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SwissFEL C-band LLRF Prototype System

LLRF

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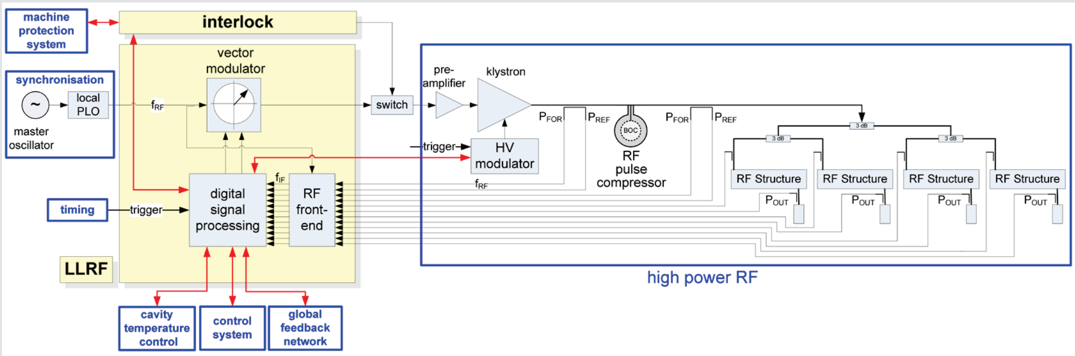
Abstract

The SwissFEL is driven by more than 30 RF stations at different frequencies (S-, C-, X-band). To control the RF a new, in-house developed digital Low Level RF (LLRF) system measures up to 24 RF signals per station and performs a pulse-to-pulse feedback at a repetition rate of 100 Hz. The RF signals are down-converted to a common intermediate frequency. The state-of-the-art digital processing units are integrated into the PSI's EPICS controls environment. Emphasis has been put on modularity of the system to provide a well-defined path for upgrades. Thus the RF front-ends are separated from the digital processing units with their FMC standard interfaces for ADCs and DACs. A first prototype of the LLRF system consisting of the digital back-end together with a C-band RF front-end was installed in the SwissFEL C-band test facility.

Topology of a SwissFEL C-band Station



SwissFEL Design Parameters

Charge per bunch	200 pC
Beam energy for 1 Å	5.8 GeV
Peak current at undulator	2.7 kA
Electron bunch length	25 fs (rms)
Bunch compression factor	125
Number of bunches	2
Bunch spacing	28 ns

Requirements for C-band Station

C-band frequency:	5.712 GHz
Repetition rate	100 Hz
RF pulse length	0.02 to 5 µs
Amplitude stability of C-band in LINAC	1.8e-4 rel. (rms)
Phase stability of C-band in LINAC	0.036 deg (rms)
Number of channels per RF station	24 (prototype: 16)
Channel-to-channel drift	0.1 deg/day

Phase stability of vector modulator	0.017 deg (rms)
Phase resolution of receiver	0.020 deg (rms)
Amplitude resolution of receiver	1e-4 rel. (rms)
Signal distortion of receiver	1 %
Phase readback error	< 0.1 deg
Amplitude readback error	< 0.1 %

Analog Front-End

Vector Modulator

- VM and LO in 1 unit 19" box
- Baseband modulator with DC-coupled, differential I/Q inputs
- Common mode spurs from the DACs are suppressed by 40 dB
- Added jitter of the vector modulator driven by the DACs is around 1 fs

LO & Clock Generation

- Reference signal: 5712 MHz (jitter: < 10 fs) from optical-to-electrical reference distribution
- LO frequency: 5751.667 MHz
- IF reference: 39.667 MHz (f_{ref} / 144)
- ADC/DAC clock: 238 MHz (f_{ref} / 24)

Down Converter

- 16 channel in 2 unit 19'' box
  4 individual 4-channel receiver modules with additional LO amplifiers
- IF output: 39.667 MHz at +12 dBm
- Bandwidth: 48 MHz
- Added jitter around 1 fs (10 Hz – 10 MHz)

