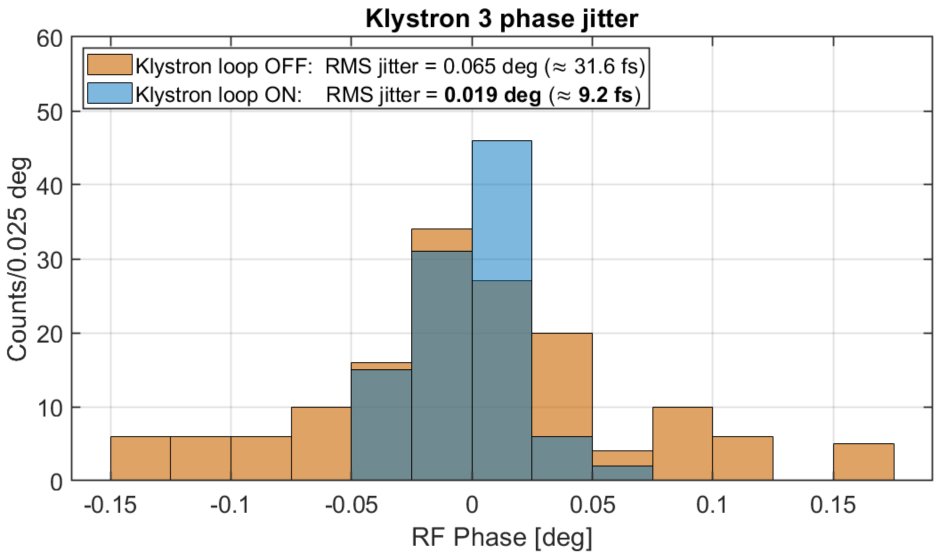


Figure 6. Intra-pulse feedback prototype measurement results at SPARC_LAB facility on the C-band power plant. In bold the results obtained with the new feedback on.

5. Discussion and Future Research Direction

While the presented results on the C-band klystron phase stabilization are promising and align with the state of the art, some key areas require further investigation to try to push the performance of the feedback system even further. Firstly, evaluating alternative phase shifters better suited to high-speed operation could enable faster loop response convergence. This, in turn, could reduce the current settling time of the loop, which is currently estimated to be 200 ns. Moreover, the effect of electromagnetic and grounding noise in the klystron gallery needs to be quantified and minimized. This has been observed to strongly affect the measurement repeatability and the stabilization effectiveness. In particular, the best results presented in this paper were obtained when the S-band power plants were switched off. Finally, testing the same error amplifier architecture with the S-band power plants could provide valuable insights into the effectiveness of the feedback system in mitigating phase jitter in PFN-powered units. These tests are scheduled for the coming months, following the facility upgrade and machine recommissioning. Additionally, the obtained results hold particular importance in the context of the EuPRAXIA@SPARC_LAB project, where the RF stability requirements are expected to be even more challenging. The successful deployment of the system at SPARC_LAB will directly benefit the new S-band injector, while redesigned intra-pulse feedback will also be extended to X-band plants in the near future.

6. Conclusions

In this paper, we have presented the design, bench tests, and preliminary results of the new fast intra-pulse phase feedback prototype at the SPARC_LAB facility. Remarkable results have been observed, leading to a reduction in RF phase jitter on the C-band klystron forward signal from 0.065 deg RMS to 0.019 deg RMS. Although the results are very promising, there are still open points that need to be addressed to optimize the experimental setup in the future. These include considerations such as selecting a phase shifter with a larger bandwidth and addressing electromagnetic and grounding noise in the klystron gallery, both of which affect measurement stability. Recognizing the importance of this activity, a comprehensive R&D program is planned to optimize and implement such a feedback system, extending its application to S-band klystrons. This program is scheduled for the coming months at LNF, highlighting the commitment to refining and deploying the feedback system across multiple klystron configurations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/photonics11050413/s1.

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