Relative Timing Issues and Mitigations in SwissFEL RF System

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LLRF Topical Workshop – Timing, Synchronization, Measurements and
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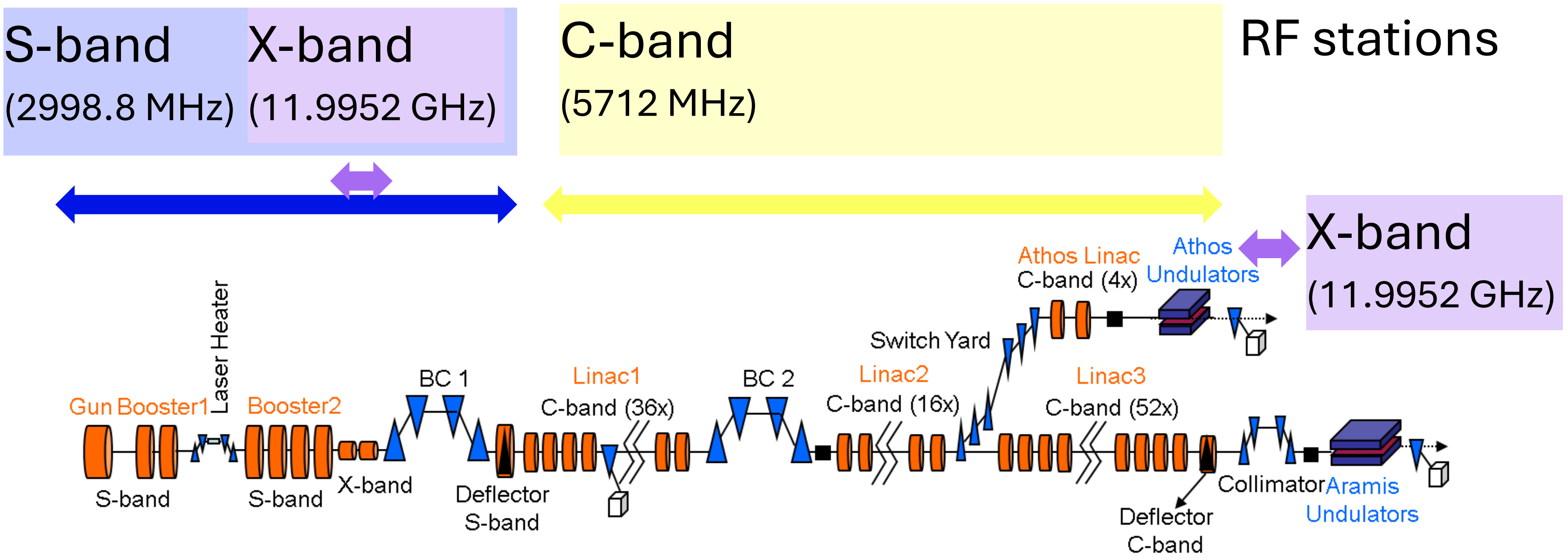
Outline

- Timing Relations at SwissFEL
- Phase Measurement Uncertainty
- Macro RF Pulse Timing Uncertainty
- Gun Laser Bucket Error
- Conclusion and Outlook

Timing Relations at SwissFEL

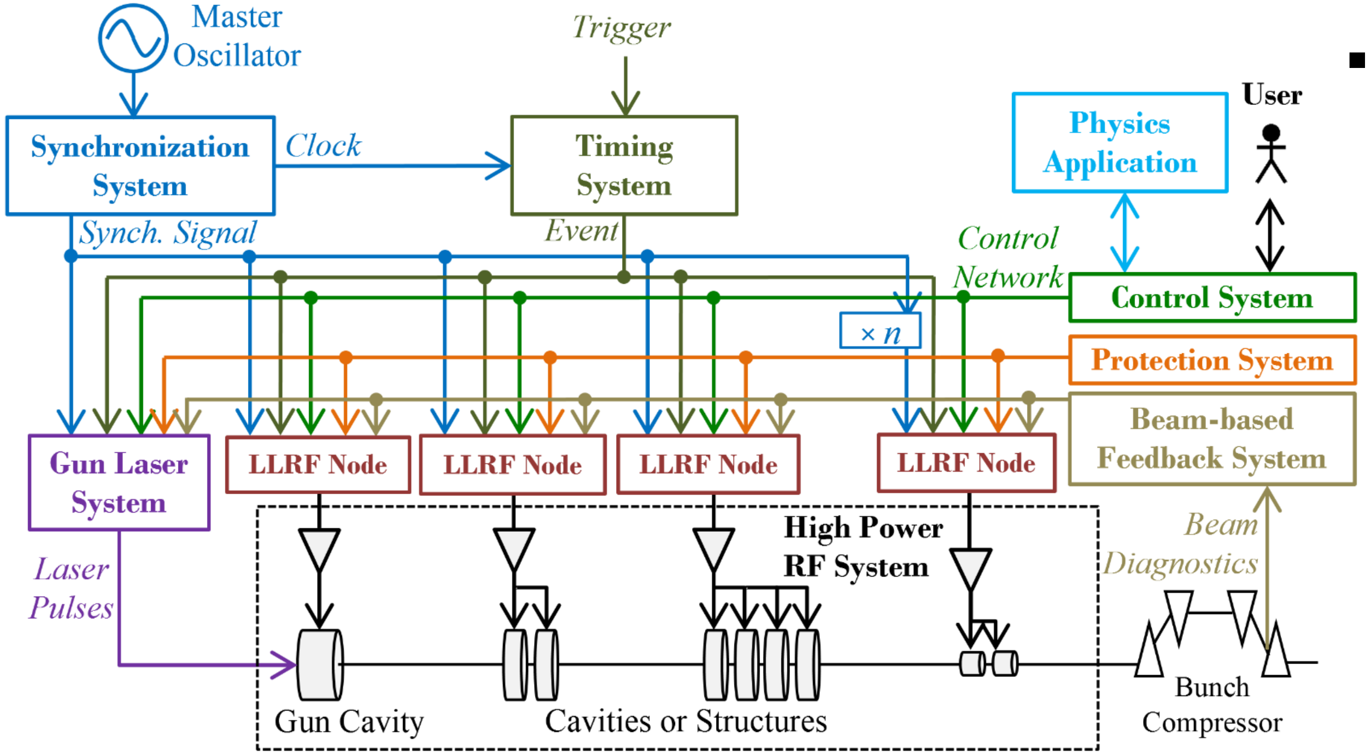
Overview of SwissFEL RF System



Highlight of RF system features:

- Technology: Normal conducting
- RF repetition rate: up to 100 Hz
- RF pulse width: 0.1 ~ 3.0 μs
- Num. of bunch/pulse: 1 ~ 2

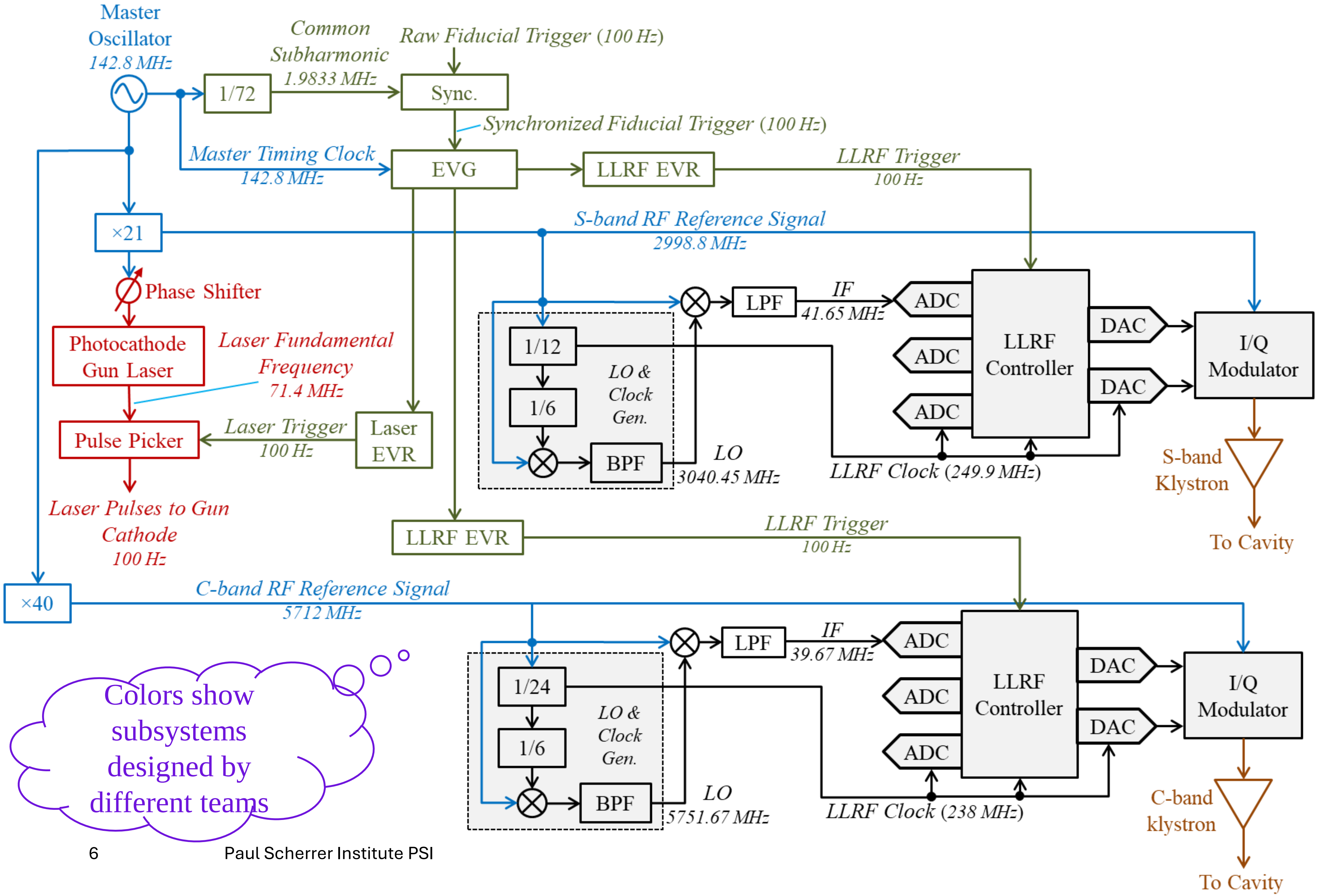
Time Relations to Accelerate a Bunch



- **Timing system** defines the trigger sequence:
  1. Start the RF pulse – fill the RF cavities/structures.
  2. Start the sampling of beam diagnostics.
  3. Select a laser pulse – generate a bunch in RF Gun.
  4. *Bunch flies across the Linac and gets accelerated in RF cavities/structures.*
  5. *RF and beam diagnostics both read data of last pulse/bunch and produces correction for the next pulse via feedbacks.*

- **Synchronization system** provides coherent references to all systems:
  - Laser is locked with the synchronization system – deterministic bunch generation time w.r.t. the sync reference.
  - Bunch travels to downstream cavities/structures, so as the sync reference.
- **LLRF** regulates the RF field phase in cavities/structures to follow the sync reference.
  - Add necessary offset to compensate for the time difference between beam flight and sync reference transmission.

