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DESIGN 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, a TEst stand for X-band (TEX) is being commissioned at Frascati National Laboratories (LNF) of INFN. TEX is born as a collaboration with CERN, aimed at carrying out high power tests of X-band accelerating structure prototypes and waveguide components, and it is of paramount importance in view of the construction of EuPRAXIA@SPARC_LAB facility at LNF. In order to generate, manipulate and measure the RF pulses needed to feed the RF power unit (solid state ScandiNova K400 modulator, CPI 50 MW 50 Hz klystron) an X-band low level RF system has been developed, making use of a commercial S-band (2.856 GHz) Libera digital LLRF (manufactured by Instrumentation Technologies) with a newly designed up/down conversion stage and a reference generation/distribution system, which is able to produce coherent reference frequencies for the American S-band (2.856 GHz) and European X-band (11.994 GHz). In this paper the main features of such systems will be reviewed together with preliminary laboratory measurement results.

INTRODUCTION

The TEX facility [1] is going to be commissioned at INFN National Laboratories of Frascati. The facility is funded by Lazio regional government within a wider R&D project, called LATINO [2], 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. Radiofrequency, vacuum, thermal treatments, magnetic and mechanical integration laboratories are being realized in a dedicated and renewed building at LNF and will be available to external users.

The RF lab, in particular, can suit users with time domain measurements up to 20 GHz and frequency domain up to 110 GHz. Moreover, exploiting the unique features of the TEX facility, a pulsed high power (50 MW, 1.5 μs) RF source will be available at 11.994 GHz.

TEX TEST FACILITY

TEX facility at LNF aims to test at high power X-band RF components. Waveguide devices as well as accelerating structures at this frequency could be evaluated in the facility exploiting the power provided by a VKX8311A 50 MW, 1.5 μs klystron from CPI LLC (USA), supplied by 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 devices under test. A Memorandum of Understanding has been also signed with CERN, to profit from the well established experience on X-band technology gained with the operation of the three XBOX test stands. A drawing of the TEX area is reported in Fig. 1, while Fig. 2 shows on the left a picture of the building (where the control room, the klystron area and the RF bunker can be identified), and on the right the RF power station in its final position. Modulator site acceptance test will take place in Fall 2021, once the building air conditioning and civil engineering works will be completed.

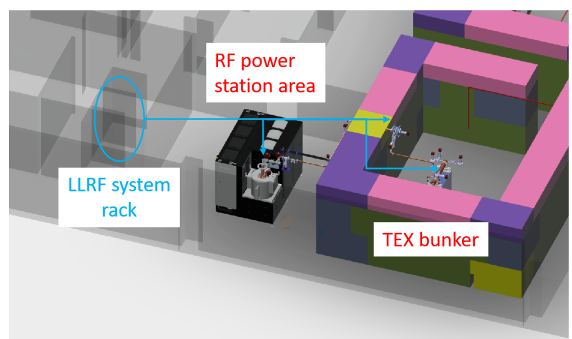

Figure 1: Drawing of the TEX facility area.

Figure 2: Pictures of the TEX control room, klystron area and bunker (left) and RF power station (right).

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, and an online measurement of the produced dark current and of the break-

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down rate will be available to guide the conditioning process. It is worth to mention that a BOC type RF pulse compressor (designed at LNF) will be installed in the next future in the waveguide network, both to increase the available RF power for the structures and components under test, and to allow the simultaneous conditioning of two accelerating sections in parallel.

TEX test facility represents also a fundamental milestone towards the future INFN accelerator project (EuPRAXIA@SPARC_LAB) [3, 4], that foresees the construction of a X-band linac booster up to 1 GeV, working with a target accelerating gradient of 60 MV/m.

LLRF SYSTEM

Due to LATINO short deadline and the lack of off-the-shelf X-band LLRF systems available on the market, a commercial S-band system (Libera LLRF, manufactured by Instrumentation Technologies, whose features and performance have been already reviewed in [5, 6] for a similar architecture) has been adapted to work at 11.994 GHz. To this purpose, the LNF RF group has developed: (i) a reference generation and distribution system able to produce coherent 2.856 GHz S-band and 11.994 GHz X-band references; (ii) an X-band up/down converter; (iii) two custom designed cavity band-pass filters to suppress the signal harmonics and the inter-modulation products in the 9.138 GHz reference and the up-converted vector modulator output, respectively. A block diagram of the complete LLRF system is shown in Fig. 3.

