PAUL SCHERRER INSTITUT

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Direct Conversion X-band Front End

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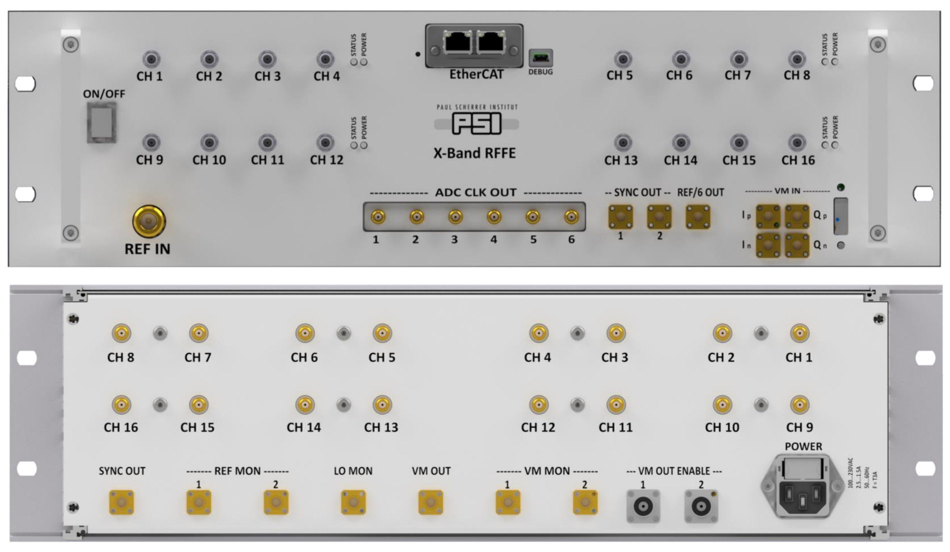


Figure 1: 3U X-band RF front end (front & back view)

Abstract

A new 16 channel LLRF front end was developed at PSI for the two X-band RF stations at SwissFEL.

This poster summarizes operational experience and performance achieved with new direct up-conversion LLRF front end. In addition, comparison between the dual conversion to the new direct conversion front end is given.

Overview

All RF front ends (S, C & X-band) at SwissFEL are based on a hybrid approach of using direct up-conversion and superheterodyne down-conversion. The new X-band RFFE differs from this by using a 4th subharmonic reference input, thus enabling the use of standard S-band fiberoptic reference links while the previous S- to X-band transverter required to have an external multiplier box providing 12 and 9 GHz.

A single RF module (Figure 7) combining a quadrupler and baseband vector modulator is used for generating pulsed RF at X-band. Down-conversion is done by deriving a LO carrier through offsetting the S-band reference by 10 MHz, followed by quadrupling and amplification. The resulting high-level LO carrier, shifted by 40 MHz with respect to the fundamental X-band signal, is fed to a cluster of 16 image-reject mixers, providing 40 MHz IF signals. Finally signal conditioning is done by adjustable IF amplifier modules, before interfacing to external ADCs.

While the direct conversion X-band front end concept developed at PSI has been presented at previous LLRF conference 2019, this poster glances on achieved performance and operational experience.

Front end performance

Down converter cross-talk

	IF [dB] (normalized to fundamental channel gain)															
RF	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	0	-73.5	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
2	-74.1	0	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
3	NF	NF	0	-75.2	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
4	NF	NF	-75.8	0	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
5	NF	NF	NF	NF	0	-72.1	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
6	NF	NF	NF	NF	-70.0	0	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
7	NF	NF	NF	NF	NF	NF	0	-76.2	NF	NF	NF	NF	NF	NF	NF	NF
8	NF	NF	NF	NF	NF	NF	-74.5	0	NF	NF	NF	NF	NF	NF	NF	NF
9	NF	NF	NF	NF	NF	NF	NF	NF	0	-73.9	NF	NF	NF	NF	NF	NF
10	NF	NF	NF	NF	NF	NF	NF	NF	-73.1	0	NF	NF	NF	NF	NF	NF
11	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	0	-74.9	NF	NF	NF	NF
12	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	-73.6	0	NF	NF	NF	NF
13	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	0	-76.5	NF	NF
14	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	77.1	0	NF	NF
15	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	0	-74.6
16	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	-73.2	0