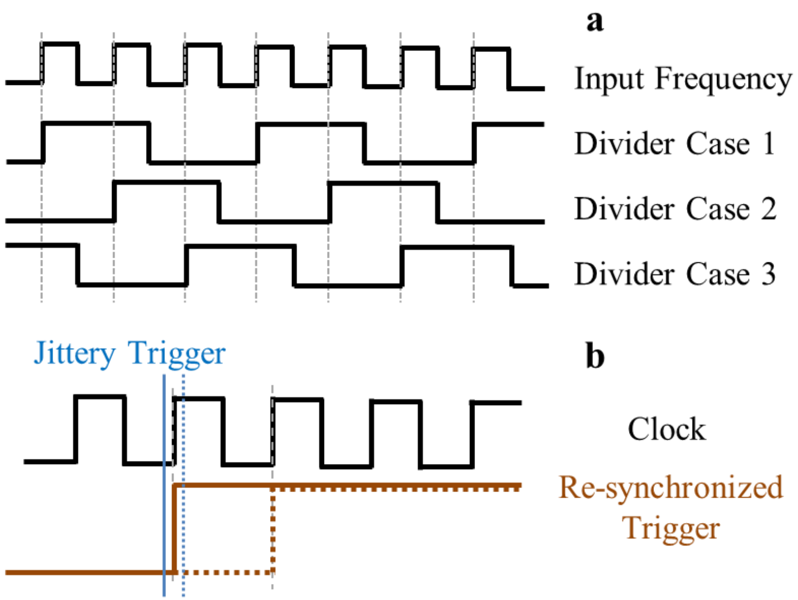
Frequencies in SwissFEL RF System



Colors show subsystems designed by different teams

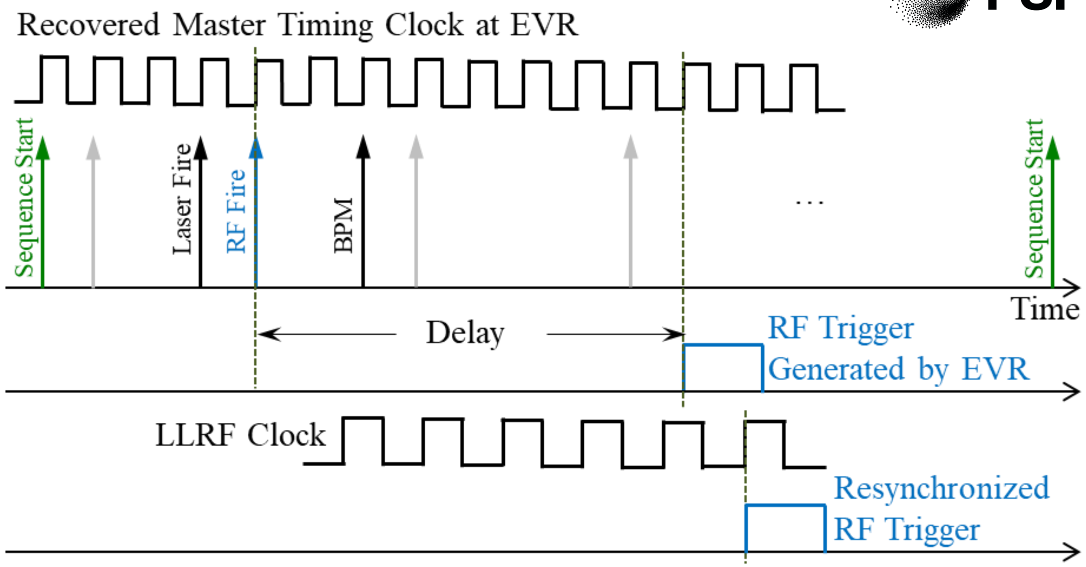
- **Reasons of timing/phase relation failures after reboot or power cycles:**
  - Phase uncertainties of frequency dividers.
  - Laser bucket jumps.
  - Racing between triggers and clocks.
- **Difficulties by SwissFEL design:**
  - C-band and S-band RF frequencies use different standards (EU/US).
  - Laser oscillator frequency is ½ of the master oscillator frequency.
  - LLRF clock frequencies are not harmonics of the EVG clock frequency.

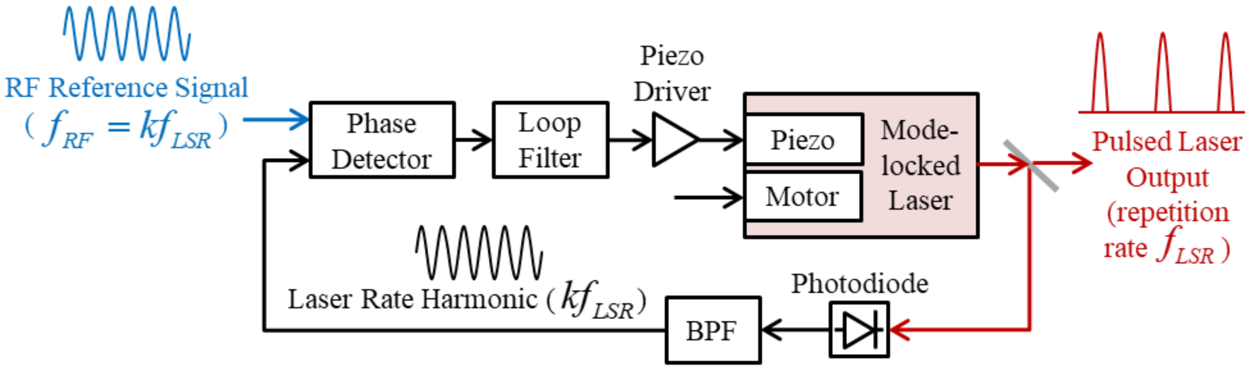
Sources of Phase Relation Errors



(a) Frequency division
(b) trigger-clock race

RF trigger resynch by LLRF clock



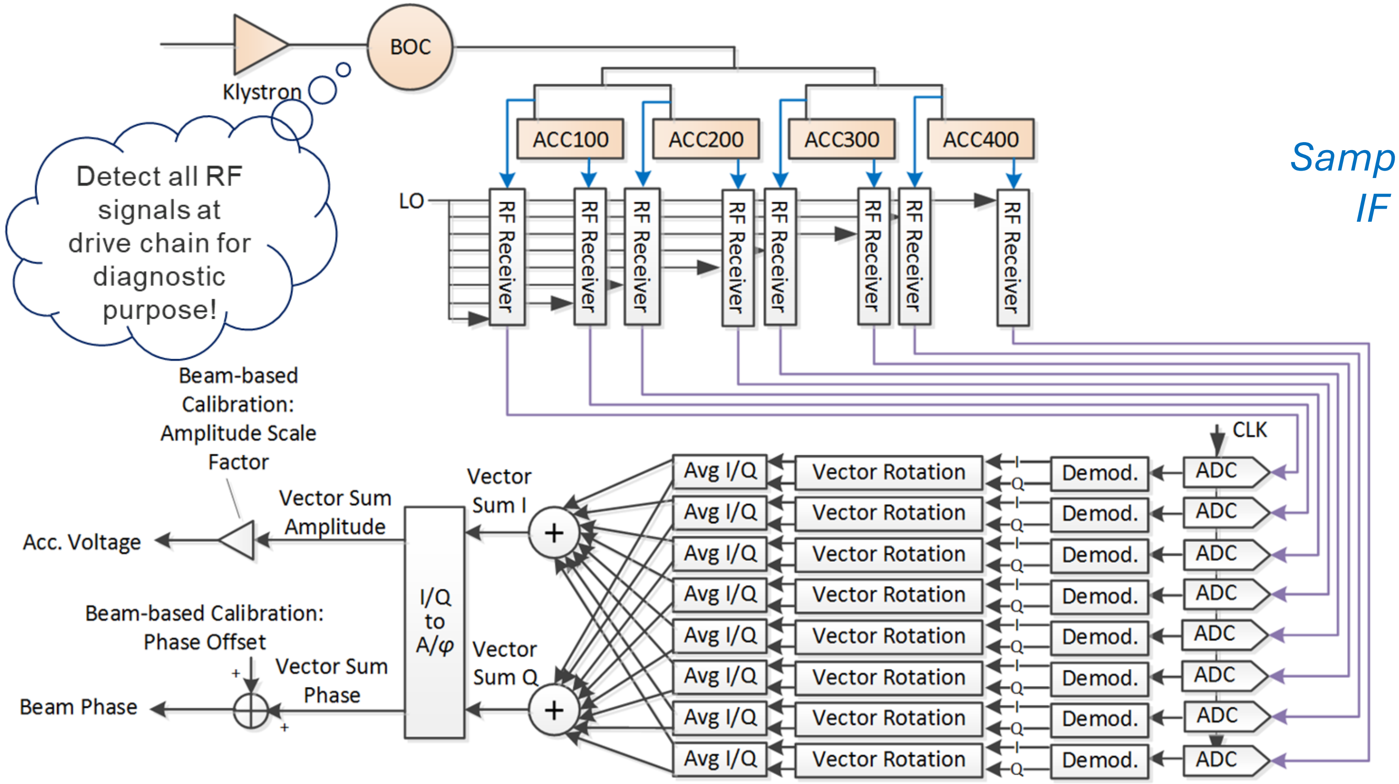


Laser oscillator synchronization

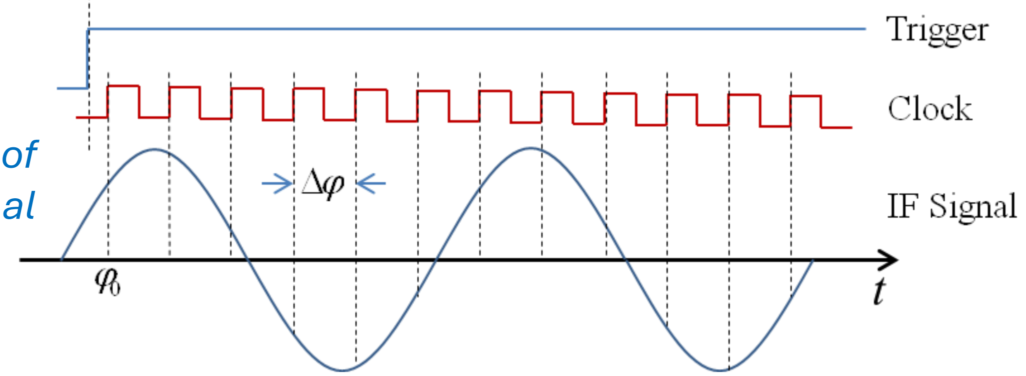
- A frequency divider (1/*n*) has *n* possible output phases after reset.
- A laser oscillator synchronized to a higher harmonic RF reference can be viewed as a frequency divider – the laser pulse can be at *n* possible timings (RF buckets) compared to the trigger time.
- Racing between trigger and clock shifts the time of the resynchronized trigger by one clock cycle.
- Phase change in the LLRF clock shifts the timing of the resynchronized RF trigger up to one LLRF clock cycle.

Phase Measurement Uncertainty

RF Phase Measurement Uncertainties

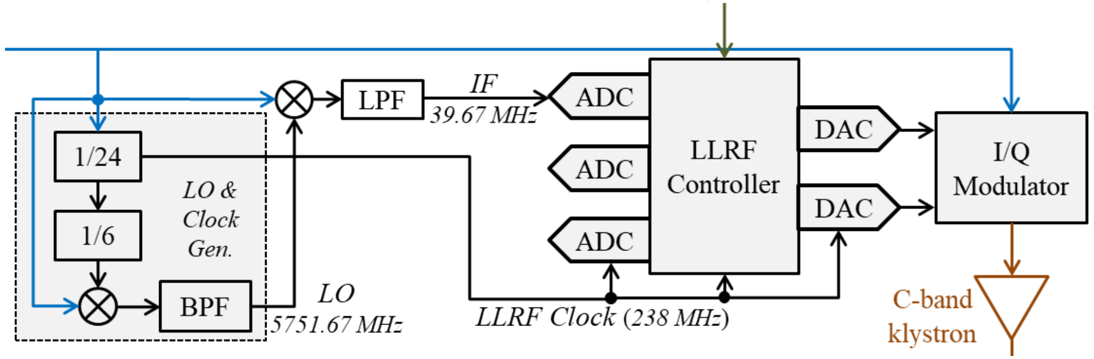


Measurements of SwissFEL RF station signals



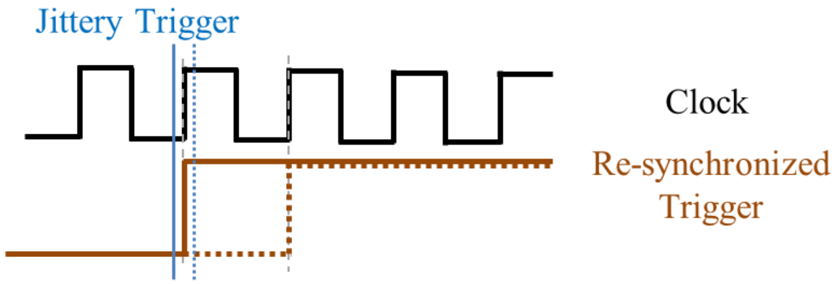
Sampling of IF signal

- The first sample after trigger is used as the phase reference for the non-I/Q demodulation algorithm (6 samples per IF cycle, $\Delta\varphi = 60^{\circ}$), i.e., demodulation is reset by the trigger.
- Phase measurement uncertainty is an integer multiple of 60º. If it happens on signals used for RF feedback, the RF field phase for beam will be wrong.
- **Possible causes**:
  - Power cycle of the LO & clock generator (phase uncertainties of frequency dividers).
  - Trigger-ADC clock race (random jump for the first sample after trigger).



