High Level Applications for SwissFEL LLRF System

PAUL SCHERRER INSTITUT

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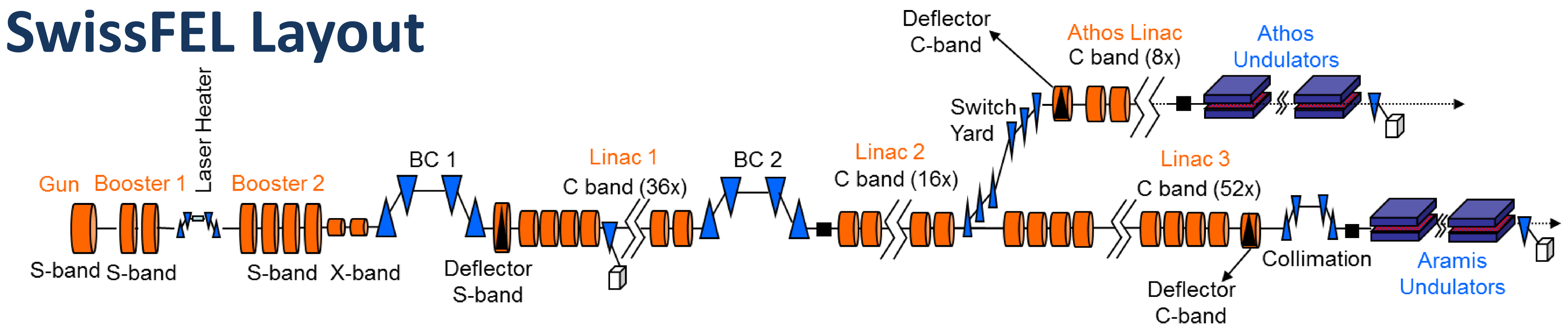
Abstract

SwissFEL, which is under commissioning at Paul Scherrer Institut (PSI), Switzerland, consists of multiple RF stations either with standing wave cavities (e.g. RF Gun) or with travelling wave accelerating structures working at different frequencies. LLRF systems are used to measure the RF fields in cavities or structures and correct the fluctuations in RF fields with pulse-to-pulse feedback controllers. To facilitate the operations of multiple RF stations, the LLRF system should also provide algorithms and procedures to automate the setup, calibration and optimization of the RF systems. In this paper, several typical algorithms will be described, such as calibrating the DAC offset to reduce the RF leakage from vector modulator, calibrating the RF signal group delay and flattening the intra-pulse phase distribution with adaptive feed forward. The algorithms have been implemented as a LLRF High Level Applications (HLA) software for SwissFEL. The architecture of the LLRF HLA software will be introduced and the test results at SwissFEL will be also described.