Table 1: Down converter cross-talk matrix

Image rejection

f_{IF} [MHz]	IF LSB [dBm]	IF USB [dBm]	Image rejection [dB]
15	8.52	-22.04	30.56
20	8.93	-22.83	31.76
25	9.36	-21.05	30.41
30	9.71	-19.11	28.82
35	9.90	-18.29	28.19
40	10.00	-18.05	28.05
45	10.05	-17.63	27.68
50	10.04	-17.67	27.71
55	9.95	-19.08	29.03
60	9.83	-22.06	31.89
65	9.72	-25.08	34.8

Lower Side-band (LSB): 11.9702...12.0202 GHz
Upper Side-band (USB): 12.0535...12.1035 GHz

Table 2: Down converter image rejection

Down converter:

- Cross-talk < -70 dBc between channel pairs inside one dual channel module (Table 1), otherwise < -83 dBc (below ADC noise floor)
- Image rejection > 27 dB (matters if broadband noise is present at input, e.g. vector modulator and pre-amplifier output) -> Table 2
- Conversion gain RF -> IF: 10 to 17 dB
- Gain variation between 16 channels: < 1dB

Up converter:

- Full scale output power: 10dBm
- RF leakage (IQ adjusted, switch closed): -49.5 dBm
- Imbalance and bandwidth see figure 3
- PIN-switch ON/OFF attenuation: 35 dB

Multiplier (quadrupler):

- Design based on balanced passive varactor quadrupler with high conversion efficiency
- Output spectrum see Figure 2

X-band reference & LO spectrum

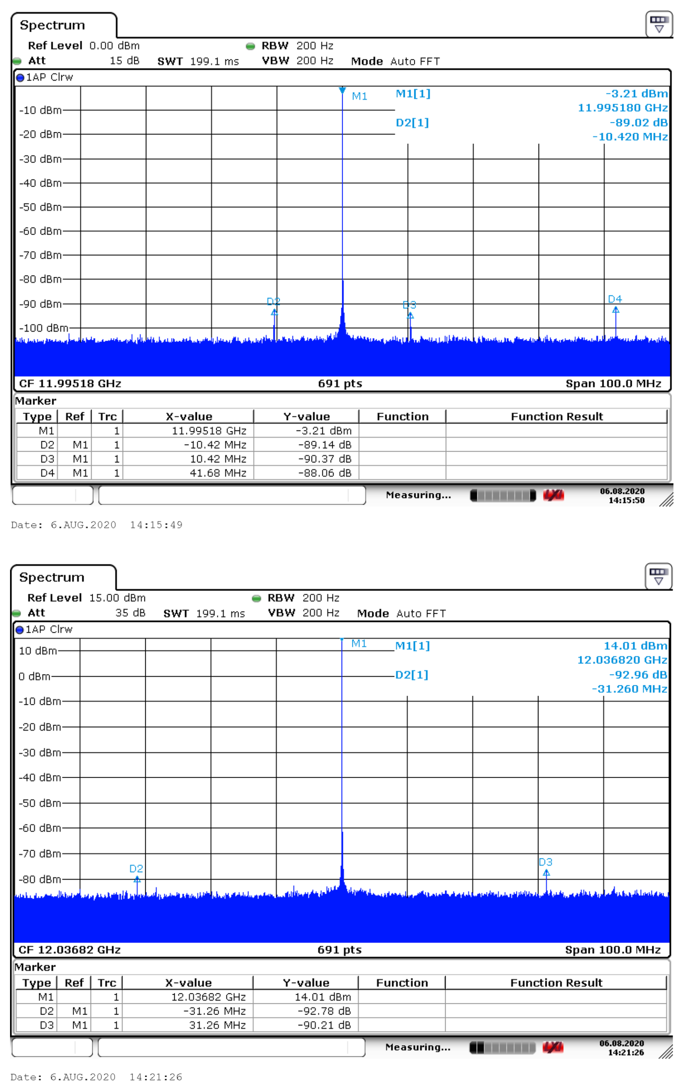
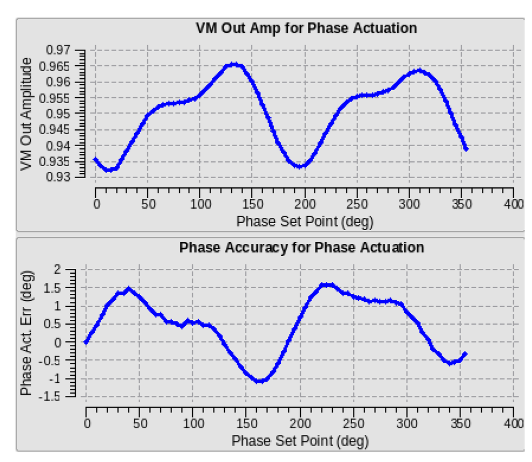


