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Commissioning and first results of an x-band LLRF system for TEX test facility at LNF-INFN

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Abstract. In the framework of LATINO project (Laboratory in Advanced Technologies for INnOvation) funded by Lazio regional government, the commissioning of the TEst stand for X-band (TEX) facility has started in 2021 at Frascati National Laboratories of INFN. Born as a collaboration with CERN to test high gradient accelerating structures, during 2022 TEX aims at feeding the first EuPRAXIA@SPARC_LAB X-band structure prototype. During 2021 the commissioning has been successfully carried out up to 48 MW. The power unit is driven by an X-band low level RF system, that employs a commercial S-band (2.856 GHz) Libera digital LLRF (manufactured by Instrumentation Technologies), with an up/down conversion stage and a reference generation and distribution system able to produce coherent frequencies for the American S-band and European X-band (11.994 GHz), both designed and realized at LNF. The performance of the system, with a particular focus on amplitude and phase resolution, together with klystron and driver amplifier jitter measurements, will be reviewed in this paper. Moreover, considerations on its suitability and main limitations in view of EuPRAXIA@SPARC_LAB project will be discussed.

1. Introduction

The TEX facility [1] is one of the pillars of the LATINO project [2], funded by Lazio regional government, that aims to provide companies and the scientific community with the advanced technologies and skills developed in the field of particle accelerators for research, medical and industrial applications. Its commissioning has started in November 2021 at INFN National Laboratories of Frascati with the Site Acceptance Test (SAT in the following) of the RF power unit [3]. During these preliminary tests also the LLRF system has been commissioned, showing some promising results, but also highlighting some critical aspects concerning, for instance, sample rate, front-end and back-end bandwidth, which are particularly important for a future LLRF system development for an X-band driven linac.

2. TEX test facility

The TEX facility main goal is to test at high power X-band RF components at LNF. Waveguide devices and accelerating structures could be conditioned at this frequency in the facility, which is supplied by a VKX8311A 50 MW, 1.5 μs klystron from CPI LLC (USA), and a K400 450 kV solid state modulator from Scandinova (Sweden). The repetition rate will be at least 50 Hz. A new control room has been realized and equipped, and a concrete shielded bunker has been built to host the structures under test. A Memorandum of Understanding has been also signed with CERN, to profit from the well established experience on X-band technology acquired with the operation of the XBOX test stands. In fact, the test-facility will be also used to test and condition CLIC structures. TEX will be also an R&D and test facility for X-band RF components, LLRF systems, beam diagnostics, vacuum technologies and control system in view of INFN future accelerator EuPRAXIA@SPARC_LAB [4, 5] that will be built at LNF. This project foresees in fact the construction of a X-band linac booster up to 1 GeV, working with a target accelerating gradient of 60 MV/m.

A sketch of the TEX area is reported in figure 1, where the modulator cage, the bunker and the waveguide network CAD design is reported.

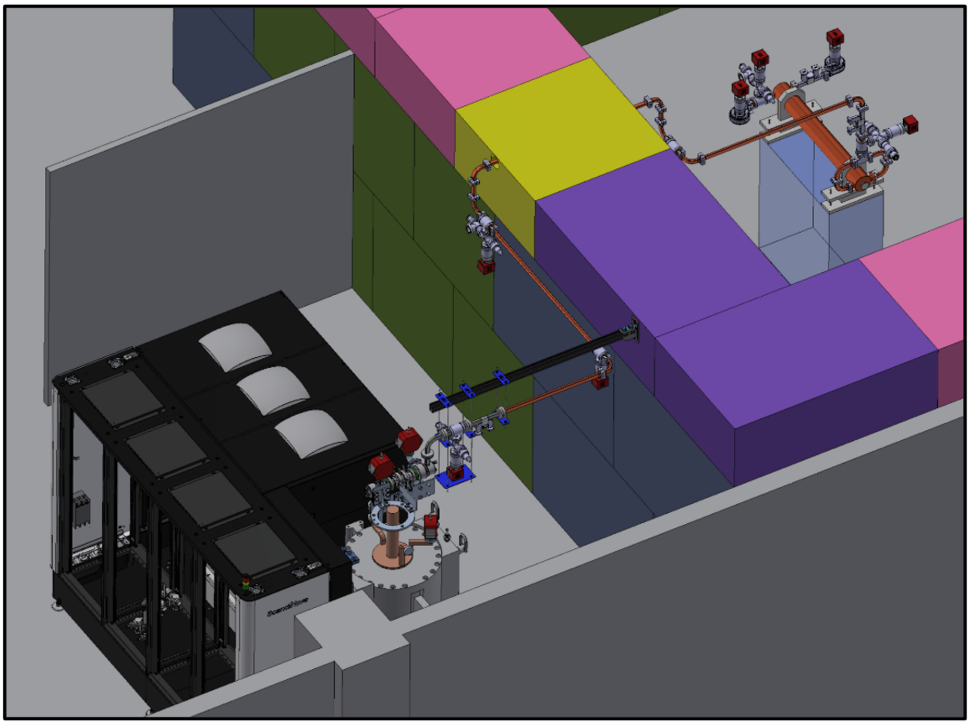

Figure 1. 3D CAD drawing of the TEX facility experimental area.