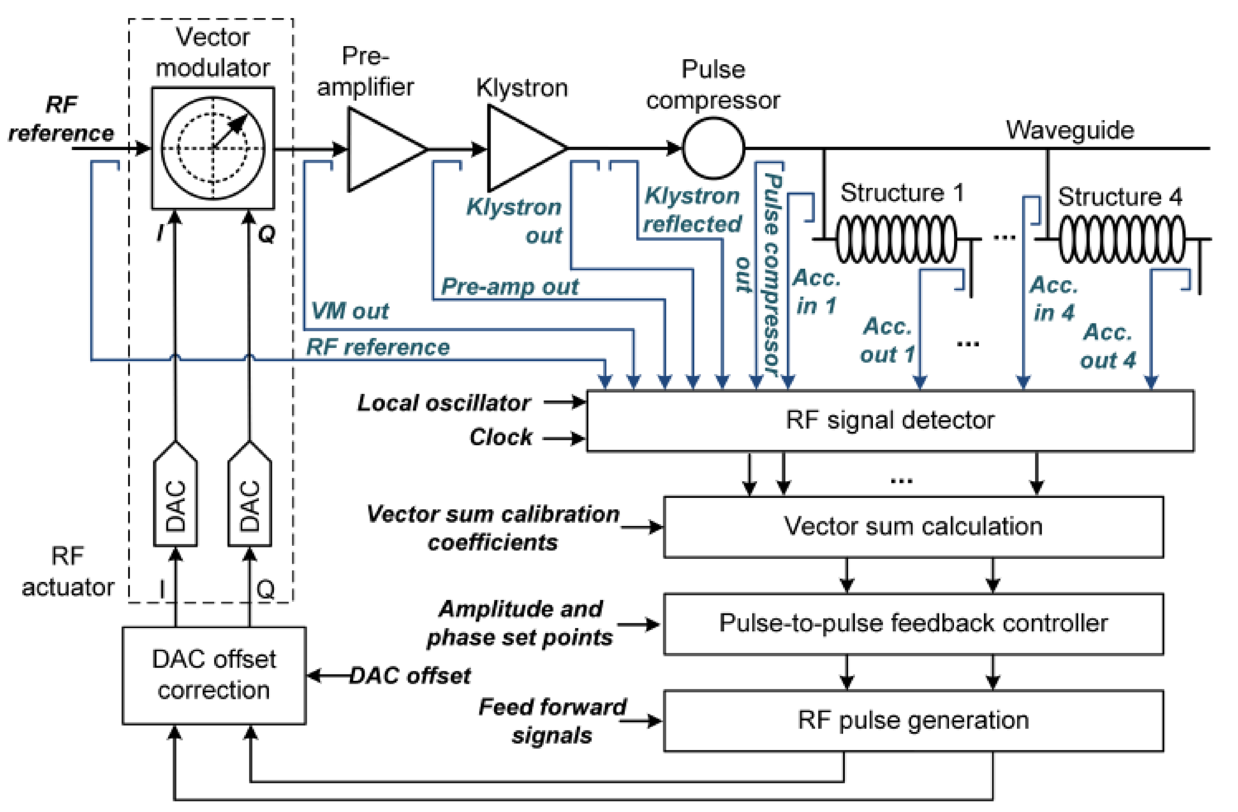
SwissFEL Layout



RF Stability Requirements

RF Station	Phase Tolerance (rms)	Voltage Tolerance (rms)
S-band (2.9988 GHz)	0.018 degS	0.018 %
C-band (5.7120 GHz)	0.036 degC	0.018 %
X-band (11.9952 GHz)	0.072 degX	0.018 %

LLRF Overview

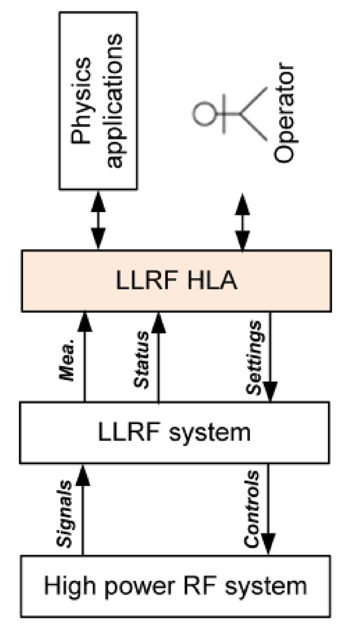


The LLRF system provides the following functions:

- ❑ Provides precise and accurate phase and amplitude measurements of RF signals at various locations of the RF system.
- ❑ Suppresses RF field fluctuations in cavities and accelerating structures.
- ❑ **Facilitates the operators to easily setup and operate the RF stations.**