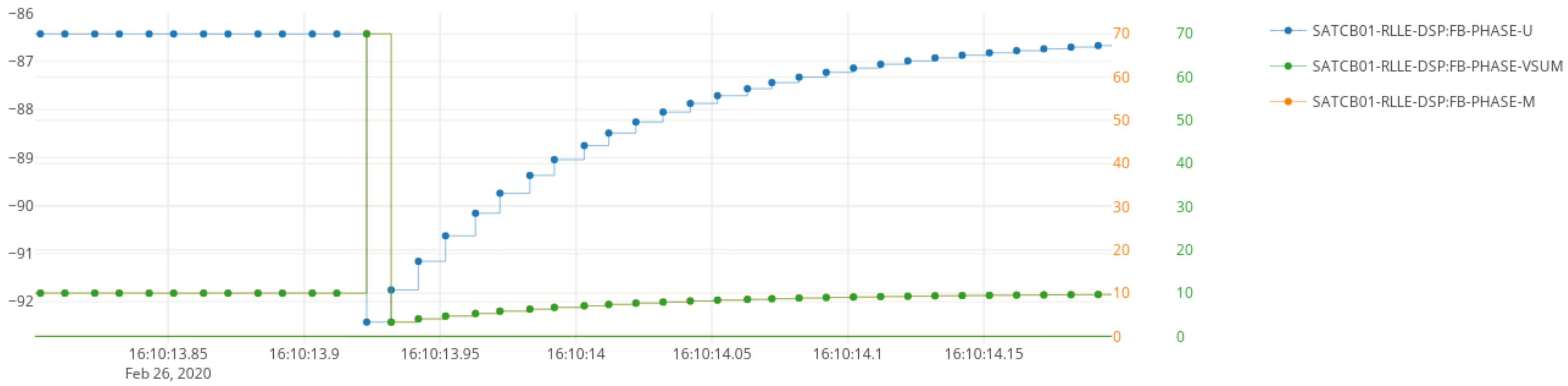
LLRF LO & Clock Generator

Mitigation Methods – RF Phase Feedback Exception Handling

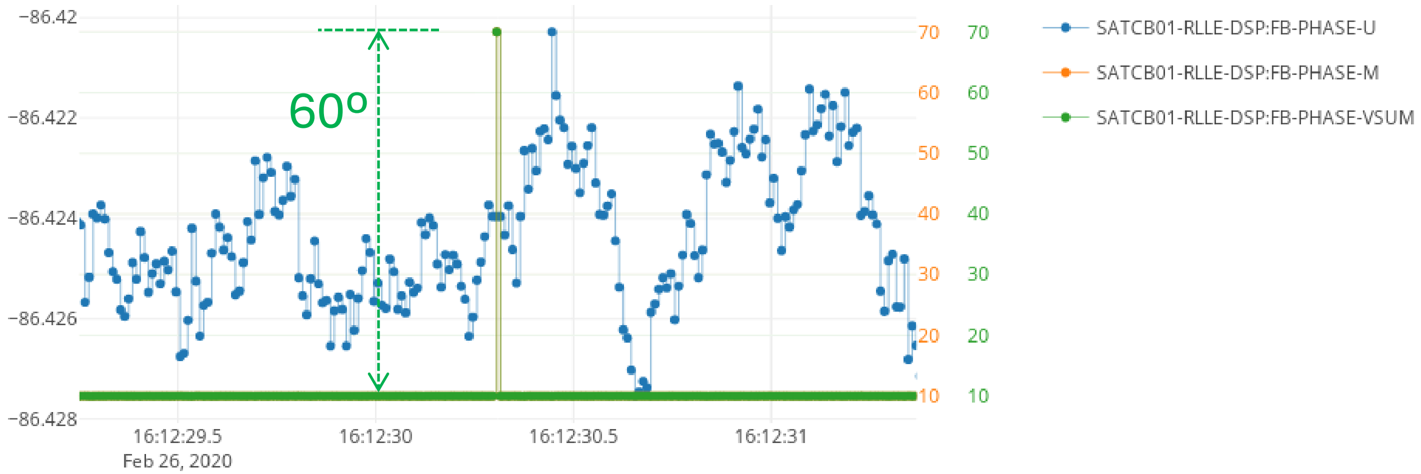


Trigger-clock race

- With the trigger-clock race, the jittery trigger may cross the rising edge of the clock from time to time, resulting in a single-shot phase jump of ±60º.
- The pulse-to-pulse phase feedback captures this jump and causes transient in the actual cavity phase.
- Exception handling in the phase feedback loop can detect such a single-shot jump in measurement and ignore it.

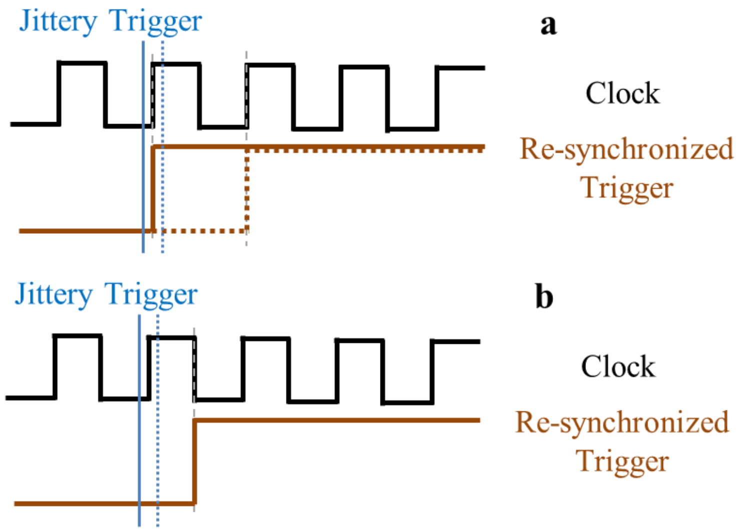


Phase-loop transient caused by the fake phase jump due to the trigger-clock race

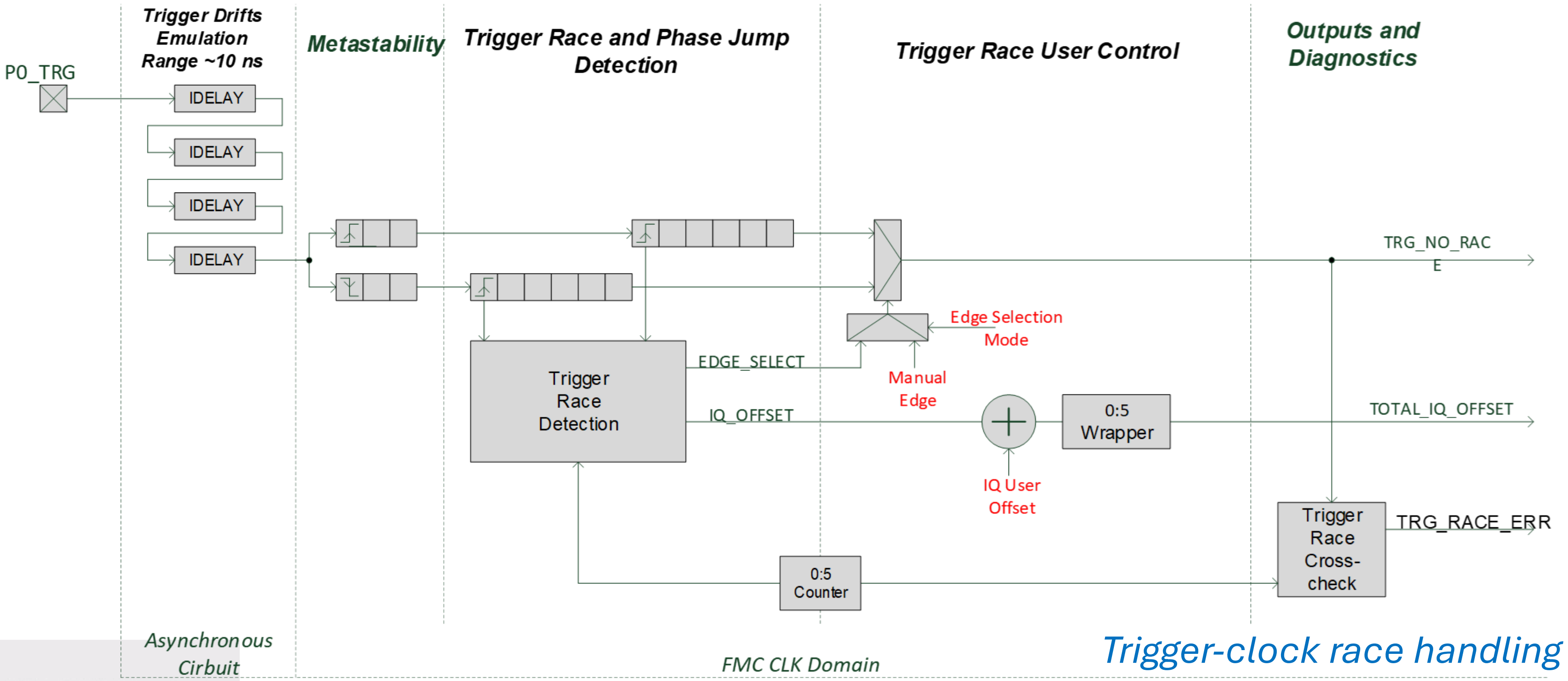


Single-shot phase jump exception handling in the phase feedback loop

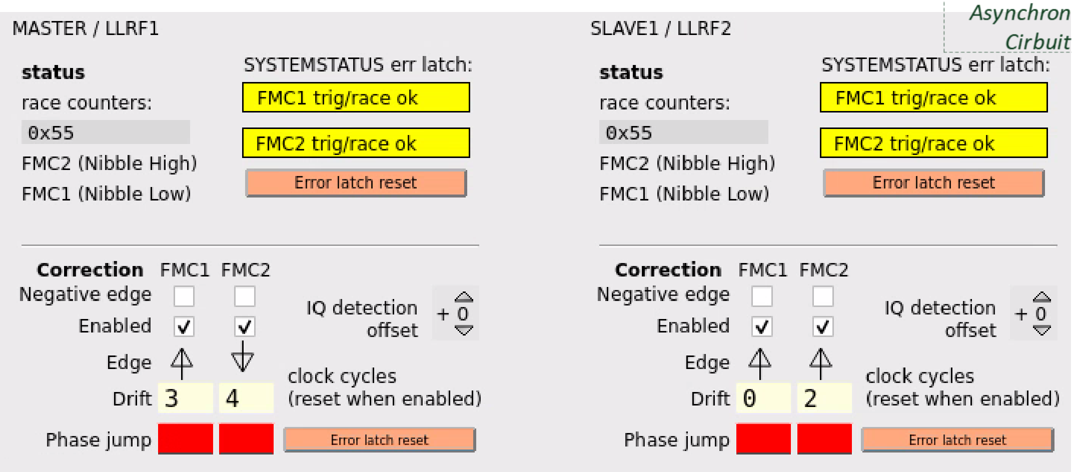
Mitigation Methods – Trigger-clock Race Handling