Figure 2: Reference (top) & LO (bottom) spectrum

Vector modulator imbalance (unadjusted)



- Amplitude: 0.3 dB
- Phase: 2.6 deg
- Can easily be corrected by DAC LUT

Vector modulator + DAC bandwidth

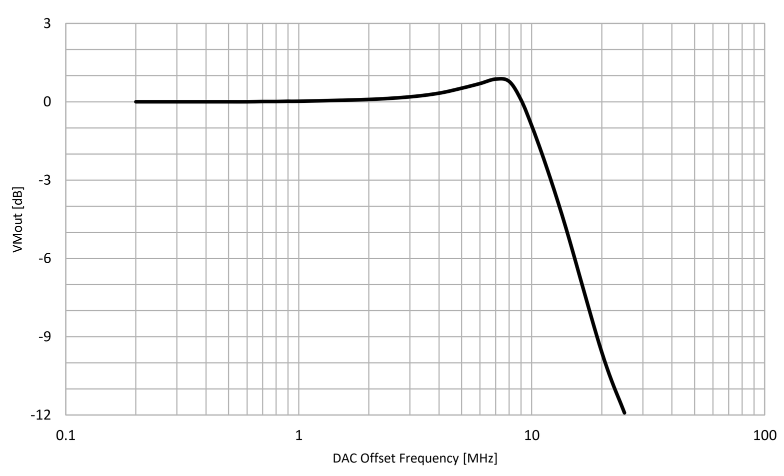


Figure 3: Vector modulator imbalance (top) and bandwidth (bottom)