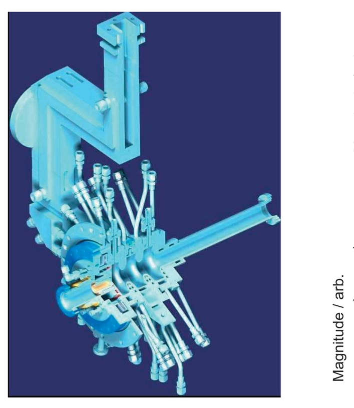
Typical LLRF HLAs

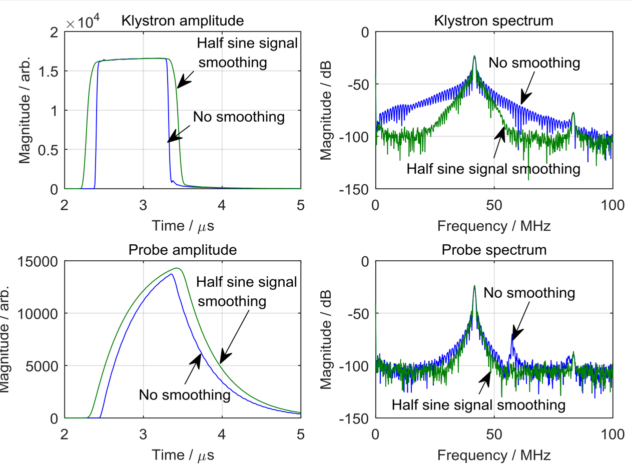
Category	HLA algorithm and procedure
RF setup	**Pulse shape optimization.**
	DAC offset correction.
	Klystron working point determination.
Calibration	**Group delay calibration.**
	Loop gain and loop phase calibration.
	Accelerating voltage and beam phase calibration.
Optimization	**RF pulse shaping.**
	Feedback gain optimization.
Diagnostics	Cavity detuning measurement.
	Structure detuning measurement.

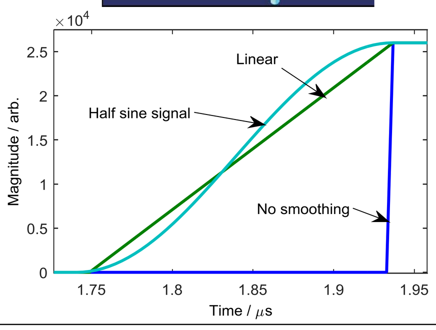


Pulse Shape Optimization

SwissFEL RF Gun is a 2.6-cell standing wave cavity working at 2998.8 MHz (π mode). The nearest pass-band mode (π/2 mode) is about 16 MHz away in spectrum. A sharp square pulse generated by DAC results in a wide band in the klystron output which stimulates the π/2 mode significantly. In order to reduce the bandwidth of the Gun drive power, the rising and falling edges of the RF pulse was smoothened with a half sine signal.

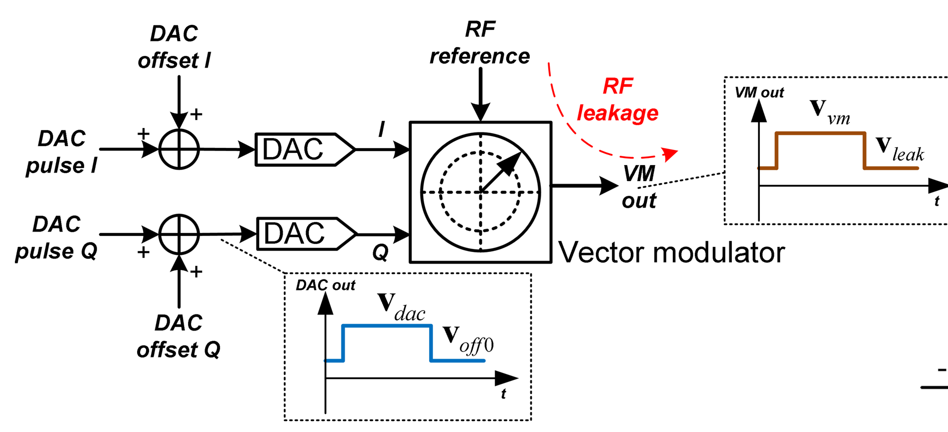






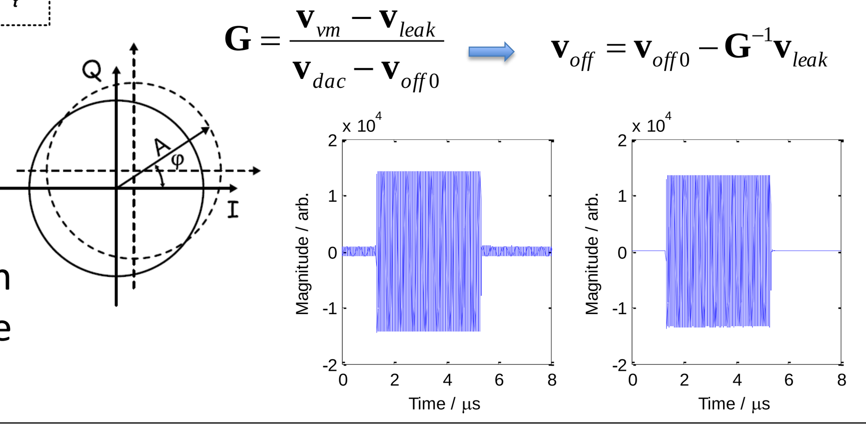
Amplitude waveforms and spectrums of klystron output and cavity probe signals. The spectrums were calculated with the ADC samplings of the down converted IF signals at 41.65 MHz. The sampling frequency of the DAC and ADC was 249.9 MHz.