Method to avoid racing: synchronize the trigger at the opposite clock edge



Trigger-clock race handling in FPGA firmware



MASTER / LLRF1

status
race counters:
0x55
FMC2 (Nibble High)
FMC1 (Nibble Low)

SYSTEMSTATUS err latch:
FMC1 trig/race ok
FMC2 trig/race ok
Error latch reset

Correction	FMC1	FMC2
Negative edge	☐	☐
Enabled	☑	☑
Edge	↑	↓
Drift	3	4
Phase jump	🟥	🟥

IQ detection offset + 0
clock cycles (reset when enabled)
Error latch reset

SLAVE1 / LLRF2

status
race counters:
0x55
FMC2 (Nibble High)
FMC1 (Nibble Low)

SYSTEMSTATUS err latch:
FMC1 trig/race ok
FMC2 trig/race ok
Error latch reset

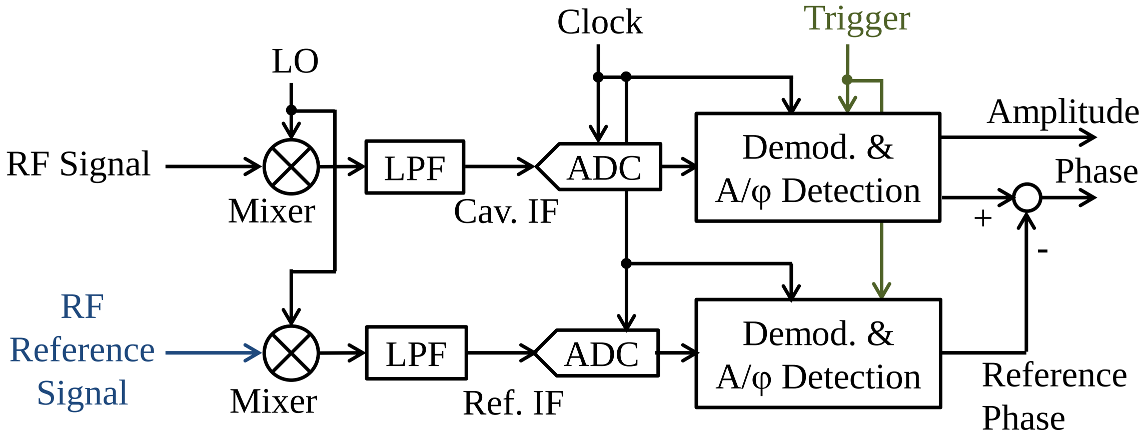
Correction	FMC1	FMC2
Negative edge	☐	☐
Enabled	☑	☑
Edge	↑	↑
Drift	0	2
Phase jump	🟥	🟥

IQ detection offset + 0
clock cycles (reset when enabled)
Error latch reset

Trigger-clock race handling GUI

- **Firmware implementation:**
  - Detect the trigger-clock race by counting the clock cycles between two adjacent triggers – should be a multiple of 6.
  - Automatically select a clock edge to synchronize the trigger input.
  - Correct the phase measurement jump by adjusting the index-offset of the non-I/Q demodulation coefficients array.
  - Compensate for the trigger timing jump (by ±1 clock cycle) caused by the selection of an opposite edge. Note: this may fail if at the edge of the shift registers (with 6 stages – “Drift” field on GUI).

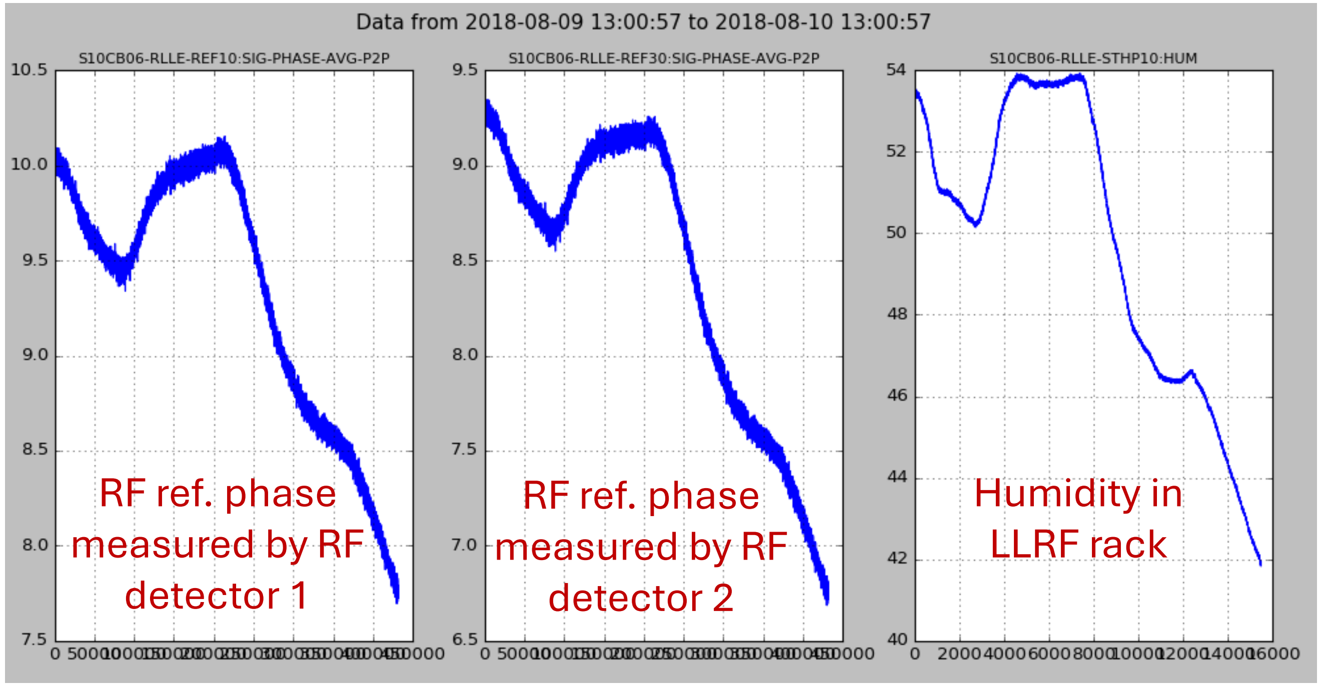
Mitigation Methods – Reference Tracking



Schematic of reference tracking

- SwissFEL LLRF uses reference tracking implemented in the real-time software to mitigate the phase measurement uncertainties.
- **Important**: the RF reference signal should be measured with the same LO, clock and trigger as the RF signals.
- The RF reference signal phase is low-pass filtered so that the common-mode slow drift (including static error) in the RF signal phase are removed, without introducing much uncorrelated noise.

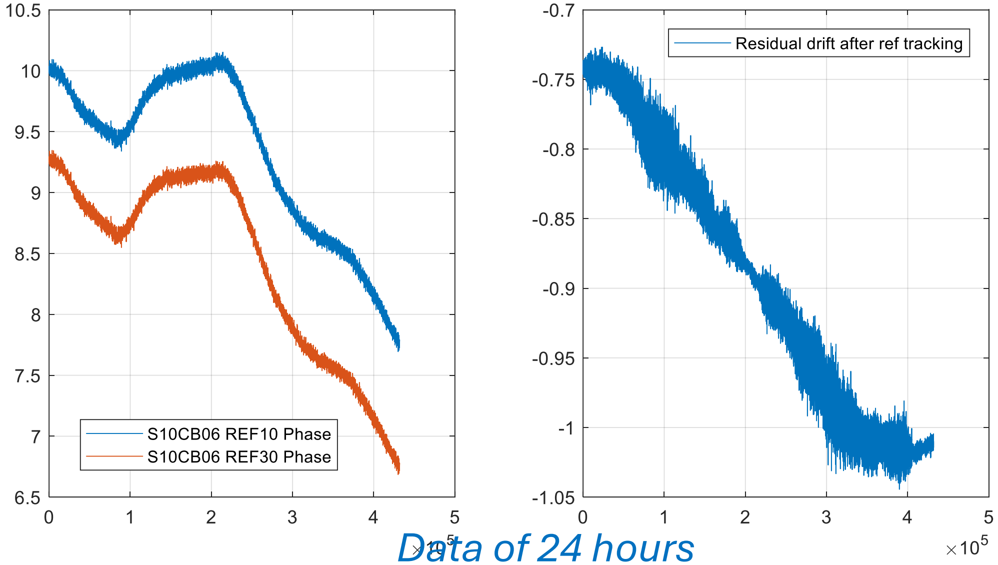
Phase measurement drift VS humidity



RF ref. phase measured by RF detector 1

RF ref. phase measured by RF detector 2

Humidity in LLRF rack

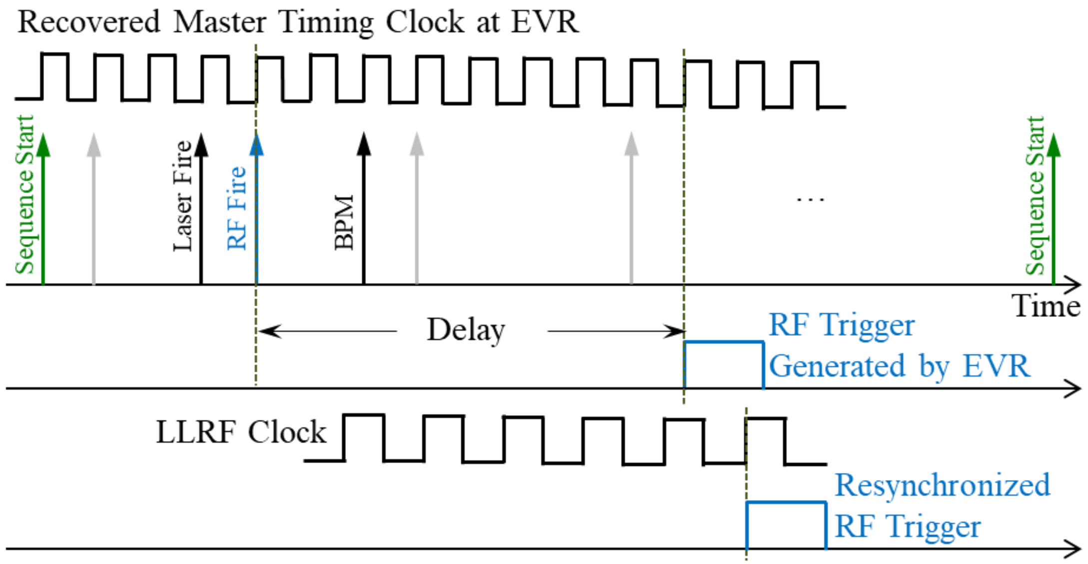


Data of 24 hours

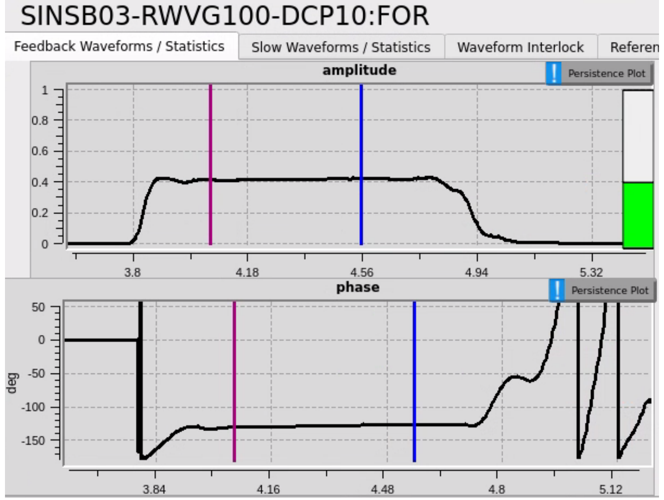
Residual drift in phase measurement with reference tracking (effects will be corrected with beam-based feedback)

