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EVALUATION OF AN X-BAND LLRF PROTOTYPE FOR THE EUPRAXIA@SPARC_LAB LINAC*

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Abstract

EuPRAXIA, the "European Plasma Research Accelerator with eXcellence In Applications," represents the next generation of free-electron lasers (FEL). It aims to develop a compact, cost-efficient particle accelerator using innovative wake-field accelerator technology. High-energy physics often demands higher acceleration voltages, and X-band technology offers high gradients in compact structures. The EuPRAXIA@SPARC_LAB LINAC injector, featuring an S-band RF gun, four S-band structures, and sixteen X-band structures, achieves a maximum beam energy of 1 GeV. For femtosecond-level synchronization and stability, Low-Level Radio Frequency (LLRF) systems are essential. However, commercial X-band LLRF solutions are unavailable. This project, in context of the EuPRAXIA - Doctoral Network, develops an X-band LLRF prototype tailored to meet the EuPRAXIA@SPARC_LAB LINAC's stringent requirements. After validation on a testbench, the prototype will enable industrial production and commercialization. This paper presents the Front-End, Back-End analysis, and further evaluation of the prototype.

INTRODUCTION

The EuPRAXIA project represents a major step forward in the development of compact and high-brightness electron beam facilities based on plasma acceleration [1]. As a key pillar of the broader EuPRAXIA initiative, the EuPRAXIA@SPARC_LAB implementation at INFN-LNF aims to provide as a user-ready Free Electron Laser (FEL) facility powered by an advanced plasma-based accelerator. The accelerator employs a hybrid layout consisting of a high-performance RF linac injector—comprising one S-band RF gun, four S-band accelerating structures, and sixteen X-band structures—followed by a plasma module, as shown in Fig. 1. This configuration enables ultra-high accelerating gradients, making the system one of the most compact Free Electron Laser (FEL) demonstrators in its class.

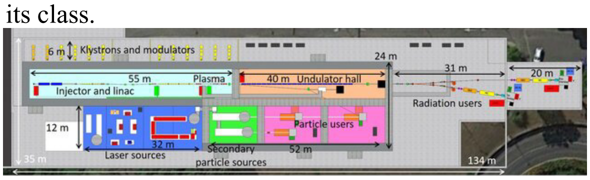

Figure 1: EuPRAXIA@SPARC_LAB machine layout [2].

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Compared to conventional S-band systems, X-band technology enables much higher accelerating gradients often exceeding 60 MV/m, allowing significantly shorter LINAC sections and a more compact accelerator layout, which is ideal for facilities like EuPRAXIA@SPARC LAB. However, the higher operating frequency introduces increased sensitivity to timing jitter and thermal fluctuations. To address these challenges and fully exploit the advantages of X-band technology, a critical subsystem which is foreseen in this project is the X-band Low-Level RF (LLRF) system. The LLRF system ensures tight phase and amplitude stability, actively compensates thermal drifts, and incorporates fast feedback and feedforward control loops to maintain reproducible beam conditions. These features are essential for achieving the stability and precision required in beam-driven plasma acceleration and FEL operation.

This paper presents the development and validation of the X-band Low-Level RF (LLRF) prototype carried out at Instrumentation Technologies, Slovenia, as part of the EuPRAXIA Doctoral Network. It details the system design specifications, conceptual block diagram, and laboratory measurement setup, followed by an in-depth analysis of amplitude and phase stability results achived in the laboratory, thus demonstrating the system's ability to meet the stringent performance requirements.

Design Specifications

The below Table 1 summarizes the main design specifications and performance targets for the development of the X-band LLRF prototype. The system is designed to operate in pulsed mode at 11.9942 GHz with a nominal RF pulse length of 1.55 µs and supports RF pulse repetition rates of at least 400 Hz. To meet the demanding stability requirements of this X-band LINACs, the system should comply with strict limits on pulse-to-pulse amplitude and phase noise $\leq 0.015\%$ RMS and $\leq 0.015°$ RMS, respectively across both the front-end and back-end signal paths. With high-speed sampling ADCs (>230 MS/s), fast back-end response (< 20 ns), and robust LO feedthrough suppression (< –40 dBc), the prototype LLRF is equipped to deliver the precision and performance stability needed for future integration. The architecture includes two RF input channels to enable front-end phase evaluation against a reference, and one output channel for back-end drive signal generation.