DAC Offset Correction



Solution: Add constant offsets in the DAC signals to generate an extra RF output with the same amplitude but opposite phase with respect to the RF leakage signal, resulting in the cancellation of the leakage.

$$G = \frac{\mathbf{v}_{vm} - \mathbf{v}_{leak}}{\mathbf{v}_{dac} - \mathbf{v}_{off0}} \Rightarrow \mathbf{v}_{off} = \mathbf{v}_{off0} - \mathbf{G}^{-1}\mathbf{v}_{leak}$$



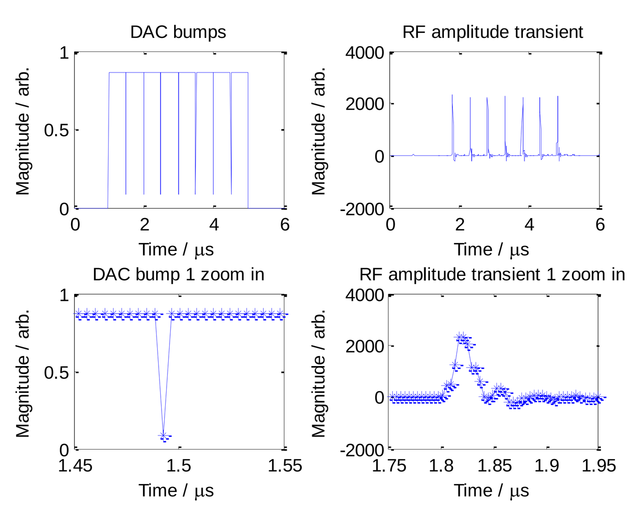
SwissFEL LLRF system employs direct up-conversion scheme for RF actuation. The leakage will generate significant errors in phase and amplitude actuations.

Group Delay Calibration

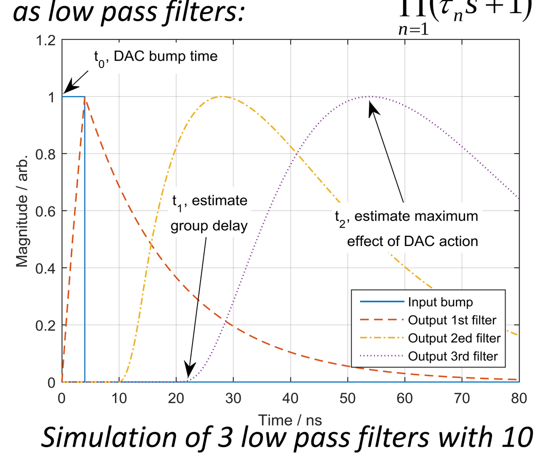
Why do we need to calibrate the group delays of RF signals with respect to the DAC pulse?

- To compare the relative RF errors in different locations of the RF system.
- To find out which DAC point needs to be adjusted to suppress the intra-pulse ripple at a certain point within the RF pulse.

Solution: A single point in the DAC pulse can be varied (e.g. with smaller magnitude) as a bump in the pulse to generate a transient in all RF signals.



RF components in the path can be viewed as low pass filters: $H(s) = \frac{\prod_{n=1}^{N} k_n}{\prod_{n=1}^{N}(\tau_n s + 1)}$