Macro RF Pulse Timing Uncertainty

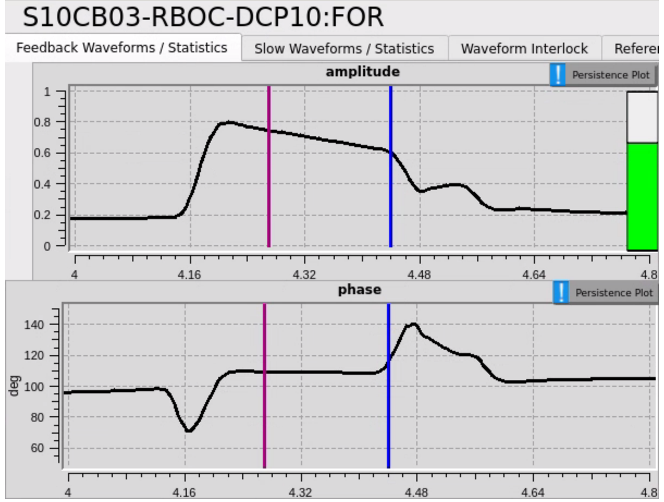
Reasons for Macro RF Pulse Timing Uncertainties



Generation of the synchronized trigger in the LLRF firmware



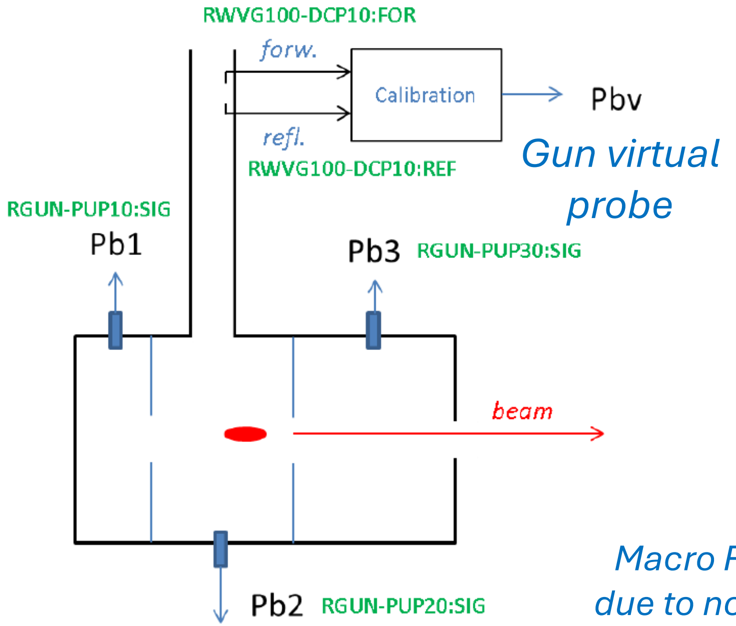
S-band macro RF pulse

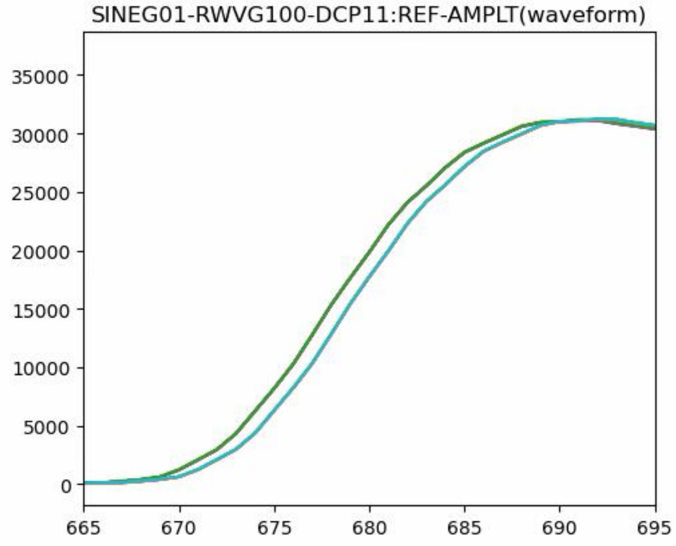


C-band macro RF pulse

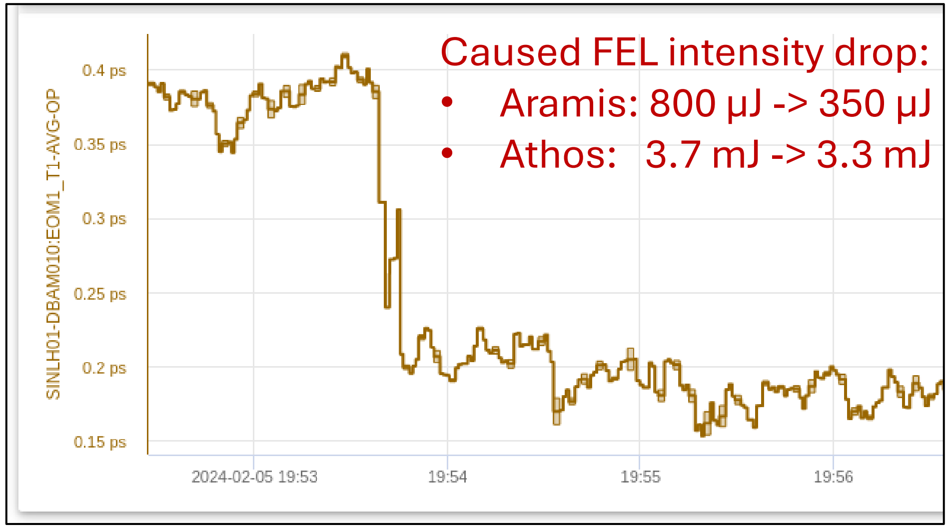
- The macro RF pulse is produced by DAC, starting from the first rising edge of DAC clock after the synchronized trigger in the LLRF firmware logic.
- Two major sources of macro RF pulse timing uncertainties:
  - LLRF clock phase uncertainty after reboot of LO & clock generator (EVR clock = 142.8 MHz, LLRF clock = 249.9 MHz or 238 MHz).
  - Shift register failure (reaching the edges) in trigger-clock race handling firmware.
- The macro RF pulse timing error is up to ±1 clock cycle of LLRF. The consequences are:
  - The beam will be accelerated by a different part of the RF pulse, resulting in amplitude and phase errors, especially for C-band with pulse compressors.
  - The RF pulse step time for bunch2 control needs to be recalibrated, otherwise, the tuning of bunch2 may affect bunch1 (not discussed in this talk).
- **Mitigation methods**: the macro RF pulse timing error is a random error after machine restart – we cannot make the RF totally repetitive – beam-based feedback is required to handle this issue.

Macro RF Pulse Timing Issue at RF Gun





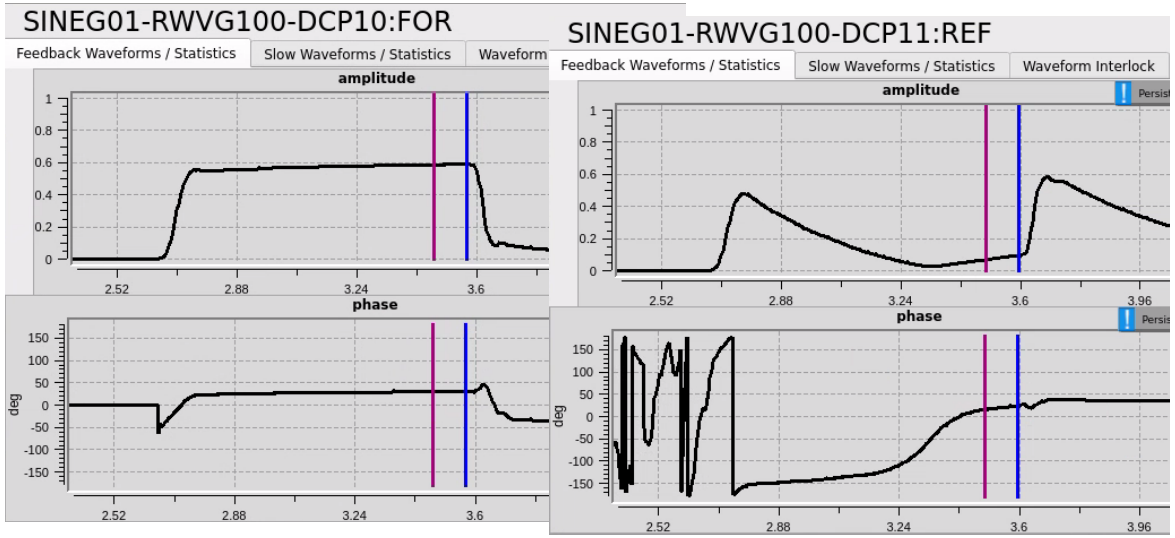
Macro RF pulse timing change by one clock cycle due to not-fully-succeed trigger-clock race handling



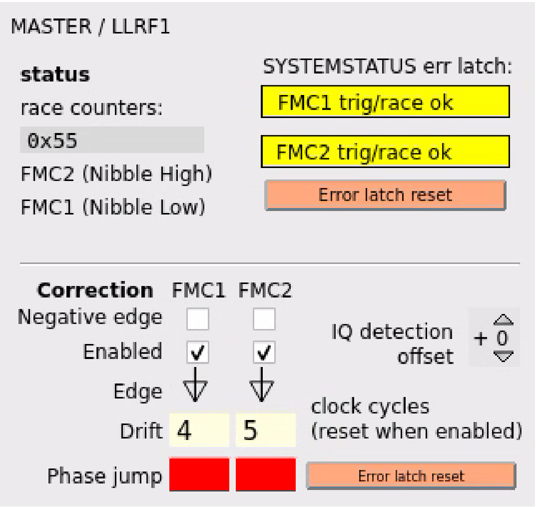
Caused FEL intensity drop:

- Aramis: 800 μJ -> 350 μJ
- Athos: 3.7 mJ -> 3.3 mJ

Resulting bunch arrival time jump at laser heater



The cavity forward (left) and reflected (right) signals for virtual probe



MASTER / LLRF1

status

race counters:

0x55

FMC2 (Nibble High)

FMC1 (Nibble Low)

SYSTEMSTATUS err latch:

FMC1 trig/race ok

FMC2 trig/race ok

Error latch reset

Correction	FMC1	FMC2
Negative edge	☐	☐
Enabled	☑	☑
Edge		
Drift	4	5
Phase jump	🟥	🟥