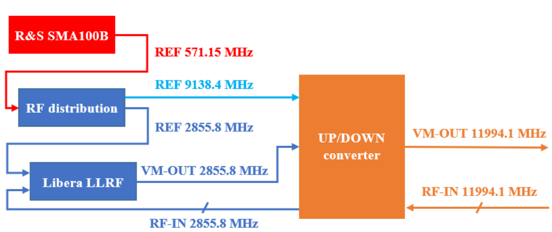

Figure 3: Block diagram of TEX LLRF system.

Reference Generation and Distribution System

A 571.15 MHz continuous sine wave, sub-harmonic of both S-band and X-band references, is generated by means of a frequency synthesizer (Rohde&Schwarz SMA100B) and is used as seed for the reference generation and distribution system. This module generates three outputs at 5·RF = 2.855 75 GHz (one is needed by Libera LLRF, the rest are used for base-band demodulation of klystron forward and reverse signals for machine protection system) and one at 16·RF = 9.138 GHz (that feeds the up/down converter). In order to drive the down-converter mixers with the appropriate power level, a narrow-band 8 W RF solid state amplifier (Microwave Amplifier AM53-06-007-RB) has been employed, producing a 38 dBm reference that is distributed to the up/down conversion mixers. Before the final amplification stage, a custom designed cavity filter, centered at 9.138 GHz, is used to cancel the harmonics generated by frequency multiplication and signal amplification.

Up-Down Converter

In order to down-convert the 11.994 GHz RF signals of the facility to the S-band frequency, an 8 channels front-end has been designed. To fully exploit the Libera LLRF front-end capabilities (13 available input channels), the number of RF inputs of the up/down converter can be upgraded up to 12. The RF signals arriving from the klystron area and the accelerating structures are frequency down-converted by means of Marki Microwave mixers MT3-0113HCQG. These mixers can be operated with a LO power as high as 24 dBm and have an high linearity with respect to RF power. This effect is particularly beneficial, since the Libera front-end dynamic range extends up to +10 dBm. Their calibration, including the insertion loss of the 2.856 GHz band-pass filter and the internal distribution cables, is reported in Fig. 4.

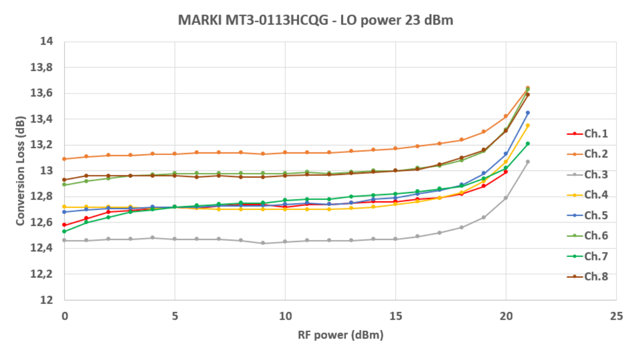

Figure 4: Calibration of Marki Microwave front-end mixers. The quoted conversion loss also accounts for the insertion loss of the 2.856 GHz band-pass filter and cable attenuation.

A Marki Microwave M2B0218HP RF mixer is used in the up-conversion stage. This choice has been driven by the high LO power (up to 22 dBm) and high linearity that allows to fully exploit the Libera 12 dBm vector modulator output at 2.856 GHz. To cancel the inter-modulation products at the IF port, a custom cavity band-pass filter has been designed and realized at LNF (in collaboration with the mechanical engineering group and the mechanical workshop of the technical division). The main features of such filter are: 3 dB bandwidth larger than 50 MHz, f_0 = 11.994 GHz and insertion loss at f_0 lower than 3 dB. In Fig. 5 the measured S_{21} parameter (absolute value) of the cavity filter actually used in the up-converter is shown. A central frequency of 11.994 5 GHz, a 3 dB bandwidth of 59.7 MHz and an insertion loss of 2.11 dB have been achieved. The effectiveness of the filter in damping the inter-modulation products is highlighted in Fig. 6, where the up-converted spectrum is shown without (blue) and with (red) the cavity band-pass filter.