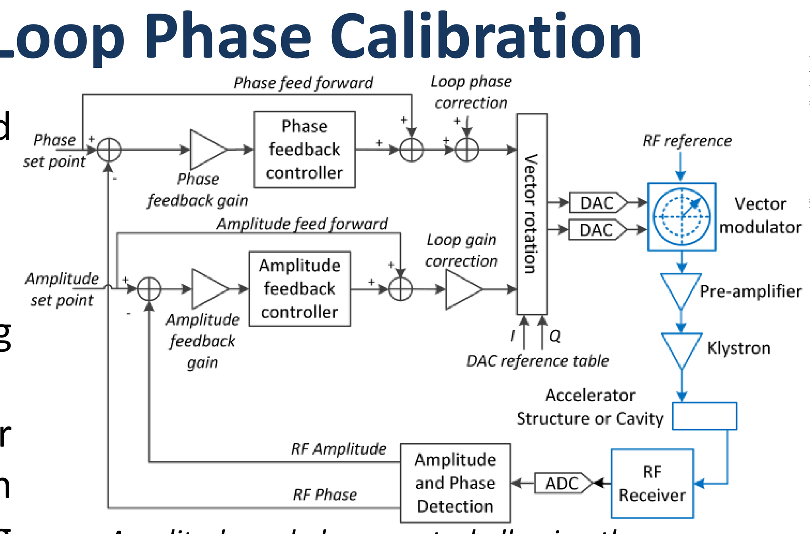


Simulation of 3 low pass filters with 10 MHz bandwidth and 10 ns group delay

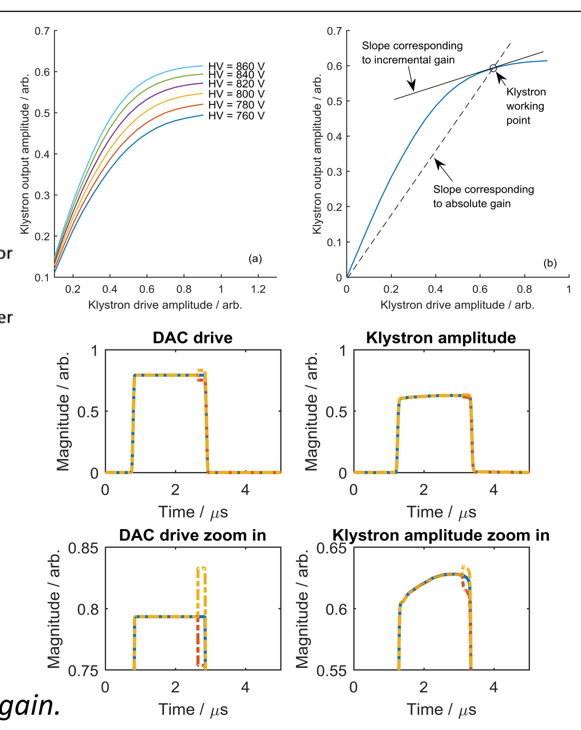
Loop Gain and Loop Phase Calibration

Goals of loop gain and loop phase calibration:

- Determine amplitude feedback gain.
- Avoid klystron working over saturation.
- After amplitude or phase tuning in open loop, avoid jumping when closing the loop.



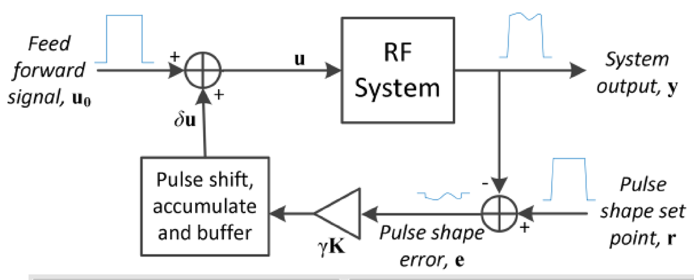
Amplitude and phase control allowing the klystron to work in saturation but still with phase feedback applied.



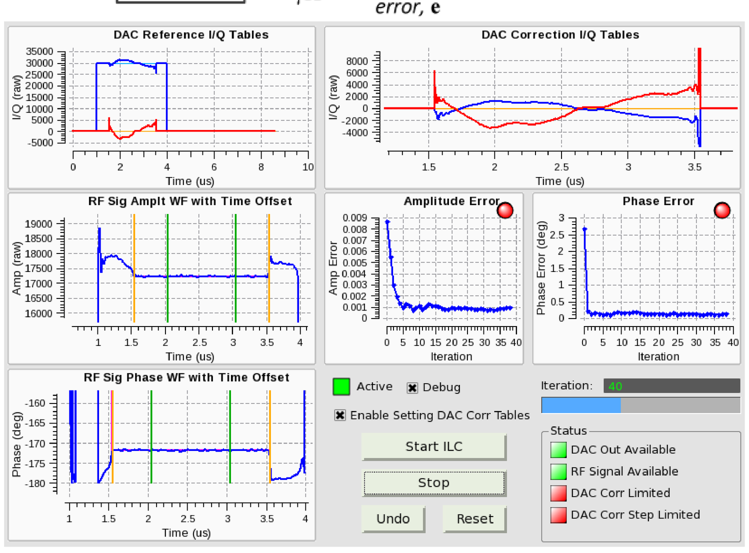
Method to calibrate the incremental gain.