The SAT of the RF power unit took place in November 2021, once the building air conditioning and civil engineering works have been completed. The entire waveguide network is now in place up to the final RF splitter right before the accelerating structure input coupler (where two 25 MW RF loads have been connected in parallel for the high power tests instead). Using this RF layout, it was possible to reach 48 MW, with a pulse length of 150 ns at 50 Hz repetition rate during the SAT. In figure 2 is shown the waveguide network outside (left) and inside (right) the bunker.

To ensure a safe and repeatable accelerating structure test, aiming to reach the nominal accelerating gradient minimizing the operation time, a complex automatic conditioning/interlock algorithm has been foreseen, implemented and preliminarily tested during the modulator SAT [6]. In its final version, it will include also an online measurement of the produced dark current and of the breakdown rate, to safely guide the conditioning process. An EPICS based Telegram integration has been also deployed for the alarms handling of the facility [7].

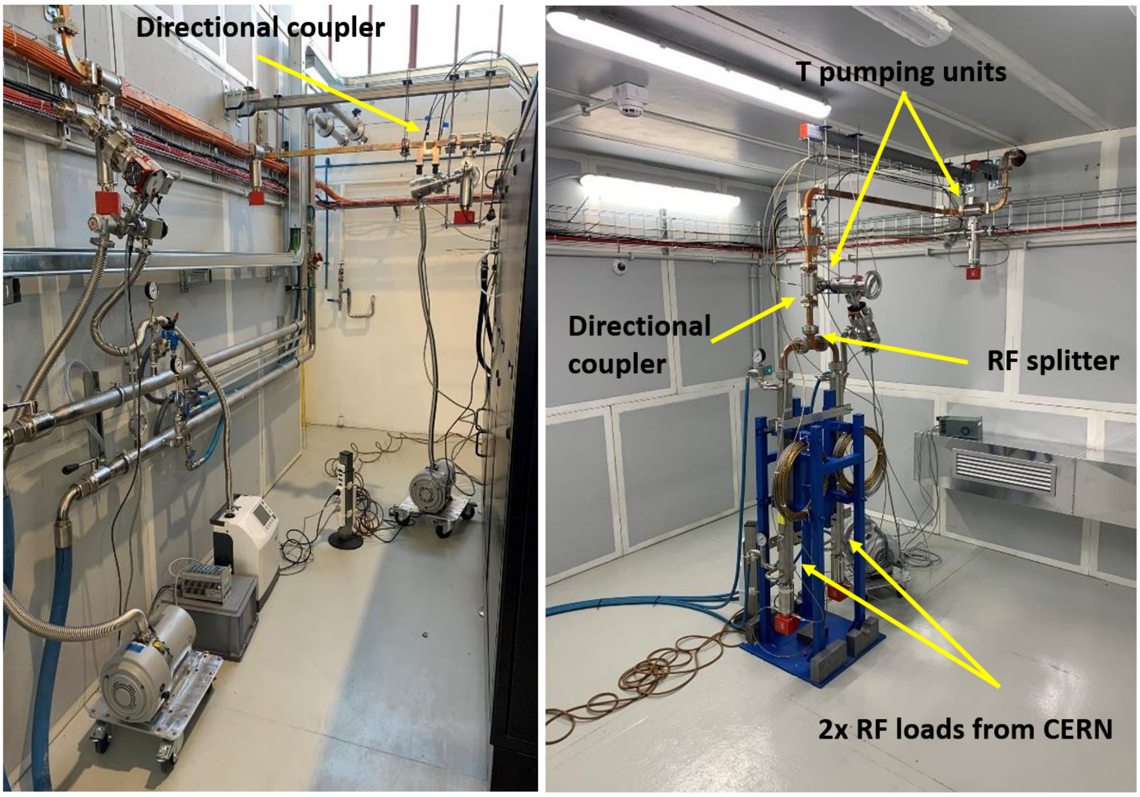

Figure 2. Pictures of the waveguide network in the klystron area (left) and inside the bunker (right).