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Table 1: EuPRAXIA LLRF Prototype Requirements

Parameter	Desired Value
Mode of operation	Pulsed
LLRF Frequency	11.9942 GHz
MO input level	0 dBm
Nominal Pulse length	1.55µs
Averaging window	final 0.15 µs of the RF pulse
Back-end risetime	< 20 ns
Back-end output level	> +10 dBm
Front-end BW	> 20 MHz
Front-end max. input level	+10 dBm
Sampling rate	>230 MHz
RF pulse max. repetition rate	≥ 400 Hz
Performance evaluation power range (from full scale)	3 dB
Front-End pulse-to-pulse detectable amplitude noise (400 pulses)	≤ 0.015% RMS
Front-End pulse-to-pulse detectable phase noise (400 pulses)	≤ 0.015° RMS
Back-end pulse-to-pulse added amplitude noise (400 pulses)	≤ 0.015% RMS
Back-end pulse-to-pulse added phase noise (400 pulses)	≤ 0.015° RMS
Num. RF input channels	2
Num. RF output channels	1
VM output spurious components	< -40 dBc
Mode of Operation	Open Loop only

SYSTEM DESIGN OVERVIEW

Figure 2 shows the conceptual block diagram of the X-band LLRF prototype, based on a single-stage down-conversion and double-stage up-conversion architecture able to support open-loop operation [3]. The system consists of separate front-end and back-end subsystems. A 11.9942 GHz master oscillator provides the reference signal, and a dedicated local oscillator generation module provides the 250 MHz ADC clock, a 12 GHz LO for down-conversion (X-Band LO), a 9 GHz LO for final up-conversion, and a 3 GHz+IF signal (LO-S) for the IQ modulator.

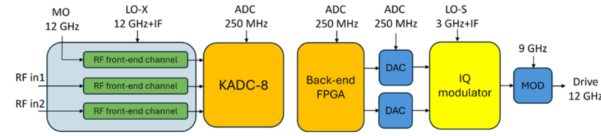

Figure 2: Prototype Architecture.

Two RF input signals are processed in parallel by front-end channels, each performing amplification, filtering, and down-conversion to IF using the X-Band LO signals. The resulting signals are digitized by 250MS/s ADCs and provided to the FPGA for data acquisition and offline processing. Operating in open loop, the system uses DACs to generate defined amplitude and phase patterns, which are modulated using an IQ modulator and up-converted to the intermediate drive 2.99855 GHz signal and then finally to 11.9942 GHz drive signal using a 9 GHz LO signal.

PROTOTYPE SETUP AND MEASUREMENTS

The measurement setup shown in Fig. 3, designed for X-band LLRF signal acquisition and generation, is divided into two main sections as previously described. The front-end setup employs a 4-way splitter to distribute an 11.9942 GHz reference signal from a signal generator to both the LO and ADC signal synthesis blocks, as well as to two RF channels. Here the two RF signals are down-converted to IF and digitized using 250 MSps ADCs connected to an FPGA. A critical aspect of this configuration is the signal integrity across both channels, which directly impacts the accuracy of phase noise measurements.

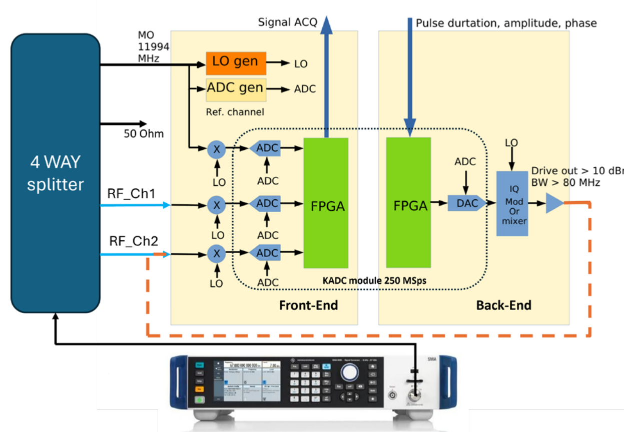

Figure 3: Prototype setup.

The back-end setup uses an FPGA to generate pulsed signals with controlled duration, amplitude, and phase. These signals are converted to analog, modulated, and up-converted to the final X-band drive signal. The resulting RF output exceeds 10 dBm, with a bandwidth greater than 80 MHz, and is looped back into one of the front-end RF channels. A critical aspect of the setup is ensuring consistent pulse shaping and synchronization. The loopback configuration enables direct evaluation of the amplitude and phase noise introduced by the back-end by comparing

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the generated and acquired signals, thereby ensuring accurate validation of back-end performance.

Figure 4 illustrates the front & rear panel of the X-band LLRF prototype. The RF components are housed in a 19” 3U aluminium chassis with a regulated power supply. The digital Libera LLRF platform [4] is also shown, which contains the 250 MHz clock distribution module, as well as the ADC and DAC modules.