IQ detection offset + 0

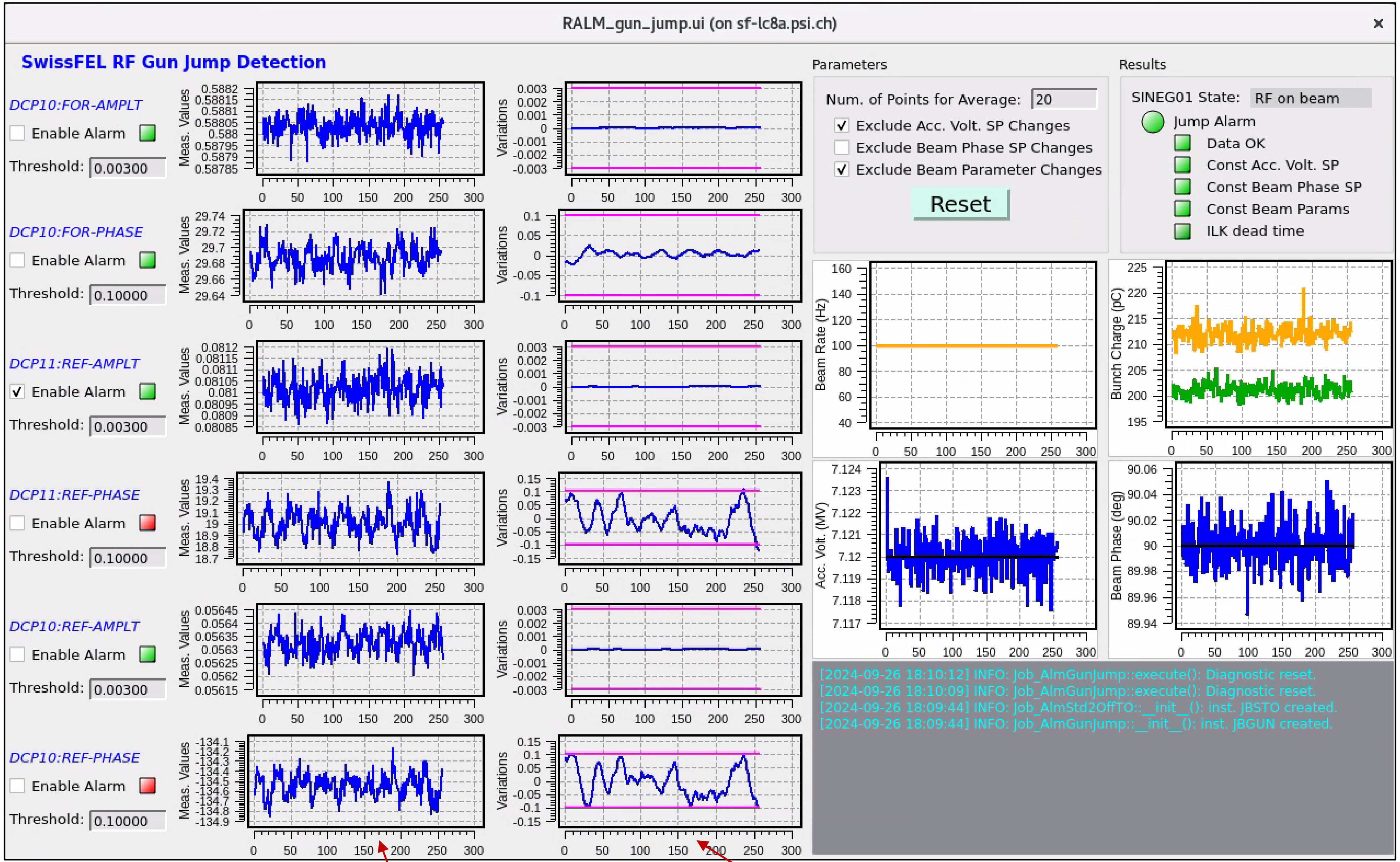
clock cycles (reset when enabled)

Error latch reset

Shift register failure (at edge 5) in trigger-clock race handling

- The RF Gun is not well covered by the beam-based feedback, and FEL lasing is very sensitive to Gun amplitude/phase changes.
- **Mitigation methods**: detect the jumps in forward and reflected signals and produce alarm. Then the operator can adjust the Gun amplitude/phase setpoints or solenoid current to restore the FEL lasing.

Macro RF Pulse Timing Issue at RF Gun (cont.)



SwissFEL RF Gun Jump Detection

DCP10:FOR-AMPLT
☐ Enable Alarm 🟩
Threshold: 0.00300

DCP10:FOR-PHASE
☐ Enable Alarm 🟩
Threshold: 0.10000

DCP11:REF-AMPLT
☑ Enable Alarm 🟩
Threshold: 0.00300

DCP11:REF-PHASE
☐ Enable Alarm 🟥
Threshold: 0.10000

DCP10:REF-AMPLT
☐ Enable Alarm 🟩
Threshold: 0.00300

DCP10:REF-PHASE
☐ Enable Alarm 🟥
Threshold: 0.10000

Parameters
Num. of Points for Average: 20
☑ Exclude Acc. Volt. SP Changes
☐ Exclude Beam Phase SP Changes
☑ Exclude Beam Parameter Changes
Reset

Results
SINEG01 State: RF on beam
● Jump Alarm
🟩 Data OK
🟩 Const Acc. Volt. SP
🟩 Const Beam Phase SP
🟩 Const Beam Params
🟩 ILK dead time

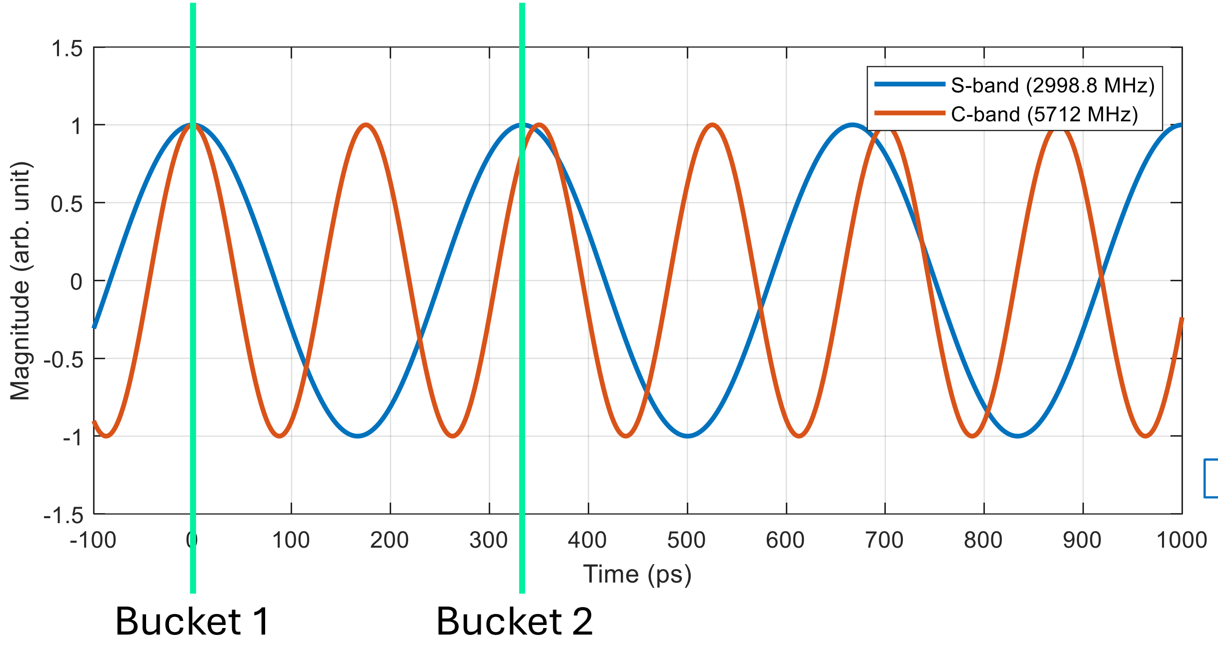
```
[2024-09-26 18:10:12] INFO: Job_AlmGunJump::execute(): Diagnostic reset.
[2024-09-26 18:10:09] INFO: Job_AlmGunJump::execute(): Diagnostic reset.
[2024-09-26 18:09:44] INFO: Job_AlmStd2OffTO::__init__(): inst. JBSTO created.
[2024-09-26 18:09:44] INFO: Job_AlmGunJump::__init__(): inst. JBGUN created.
```

5 Hz time-series of measurements

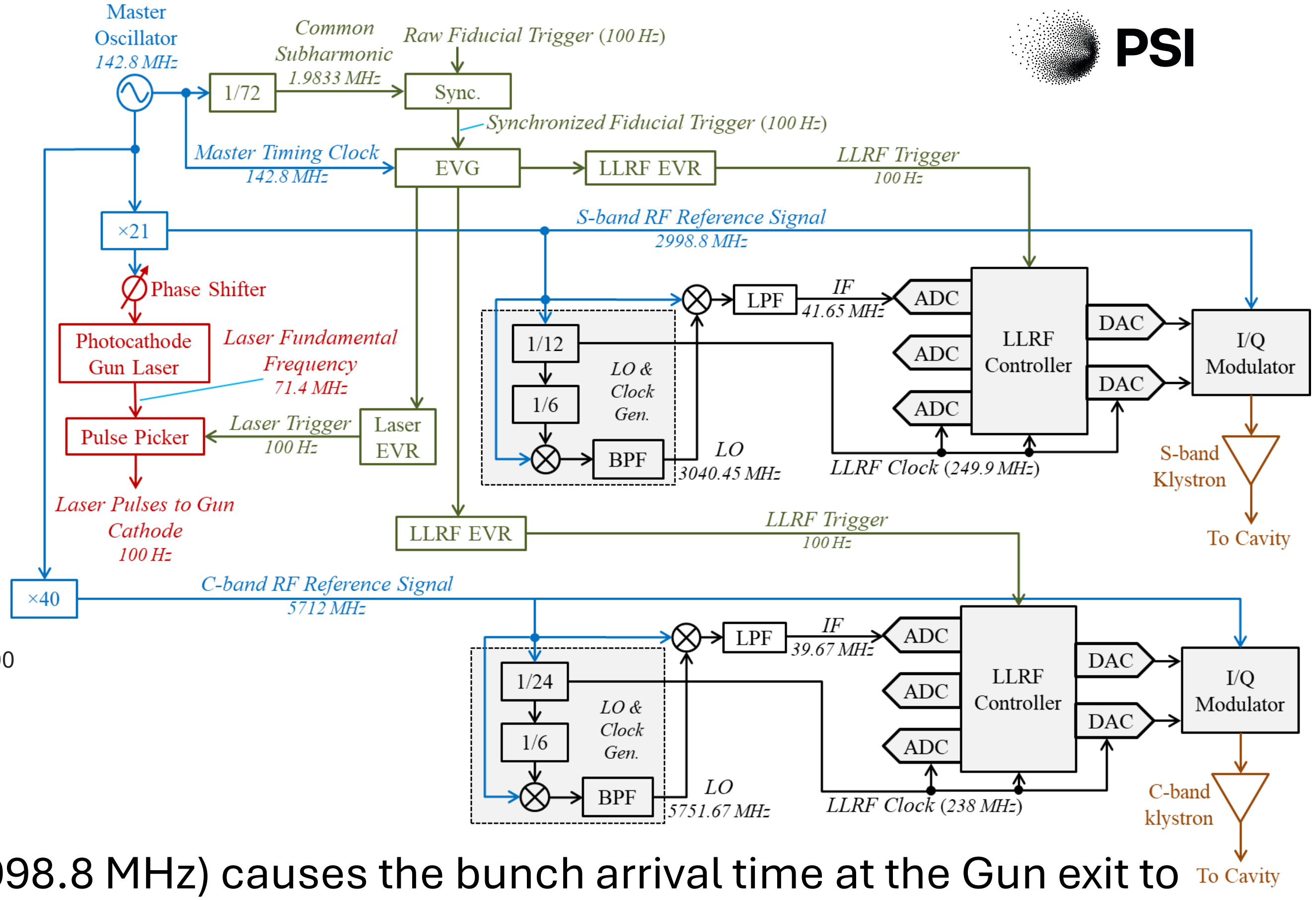
Difference of the head-tail points in the measurement buffer (updated for each point)