Down Converter

LO Generation & Vector Modulator

Data Converter

- FPGA mezzanine card (FMC) based, mounted on IFC1210
- **FMC ADC3110**: 8x AC-coupled 16-bit ADC channel with 250 Msps
  - ENOB: 11.92 bits, spurs < 89.95 dBFS
- **FMC DAC3113**: 2x DC-coupled, differential 16-bit DAC channel with 250 Msps
  - SNR 70 dB, spurs < 77.3 dBFS (DC-21MHz)
- Powered by switched power supply in VME crate

Digital Back-End

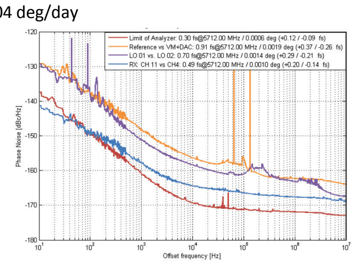
- Scalable system (PCIe, VME64x)
- 2 carrier boards (IFC1210) with 2 ADCs and 1 DAC card
- IF demodulated by 1/6 non-IQ algorithm to baseband (I/Q)
- Detection bandwidth 34 MHz (FWHM), corresponds to klystron bandwidth
- Intra-pulse resolution calculated over an user-defined window
- Pulse-to-pulse statistics calculated over sequent pulses
- Data and statistics provided with 100 Hz through EPICS IOC

Channel-to-channel Isolation

- Depends on RF-to-LO isolation of the mixers and design of power splitter in LO distribution
- Channel-to-channel isolation of 80 dB achieved, corresponds to measured amplitude stability.

Drifts

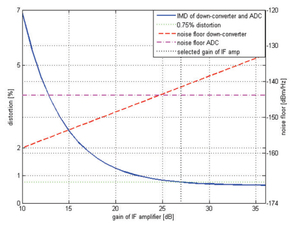
- Only important on the receiver side because slow changes on the transmitting path are corrected by pulse-to-pulse feedback
- Temperature drift of analog front-end is 4.4e-3 rel/°C and 2.5 deg/°C in phase
- Temperature controlled rack at 24 °C ±0.05°C
- Temperature generated channel-to-channel phase drift can be improved by reference tracking to ~0.1 deg/day.
- Performance of reference signal distribution: phase drift of 0.04 deg/day



Additive phase noise spectra of VM incl. DAC, LO generation and down-converter

Amplitude and Phase Resolution

- Amplitude and Phase resolution of the LLRF system is limited by the noise floor at the output of the down-converter, the noise floor of the ADC and the phase jitter of ADC clock and LO signal.
- The noise floor of the down-converter measured at the IF port is -137 dBm/Hz. This is 6 dB above the ADC noise floor. For a sampled sine wave the clock jitter introduced by the onboard clock distributor increases the noise floor of the ADC by 2 dB. In contrast, the jitter of the external ADC clock from the LO unit is low enough to have no significant contribution.
- The pulse-to-pulse resolution of the whole system is 0.01 deg in phase and 1.5e-4 rel. in amplitude. It is calculated over 100 pulses with an averaging window of 300 ns per pulse. This averaging limits the bandwidth from 0.5 Hz to 1.5 MHz, which corresponds to the filling time of the C-band structures.
- The noise floor of the down-converter can be improved by increasing the input signal on cost of the intermodulation distortion of the system. Figure on the right side shows the relation between distortion and noise floor as function of the required IF gain. With a chosen IF gain of 27 dB the OIP3 measurement of the prototype down-converter results in a distortion of 0.75 %.



Signal distortion and noise floor of the down-converter as a function of the IF amplifier gain. The noise floor of the ADC is shown in addition

Conclusion and Outlook

The prototype LLRF system performs well and is an important step towards the SwissFEL LLRF system. Further attempts are being made to reduce the noise floor of the down-converter to the noise floor level of the ADC on cost on a slightly relaxed distortion requirement of 1%. With this approach and additional filtering of power supplies the measurement resolution of the LLRF will be well below the required RF stability tolerances. The implementation of reference tracking and additional drift calibration will help to improve the channel-to-channel phase and amplitude drift. For the common digital back-end emphasis was put on setting up the firm- and software environment and its integration into the control system. Now, the focus moves on the development of specific LLRF applications.