RF Pulse Shaping

A flat RF pulse in both amplitude and phase are important for multi-bunch operation because all bunches require equal acceleration in the same RF pulse. If the response of the RF system is fast, a simpler algorithm can be used for which the errors in the output pulse can be applied to the DAC drive in a manner similar as the discrete integral feedback.



$$\mathbf{e}(k,n) = \mathbf{r}(n) - \mathbf{y}(k,n)$$
$$\delta\mathbf{u}(k+1, n-d) = \delta\mathbf{u}(k, n-d) + \gamma\mathbf{K}\cdot\mathbf{e}(k,n)$$
$$\mathbf{u}(k+1,n) = \mathbf{u}_0(n) + \delta\mathbf{u}(k+1,n)$$

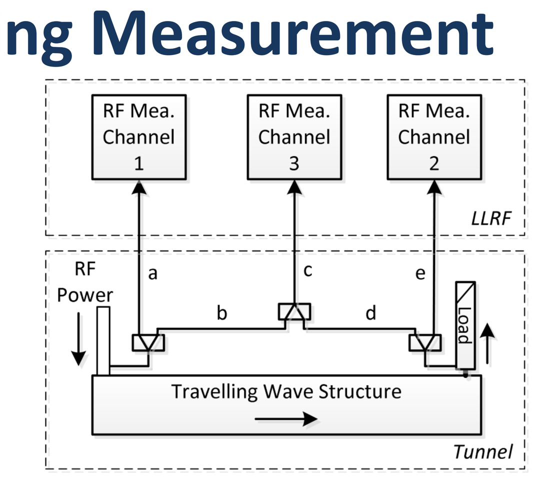


The group delay to shift the pulse has been calibrated with the "Group Delay Calibration" algorithm.

The algorithm only works for fast systems with a time constant comparable to the clock cycle of the DACs and ADCs used in the LLRF system (e.g. the clock cycle for SwissFEL LLRF system is around 4 ns).