Operational experience

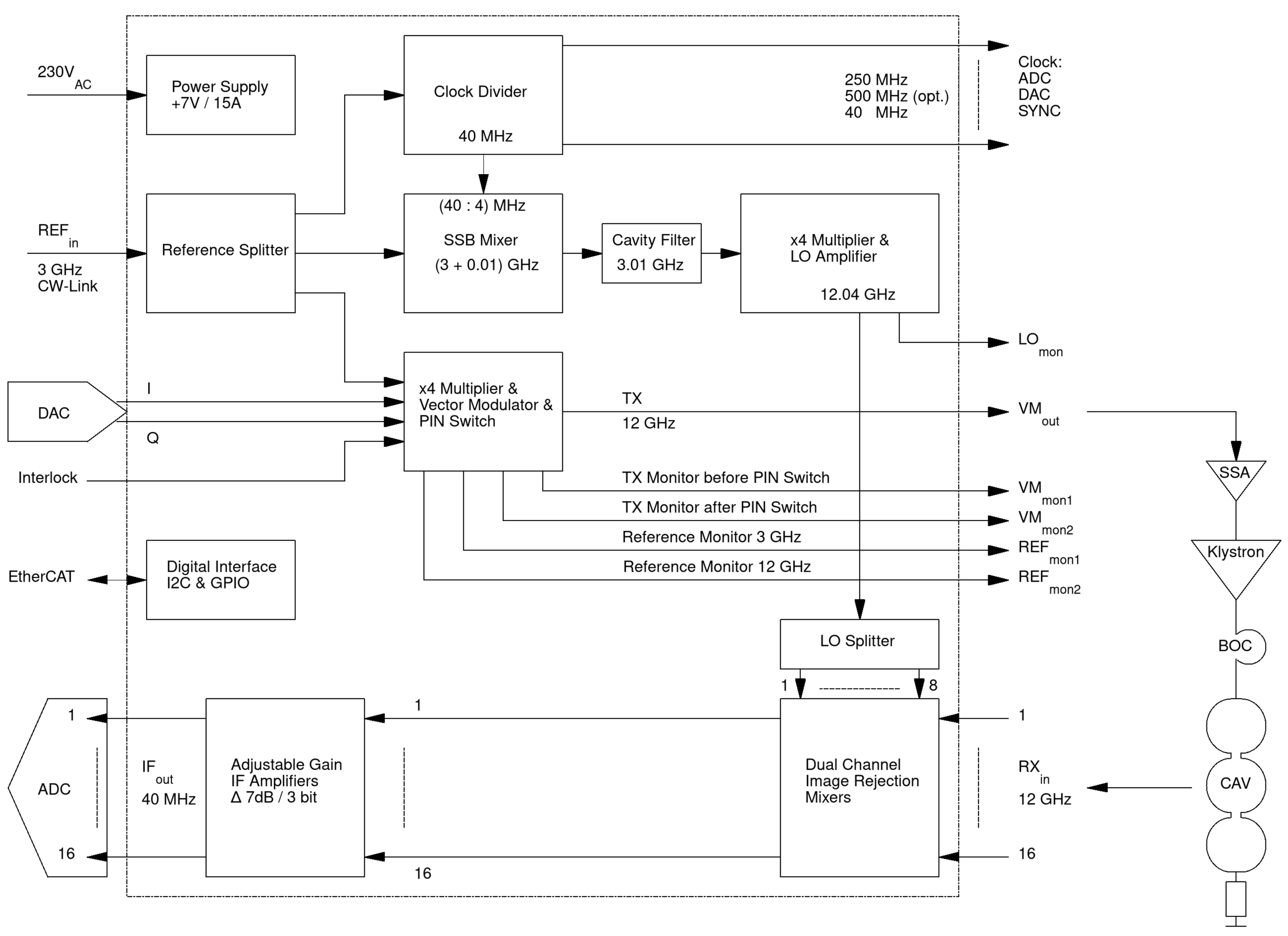


Figure 4: Front end functional schematic

RF stability / Phase drift vs. humidity

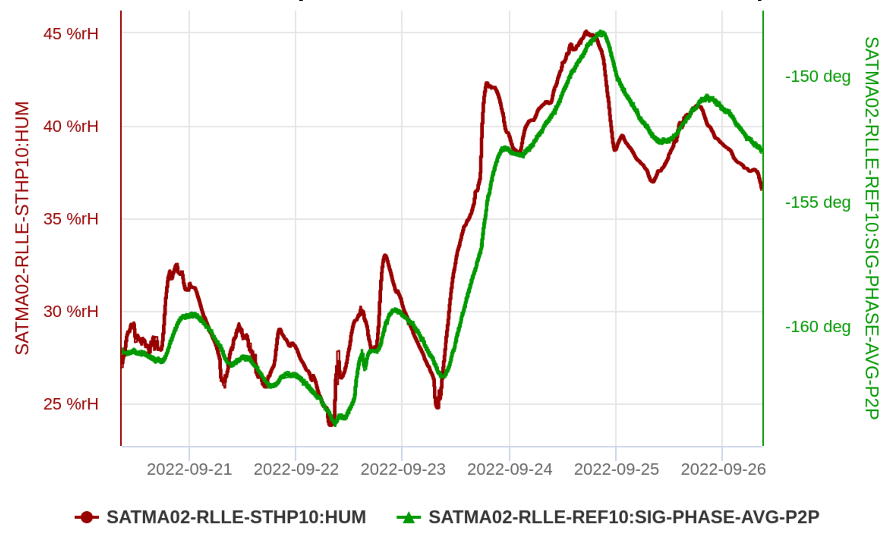
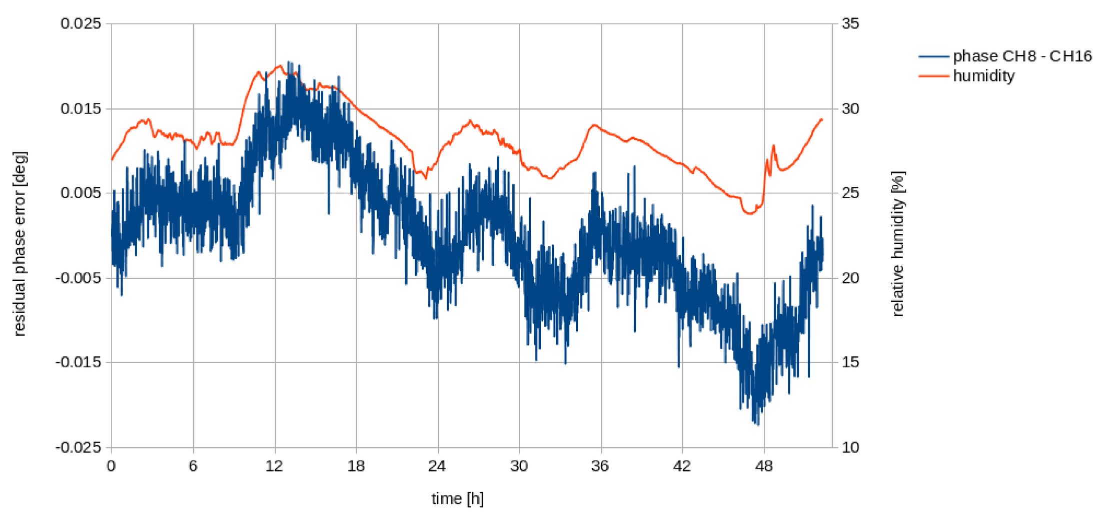