3. LLRF system commissioning

A block diagram of the whole RF layout including the BOC pulse compressor (that will allow the simultaneous conditioning of two structures in parallel, and will be installed in a second phase) is shown in figure 3 with a particular emphasis on the LLRF system and all the RF signals picked-up for diagnostics and feedback.

A detailed description of the development of the TEX X-band LLRF system is reported in [8]. The system RF source is an ultra low phase noise Rohde&Schwarz synthesizer (SMA100B). The core of the system is based on a commercial S-band (2.856 GHz) Libera LLRF (purchased from Instrumentation Technologies, and whose performance has been already reviewed in [9, 10] for a similar architecture). In addition, a custom up/down converter and reference generation stages, that translate the carrier frequency to the European X-band (11.994 GHz) and viceversa, have been both developed at LNF. It has been installed and commissioned in Fall 2021 prior to the modulator SAT. The LLRF system is hosted in the rack room adjacent the control room. A picture of the Low-Level RF rack is shown in figure 4

As visible from the picture, in addition to the up/down converter and the reference generation some ancillary systems have been also developed, in particular: (i) a splitter stage for klystron forward and reverse power signals, which are needed by the RF mask digitizer (12-bit, 3.2 GS/s Wavecatcher [11]) employed for pulse to pulse breakdown detection [12, 13]; (ii) a trigger and interlock distribution, to safely inhibit the RF pulses generation whenever the machine protection system detects a possible threat.

The RF signals picked-up by the directional couplers are routed to the LLRF system front-end by means of Andrew FSJ1-50 1/4 inch phase stable cables. Even though the phase stability

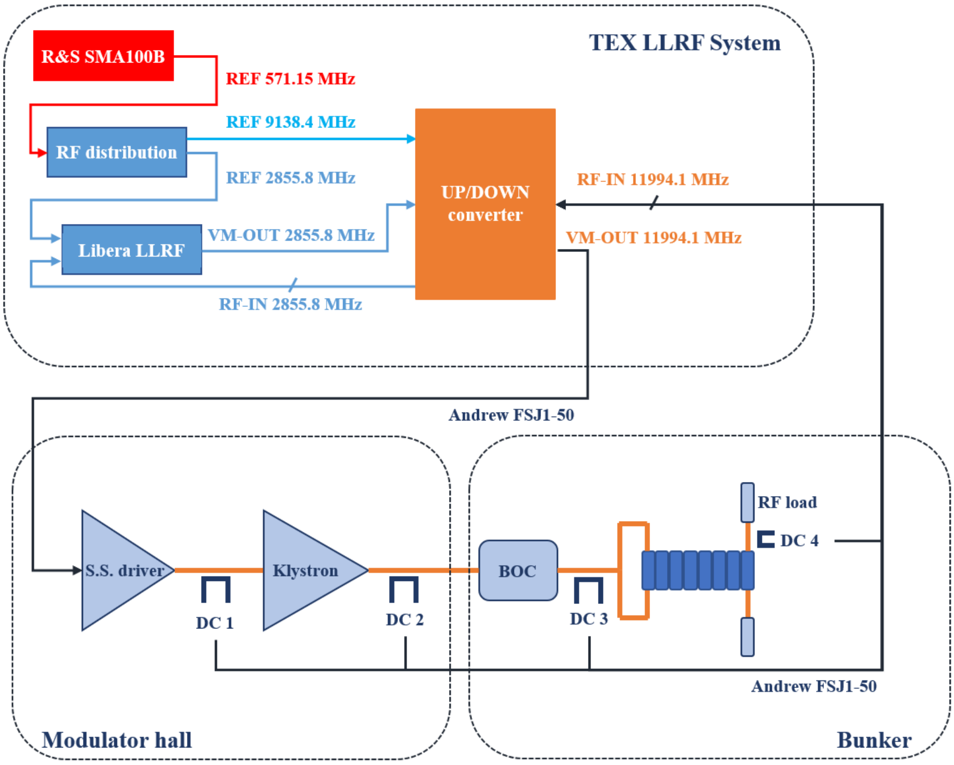

Figure 3. TEX RF system block diagram. It includes also the BOC pulse compressor that will be added in a second phase.

Figure 4. TEX LLRF rack.

Table 1. RF jitters preliminary measurement.

	Amp. jitter	Phase jitter	Time jitter
KLY FWD	0.04 %	0.0894 deg	20.7 fs

requirement is not strictly necessary in a test facility, i.e. where no beam is going to be accelerated, we have chosen such cables to test their performance (e.g. in terms of long term drifts) also in view of the EuPRAXIASPARC_LAB TDR.