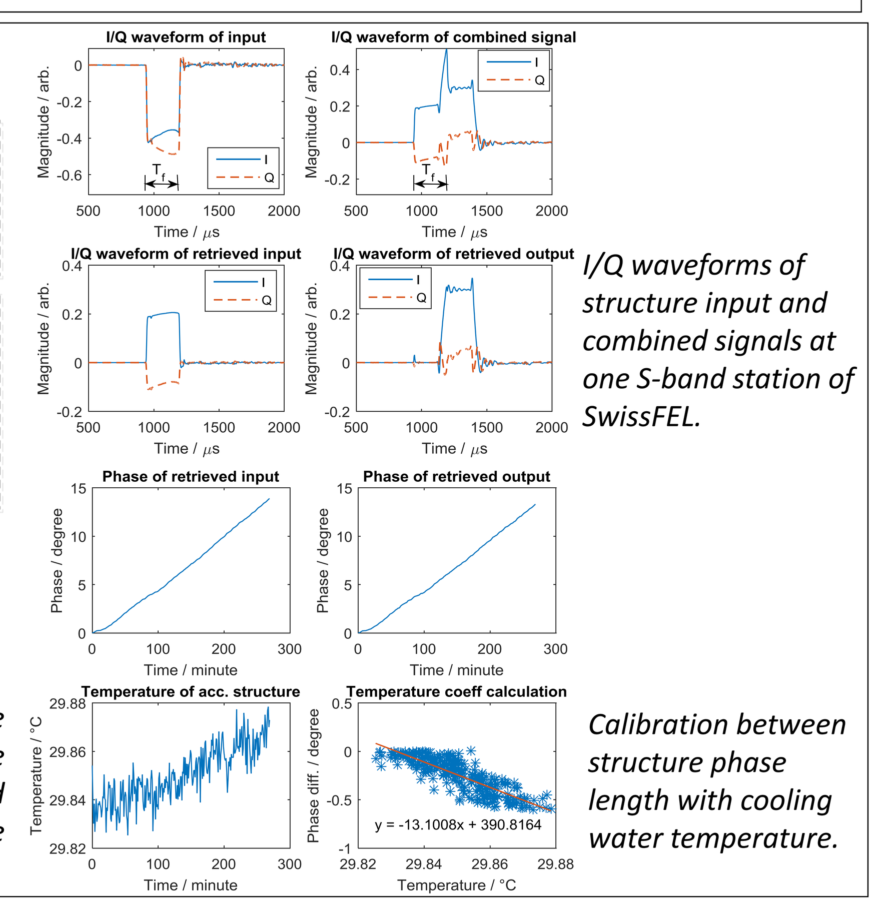
Structure Detuning Measurement

The detuning of the travelling wave structures can be measured by comparing the phases between the output and input RF signals. In order to reduce the uncertainties caused by the cable drifts, it is better to measure the structure input and output signals with the same cable and the same RF detector.



$$\mathbf{C} = \int_0^{T_f}\mathbf{v}_{in}(t)dt \Big/ \int_0^{T_f}\mathbf{v}_{cmb}(t)dt$$
$$\mathbf{v}_{in\_retrieve} = \mathbf{C}\cdot\mathbf{v}_{in}$$
$$\mathbf{v}_{out\_retrieve} = \mathbf{v}_{cmb} - \mathbf{v}_{in\_retrieve}$$

Algorithm to retrieve the structure input and output signals from the measurements of input and combined signals. The group delay of the structure enables the algorithm.

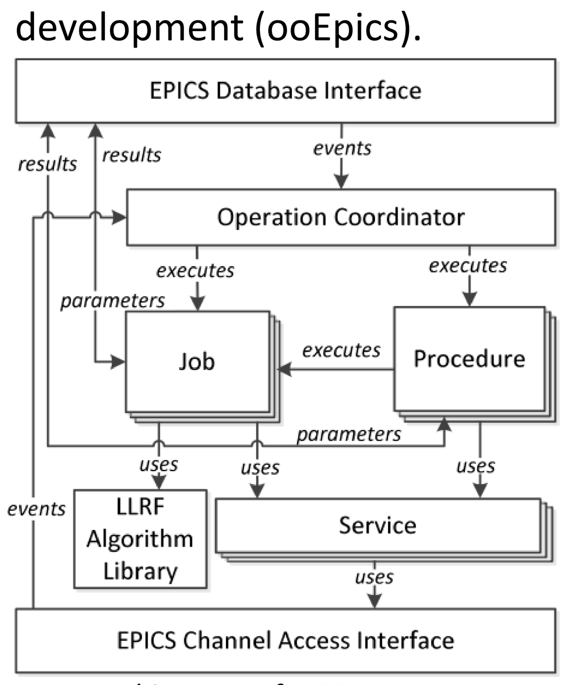


I/Q waveforms of structure input and combined signals at one S-band station of SwissFEL.

Calibration between structure phase length with cooling water temperature.

LLRF HLA Software Design

The LLRF HLA software is based a C++ framework for EPICS module development (ooEpics).



Architecture of LLRF HLA.

Components	Description
Coordinator	An active thread to coordinate the execution of the procedures and jobs.
Procedure	Automation procedure to startup, stop and setup the RF system.
Job	A function that the LLRF HLA implements.
Service	An interface to interact with a physical device in the RF system (e.g. klystron modulator).
LLRF Algorithm Library	A library implemented in C language to collect algorithms used in LLRF system (e.g. calculate DAC offset).

GUI of LLRF HLA for SwissFEL.

Conclusion / Outlook

The algorithms developed for the LLRF HLA provide practical automation to operate the RF systems of SwissFEL. A software package has been well architected and implemented based on EPICS and has been used in daily operation of SwissFEL. The HLA software tools have helped a lot in the commissioning of the RF system. The software architecture is flexible to add more functions to the HLA. Similar architecture can also be easily applied to other aspects of the accelerator control like the beam based feedback system. The experiences of the design and usage of the LLRF HLA will be also helpful for other accelerator facilities.

Reference:
[1] Z. Geng, "RF Control Optimization and Automation for Normal Conducting Linear Accelerators". IEEE Transactions on Nuclear Science, Vol. 64, No. 8, August 2017.

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