Figure 5: Phase drift vs. humidity

- LLRF rack is very well temperature stabilized (+/- 0.1 degC) but lacks control of humidity
- Phase change vs. humidity is about 0.7 deg / %rH -> unacceptable!
- Feeding a stabilized reference extracted from up converter quadrupler into one or two receiver channels and subtracting offset phase gets rid of most drift

With Reference Tracking enabled



- Residual phase error between receiver channels vs. humidity about 0.005 deg / %rH

Figure 6: Residual phase drift vs. humidity

Comparison between direct and dual conversion

Amplitude	ADC Noise Floor	Direct Conversion	Dual Conversion
Intra-pulse stddev rel.	1.16e-4	1.24e-4	8.2e-4
Pulse-to-pulse rel. jitter	3.4e-5	5.78e-5	1.52e-4
Phase			
Intra-pulse stddev rel.	0.008	0.038	0.048
Pulse-to-pulse rel. jitter	0.0015	0.015	0.015

Table 3: RF jitter comparison of reference channel

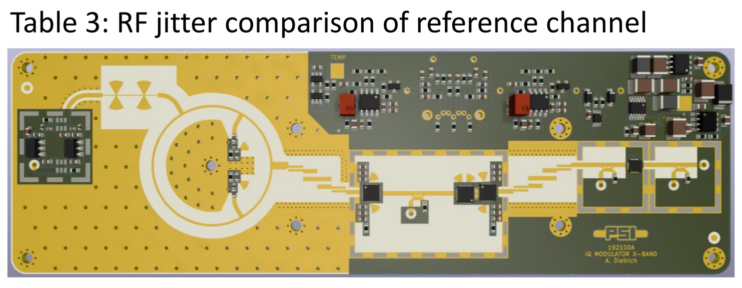


Figure 7: Direct conversion up converter

Direct conversion gives:

- Less amplitude noise at high (intra-pulse) and low (pulse-to-pulse) frequency offsets
- Slight improvement in intra-pulse phase jitter
- Compact design of single module up converter to reduce uncorrelated drifts
- Pulse-to-Pulse phase jitter equals between both systems
- Dual conversion requires two LO carriers to be generated and distributed to multiple channels and mixer stages

Conclusion / Outlook

The presented X-band RF front-end has shown reliable performance and noise improvements compared to existing X-band transverter. While many components are common with S-band units, key RF components are the direct conversion vector modulator, dual channel image reject mixer, LO SSB-Mixer with divide-by-4 regenerative frequency divider and quadrupling LO amplifier. Series production of 5 units is expected to be finished by end of this year. Improving the X-band injector front end to improve overall RF station noise is foreseen next year.

The new X-band deflector station at SwissFEL, equipped with in-house built HV-modulator, deflecting structures, pulse compressor, phase shifters and RF front end went into operation by first beam streaking in June 2022.