Gun Laser Bucket Error

Gun Laser Bucket Jump Issue

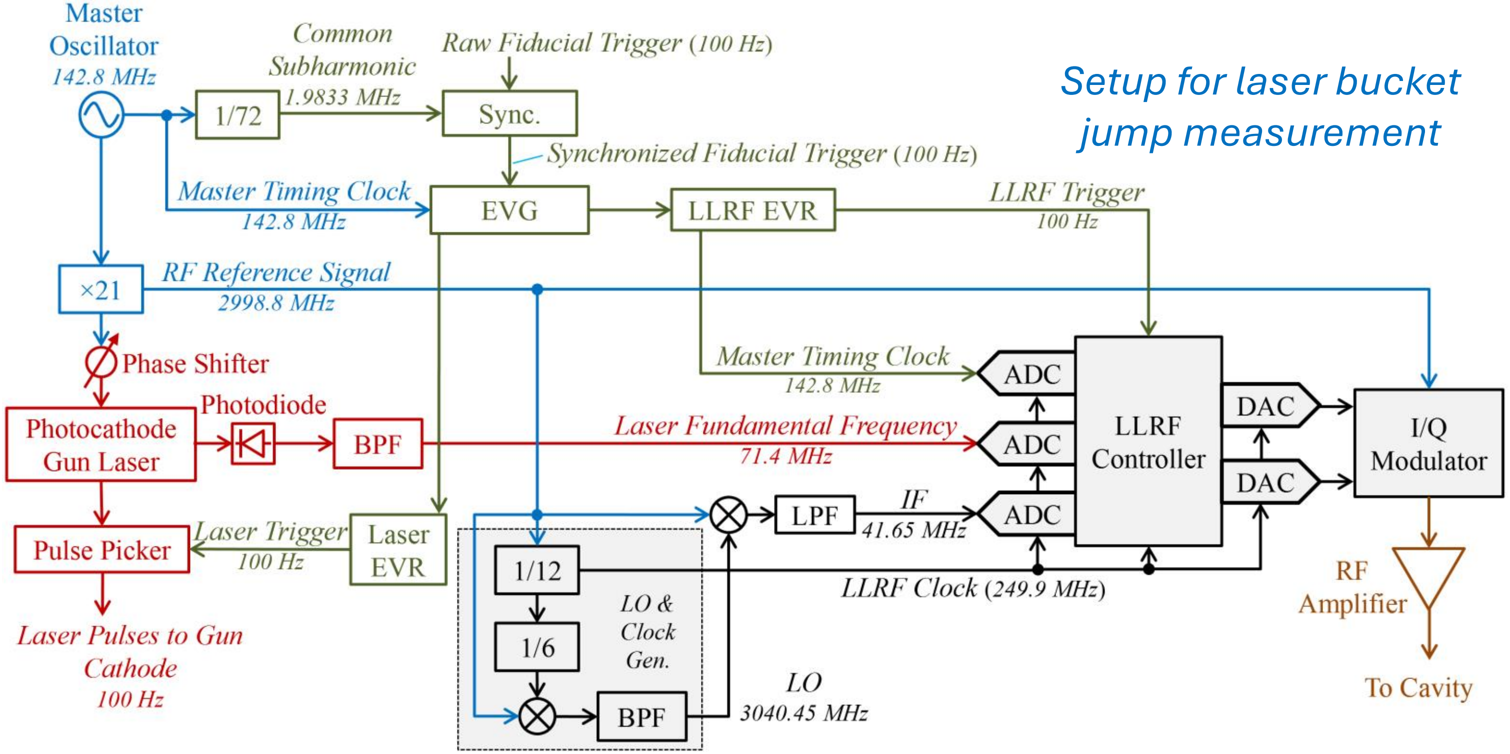


Beam phase changes for S/C-band for laser bucket jump

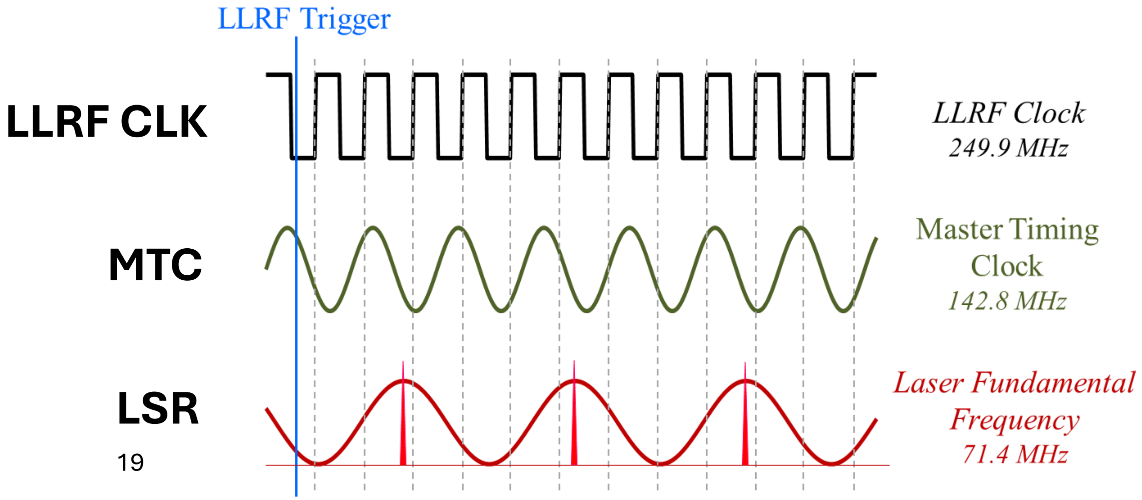


- Relocking the Gun laser to the S-band RF reference (2998.8 MHz) causes the bunch arrival time at the Gun exit to change by multiple RF periods (bucket).
- Laser bucket jump has the following consequences:
  - The bunch generation time has uncertainties compared to the trigger time. Therefore, when the bunch arrives at the RF stations, it will meet different parts of the macro RF pulse (similar effects as macro RF pulse timing error).
  - The beam phase at S-band RF stations are still correct, however, the beam phase at C-band stations will be wrong because of different standards of S/C-band frequencies!

Mitigation Methods – Detect the Laser Oscillator Phase



Setup for laser bucket jump measurement



Measuring the phases of the LSR and MTC with LLRF

- We use the Gun LLRF board to sample the fundamental frequency of the Gun laser (LSR) and the recovered master timing clock (MTC) form the EVR.
- In nominal case (*without laser bucket jump, only with LLRF trigger/clock timing/phase uncertainties*), the measured phase changes of them should satisfy

$$\frac{\Delta\varphi_{MTC}}{f_{MTC}} = \frac{\Delta\varphi_{LSR}}{f_{LSR}}$$

- Then, the phase error of the laser signal when bucket jump happens is

$$\delta\varphi_{LSR} := \Delta\varphi_{LSR} - \frac{f_{LSR}\Delta\varphi_{MTC}}{f_{MTC}}$$

- And the number of bucket jump of the laser can be calculated as

$$k_{LSR,bucket} := \delta\varphi_{LSR} / \Delta\varphi_{LSR,bucket}$$

where $\Delta\varphi_{LSR,bucket} = 71.4 / 2998.8 \times 360^\circ = 8.57^\circ$

Mitigation Methods – Detect the Laser Oscillator Phase (cont.)

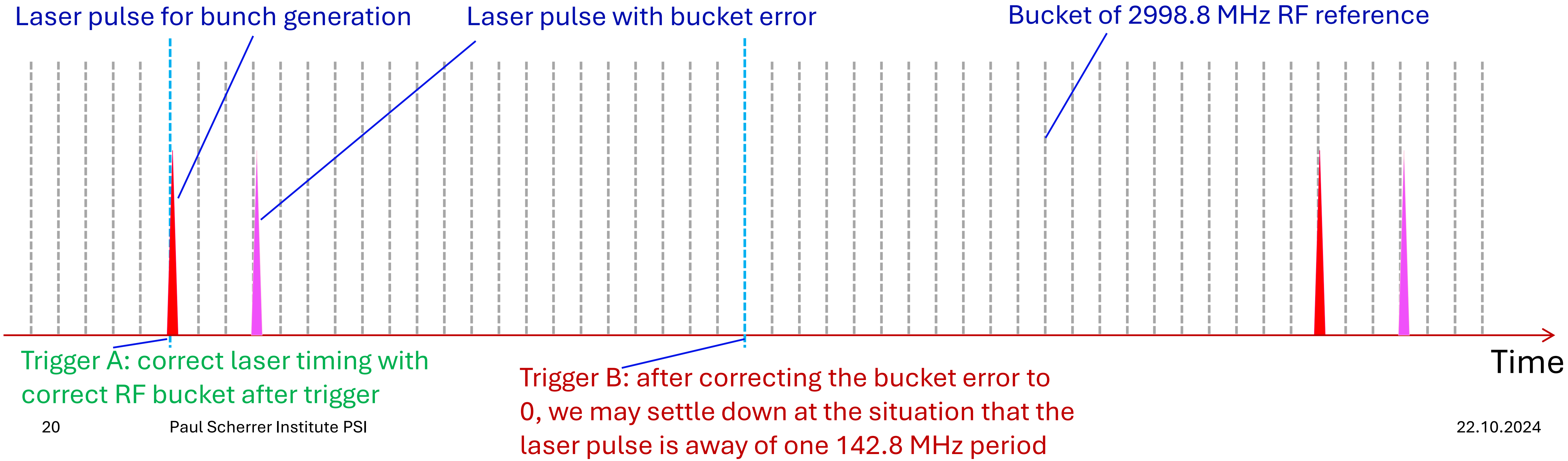
- Difficulties in calculating the phase error: the phases are wrapped every 360°.

$$\delta\varphi_{LSR} := \Delta\varphi_{LSR} - f_{LSR}\Delta\varphi_{MTC} / f_{MTC} = \Delta\varphi_{LSR} - \Delta\varphi_{MTC}/2$$

- Therefore, the measured value is always

$$\delta\varphi_{LSR,mea} := \Delta\varphi_{LSR,mea} - \Delta\varphi_{MTC,mea}/2 = \Delta\varphi_{LSR} - \Delta\varphi_{MTC}/2 + n\cdot 180^\circ, \quad \text{where } n \text{ is an integer.}$$

- Therefore, we need to remove multiple of 180° from the calculation to derive the estimate of $\delta\varphi_{LSR}$.
- **Note**: With this method, we might settle down at the position B in the figure below. The laser would be shifted by 7 ns (a period of MTC), since the MTC frequency is twice the LSR frequency. Other methods are needed to solve this ambiguity.

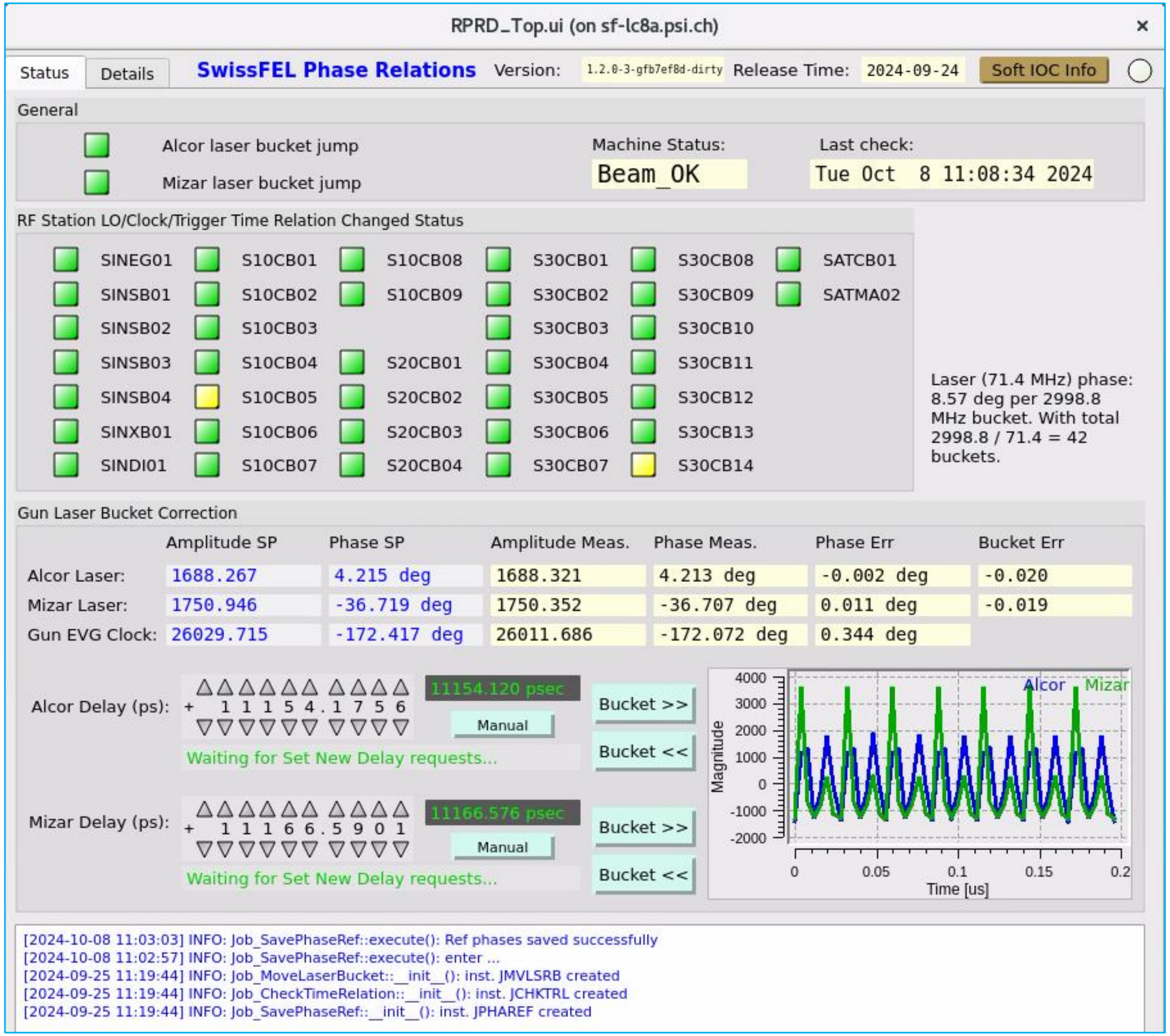


Trigger A: correct laser timing with correct RF bucket after trigger

Trigger B: after correcting the bucket error to 0, we may settle down at the situation that the laser pulse is away of one 142.8 MHz period

Mitigation Methods – Detect the Laser Oscillator Phase (cont.)