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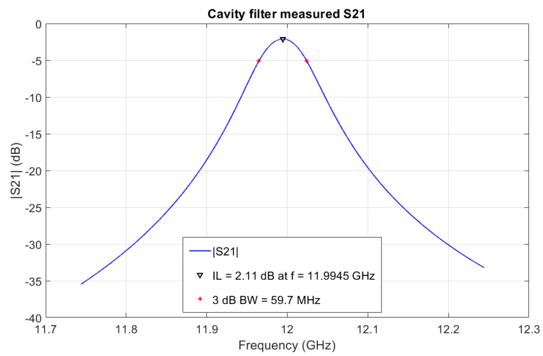

Figure 5: Measured S_{21} (absolute value) for the 11.994 GHz cavity filter.

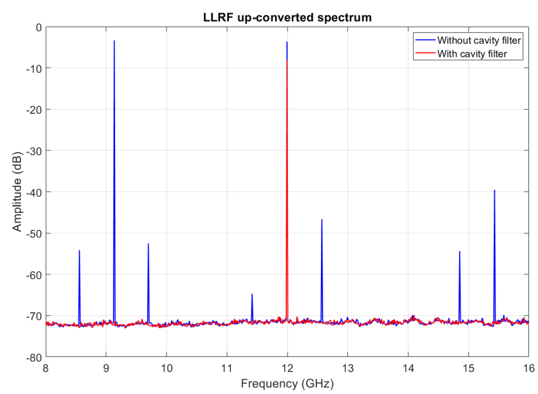

Figure 6: Up-converted measured vector modulator spectrum without (blue) and with (red) the cavity filter.

PRELIMINARY ON-BENCH MEASUREMENTS

The complete LLRF system (frequency synthesizer, reference generation and distribution, up/down converter and Libera LLRF) has been assembled, calibrated and preliminary tested by the RF group of LNF. A picture of the system under test is shown in Fig. 7.

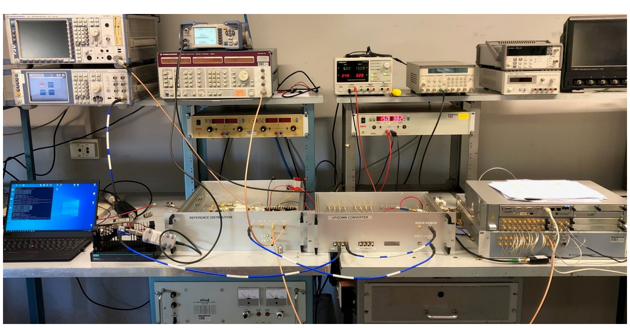

Figure 7: LLRF system under test at LNF RF laboratory.

The main goal of such characterization has been to assess whether the Libera LLRF performance (specified at 2.856 GHz) could be preserved also at 11.994 GHz. For this reason a 1.5 μs RF pulse has been generated by Libera LLRF and, in one case, it has been connected directly to its own 2.856 GHz front-end, measuring the amplitude resolution and the added phase jitter. In a second test, the same signal has been up-converted to 11.994 GHz and subsequently down-converted to 2.856 GHz, before feeding it to Libera front-end and repeating the same measurements. In order to have a fair comparison, we used the same power level at Libera front-end in both cases. The results of these preliminary measurements have been summarized in Table 1. As it can be noted, the original resolution of the Libera system is well preserved also in X-band.

Table 1: LLRF Preliminary Performance

	Amplitude resolution	Added phase jitter
S-band	0.014%	0.013 deg
X-band	0.016%	0.014 deg

All things considered, the system reviewed in this paper is certainly suitable as LLRF for a test stand, but it does not seem the optimal choice for an X-band based linac. First of all, the high conversion loss (>10 dB) of both up and down converter stages could limit the available RF power for the driver amplifier and the dynamic range of the front-end, respectively. Then, considering that the typical filling time of X-band structures ranges between 150 ns and 200 ns, the available measurement window of 8.6 μs results too wide and the sampled values too sparse (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. If we also consider that the typical bandwidth of CPI klystron is several tens of MHz, the proposed LLRF system as it is might become the bottle-neck of the RF chain. Thus, a dedicated R&D activity will be necessary to realize a different architecture (e.g. a native X-band system) with improved performance to overcome these hardware limitations.

CONCLUSION

The preliminary results of an X-band LLRF system based on a commercial S-band Libera LLRF adapted to work at 11.994 GHz for the commissioning of the TEX facility at INFN-LNF have been presented. A reference generation and distribution system, an up/down converter and custom band-pass cavity filters have been designed by the RF group and their performance on bench have been reviewed in this paper. Encouraging results have been carried out for the LLRF system, with a measured amplitude resolution below 0.02% and a phase added jitter lower than 15 fs.

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