During the SAT, signals from the DC1 and DC2 have been acquired and all the LLRF system functionalities have been successfully tested. Some preliminary measurements have been carried out aiming at characterizing the amplitude and phase jitter on the klystron output power, which is one of the most important parameters to qualify the stability of the power source. In figure 5 the outcome for 20 MW, 300 ns pulse amplitude (left) and phase (right) stability measurements are shown, while table 1 summarizes the results. Very promising jitter values have been obtained: 0.04 % and 20.7 fs rms for amplitude and phase respectively. These performance are compatible with state of the art solid state power sources, and represent a strong groundwork for the future X-band linac facility EuPRAXIASPARC_LAB.

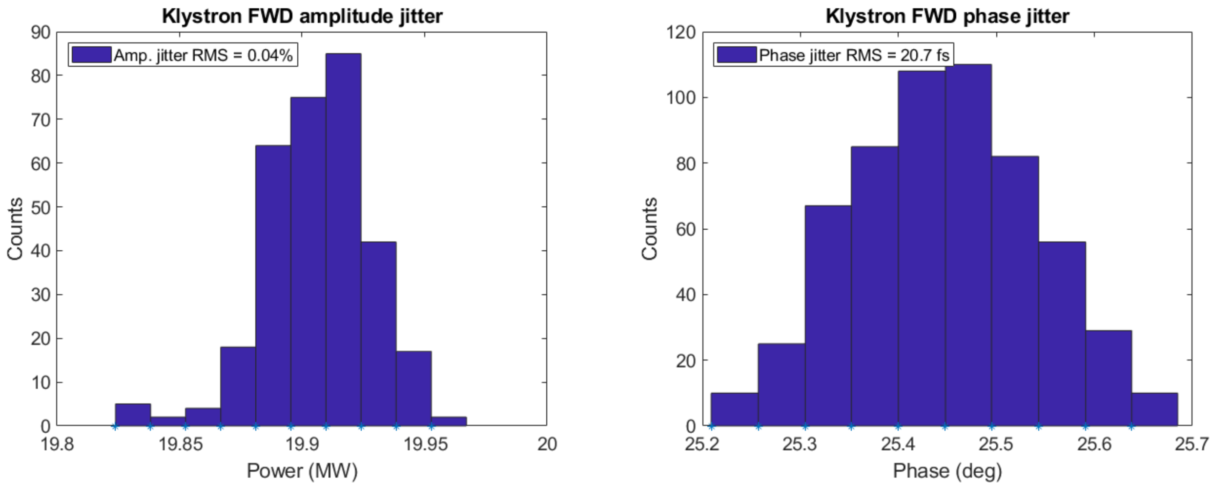

Figure 5. Measured amplitude and phase jitter of klystron output forward power. The measurements refer to 20 MW, 300 ns at 50 Hz repetition rate RF pulses.

As soon as the facility will start its experimental activity, an extensive measurement campaign will be carried out to confirm and optimize these results at full power (maximizing the signal dynamics on the front-end), to identify all the phase jitter contributions (LLRF, driver, klystron) and to evaluate the Libera LLRF noise floor.

The LLRF system reviewed in this paper, certainly suitable for a test stand, it does not seem the optimal choice for an X-band based linac for various reasons. First of all, the high conversion loss ($\approx$ 14 dB) of the down-converter stage limits the dynamic range of the front-end. In fact, even if high LO power RF mixers have been employed, the maximum RF level at the LLRF front-end is 6 dBm, while the Libera LLRF could accept signals up to 10 dBm. Then, considering that the filling time of X-band structures usually ranges between 150 ns and 200 ns, the available measurement window of 8.6 μs results too wide and the sampling frequency too low (one ADC sample every 8.4 ns). This, together with a back-end and front-end bandwidth respectively of 16 MHz and 5 MHz, represents a major limitation with such short pulses, especially if fast pulse modulations are required.

4. Conclusions

In Fall 2021 the LLRF system of the TEX facility has been successfully commissioned and the first RF pulses have been delivered to the RF loads to condition the waveguide network and to test the RF power unit during the modulator SAT. A final power of 48 MW, 150 ns at 50 Hz repetition rate has been reached before the end of the SAT. Some preliminary performance of the X-band LLRF system have been evaluated. Promising results have been obtained, with a measured amplitude and phase jitter of the klystron forward output power of 0.04 % and 20.7 fs respectively. As soon as the facility will start its experimental activity, more detailed tests on the LLRF system will be carried out.

Acknowledgments

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