Figure 4: Prototype enclosure in Chassis & Digital LLRF.

RESULTS

This section presents the experimental results validating the performance of the developed X-band LLRF prototype in terms of amplitude and phase stability. Below, Fig. 5 and Fig. 6 show the front-end amplitude and phase noise measurements, respectively. These were acquired over 400 pulses, each with a duration of 1.55 µs. The data was processed pulse-by-pulse with the final 150 ns of each pulse. The amplitude RMS noise was 0.0104% for Channel 1 and 0.0094% for Channel 2, both well below the LLRF requirements. The corresponding histograms show Gaussian-distributed variations. Similarly, the front-end phase jitter between the channels is measured as 0.0063° RMS.

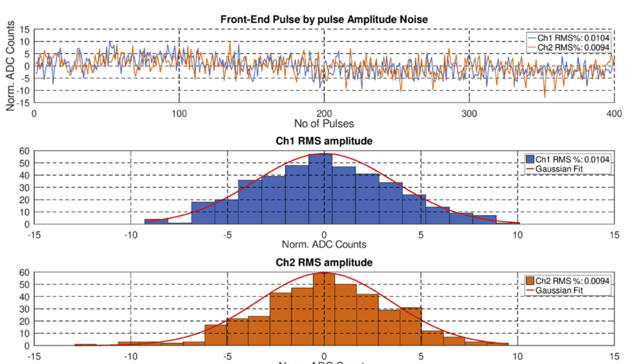

Figure 5: Front-End Pulse by Pulse Amplitude noise.

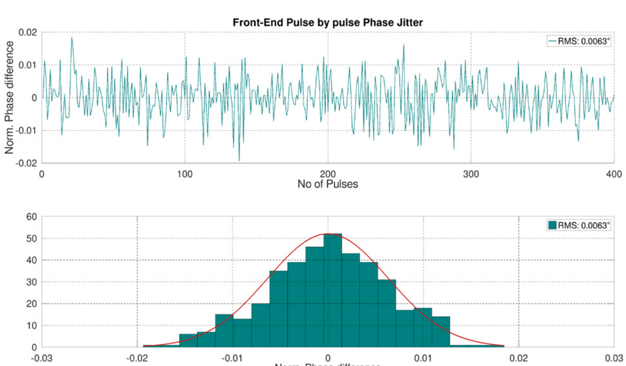

Figure 6: Front-End Pulse by Pulse Phase Jitter.

The back-end analysis was conducted in the equivalent manner as of the front-end part but on the output pulsed X-band drive signal. From the results as shown in below Fig. 7 and Fig. 8, the back-end added amplitude noise was 0.011% RMS, and the back-end added phase noise was 0.008° RMS, corresponding to a timing jitter of 1.95 fs. Histogram measurements with gaussian curve fit are presented to characterize the distribution and evaluate the quality of the results.

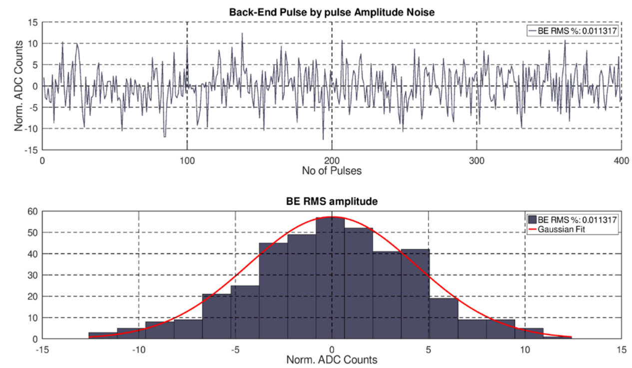

Figure 7: Back-End Pulse by Pulse Amplitude noise.

Figure 8: Back-End Pulse by Pulse Phase Jitter.

CONCLUSION

This paper presented the development and evaluation of an X-band LLRF prototype designed to meet the requirements of the EuPRAXIA@SPARC_LAB project. The prototype demonstrated excellent amplitude and phase stability, with front-end noise levels of 0.0104% and 0.0094% RMS amplitude, and 0.0063° RMS phase jitter. The back-end achieved 0.011% RMS amplitude noise and 0.008° RMS phase jitter, corresponding to a timing jitter of 1.95 fs. These results meet or surpass the stringent stability requirements of the application, validating the system's architecture and signal integrity. With the prototype successfully meeting performance targets in the lab, it is now ready for testing on a real X-band test bench facility at the TEX facility located at INFN-LNF, Frascati, Italy.

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