Panel of the soft IOC to detect the laser bucket jumps



SwissFEL Phase Relations Version: 1.2.0-3-gfb7ef8d-dirty Release Time: 2024-09-24

General

🟩 Alcor laser bucket jump

🟩 Mizar laser bucket jump

Machine Status: Beam_OK

Last check: Tue Oct 8 11:08:34 2024

RF Station LO/Clock/Trigger Time Relation Changed Status

🟩	SINEG01	🟩	S10CB01	🟩	S10CB08	🟩	S30CB01	🟩	S30CB08	🟩	SATCB01
🟩	SINSB01	🟩	S10CB02	🟩	S10CB09	🟩	S30CB02	🟩	S30CB09	🟩	SATMA02
🟩	SINSB02	🟩	S10CB03			🟩	S30CB03	🟩	S30CB10		
🟩	SINSB03	🟩	S10CB04	🟩	S20CB01	🟩	S30CB04	🟩	S30CB11		
🟩	SINSB04	🟨	S10CB05	🟩	S20CB02	🟩	S30CB05	🟩	S30CB12		
🟩	SINXB01	🟩	S10CB06	🟩	S20CB03	🟩	S30CB06	🟩	S30CB13		
🟩	SINDI01	🟩	S10CB07	🟩	S20CB04	🟩	S30CB07	🟨	S30CB14		

Laser (71.4 MHz) phase: 8.57 deg per 2998.8 MHz bucket. With total 2998.8 / 71.4 = 42 buckets.

Gun Laser Bucket Correction

	Amplitude SP	Phase SP	Amplitude Meas.	Phase Meas.	Phase Err	Bucket Err
Alcor Laser:	1688.267	4.215 deg	1688.321	4.213 deg	-0.002 deg	-0.020
Mizar Laser:	1750.946	-36.719 deg	1750.352	-36.707 deg	0.011 deg	-0.019
Gun EVG Clock:	26029.715	-172.417 deg	26011.686	-172.072 deg	0.344 deg	

Alcor Delay (ps): + 1 1 1 5 4 . 1 7 5 6 11154.120 psec

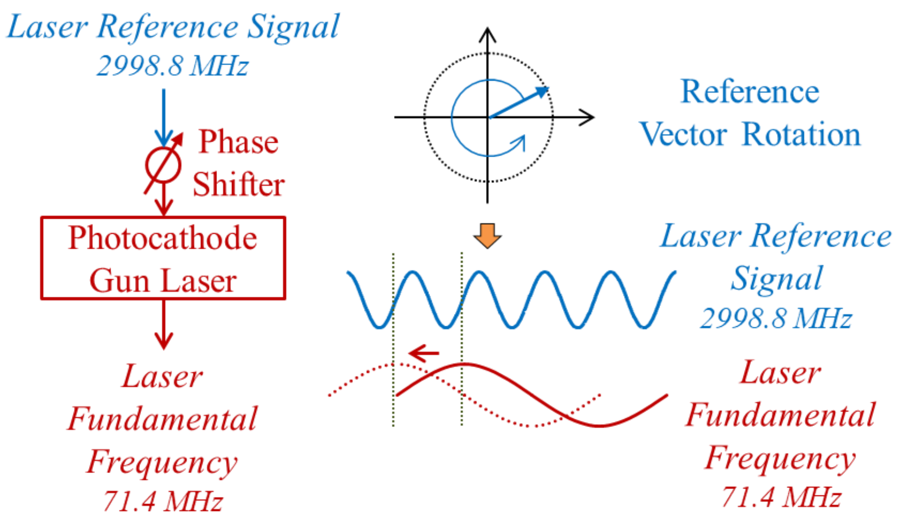
Waiting for Set New Delay requests...

Mizar Delay (ps): + 1 1 1 6 6 . 5 9 0 1 11166.576 psec

Waiting for Set New Delay requests...

```
[2024-10-08 11:03:03] INFO: Job_SavePhaseRef::execute(): Ref phases saved successfully
[2024-10-08 11:02:57] INFO: Job_SavePhaseRef::execute(): enter ...
[2024-09-25 11:19:44] INFO: Job_MoveLaserBucket::__init__(): inst. JMVLSRB created
[2024-09-25 11:19:44] INFO: Job_CheckTimeRelation::__init__(): inst. JCHKTRL created
[2024-09-25 11:19:44] INFO: Job_SavePhaseRef::__init__(): inst. JPHAREF created
```

Mitigation Methods – Laser Bucket Correction


Laser Reference Signal
2998.8 MHz

Phase Shifter

Photocathode Gun Laser

Laser Fundamental Frequency
71.4 MHz

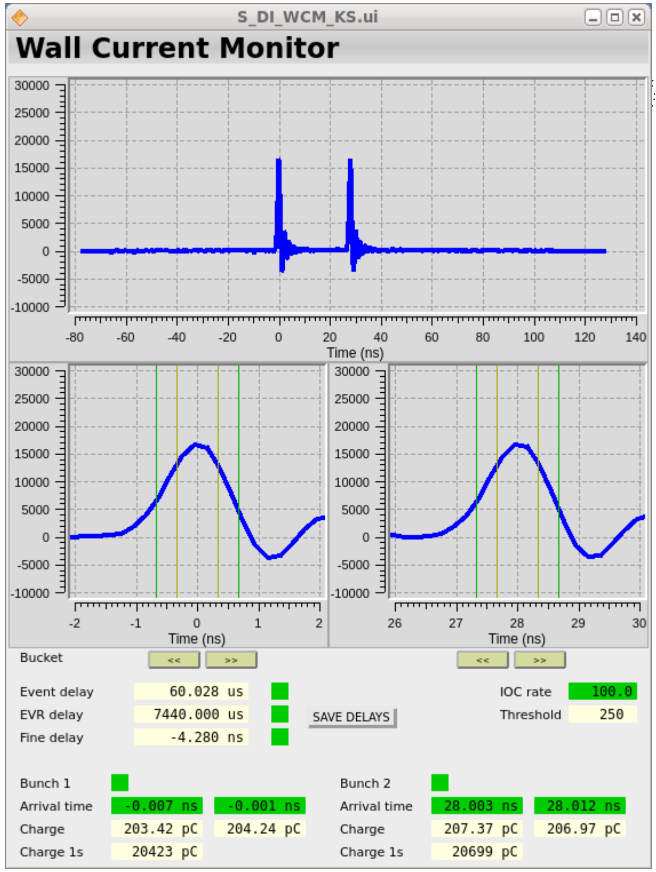
Reference Vector Rotation

Laser Reference Signal
2998.8 MHz

Laser Fundamental Frequency
71.4 MHz

Principle of laser bucket correction

- The laser bucket is adjusted by rotating the RF reference phase shifter before the laser oscillator by full cycles.
- We use the RF Gun wall current monitor to detect the case of “Trigger B”, in which the bunch will be 7 ns away compared to the initial timing. It is detectable with the oscilloscope as on the GUI.



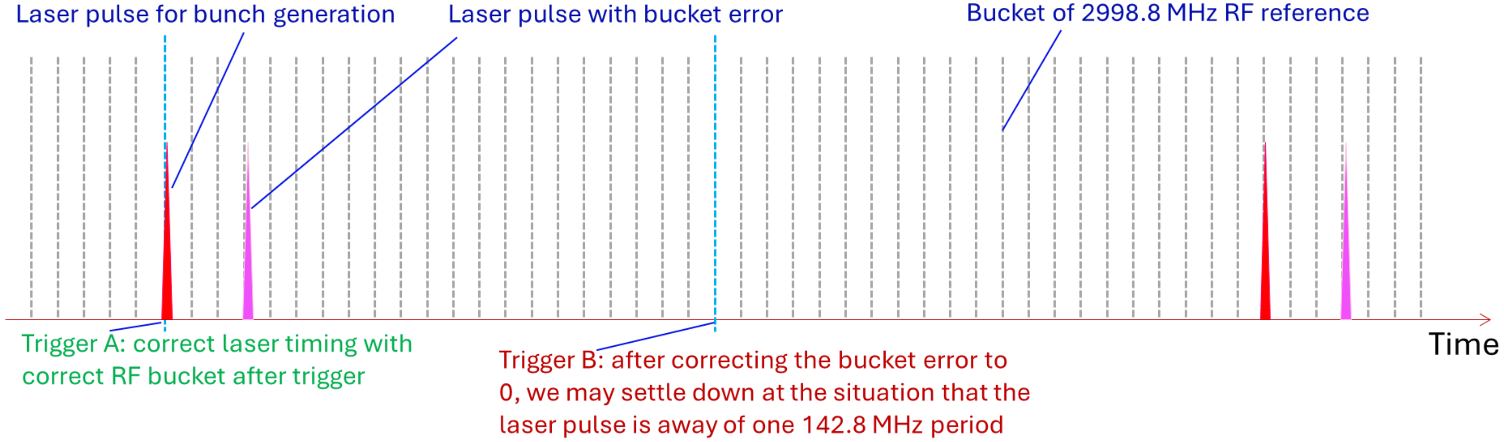
Event delay 60.028 us
EVR delay 7440.000 us
Fine delay -4.280 ns
IOC rate 100.0
Threshold 250

Bunch 1
Arrival time -0.007 ns -0.001 ns
Charge 203.42 pC 204.24 pC
Charge 1s 20423 pC

Bunch 2
Arrival time 28.003 ns 28.012 ns
Charge 207.37 pC 206.97 pC
Charge 1s 20699 pC

RF Gun wall current monitor signal

Courtesy of:
Edwin James Divall, Gian Luca Orlandi, Didier Voulot


Laser pulse for bunch generation

Laser pulse with bucket error

Bucket of 2998.8 MHz RF reference

Trigger A: correct laser timing with correct RF bucket after trigger

Trigger B: after correcting the bucket error to 0, we may settle down at the situation that the laser pulse is away of one 142.8 MHz period

Time

Note:

1. The bucket error detection method is valid if the laser optical path does not change, e.g., only the laser oscillator is unlocked and relocked.
2. If the laser optical path is changed (e.g., after optimizing the laser amplifier), the wall current monitor can indicate the laser timing change. The laser timing error should be corrected by adjusting the laser trigger delay and the reference phase shifter (may not in full cycles).

Conclusion and Outlook

Conclusions and Outlooks

Conclusions:

- After several years of consolidation, the SwissFEL LLRF system is robust against machine or subsystem reboots or power cycles. The beam phases of all RF stations can be kept after a machine restart.
- Due to the residual uncontrollable errors, mainly from the macro RF pulse timing uncertainties, the SwissFEL RF system is not fully repetitive. However, these are minor errors not affecting the beam startup and can be compensated for by the beam-based feedback.

Outlooks:

- A new method based on multiplying the common-subharmonic frequency (1.9833 MHz) is under consideration to better diagnose the laser bucket error. It needs a new hardware to multiply the frequency.
- Pulse-to-pulse reference tracking with configurable moving average is under test for common-mode phase noise cancellation.
- Automation tools to identify the RF pulse step time for bunch2 adjustment is under test.

Thank you!