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PSI

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RF and Beam Stability at SwissFEL

LLRF2019 Workshop, Chicago, USA
September 29 – October 3, 2019

Presented at LLRF Workshop 2019 (LLRF2019, arXiv:1909.06754)

Outline

- SwissFEL RF System Overview
- RF System Stability
- RF Jitter Mitigation
- Beam Stability
- Summary and Outlook

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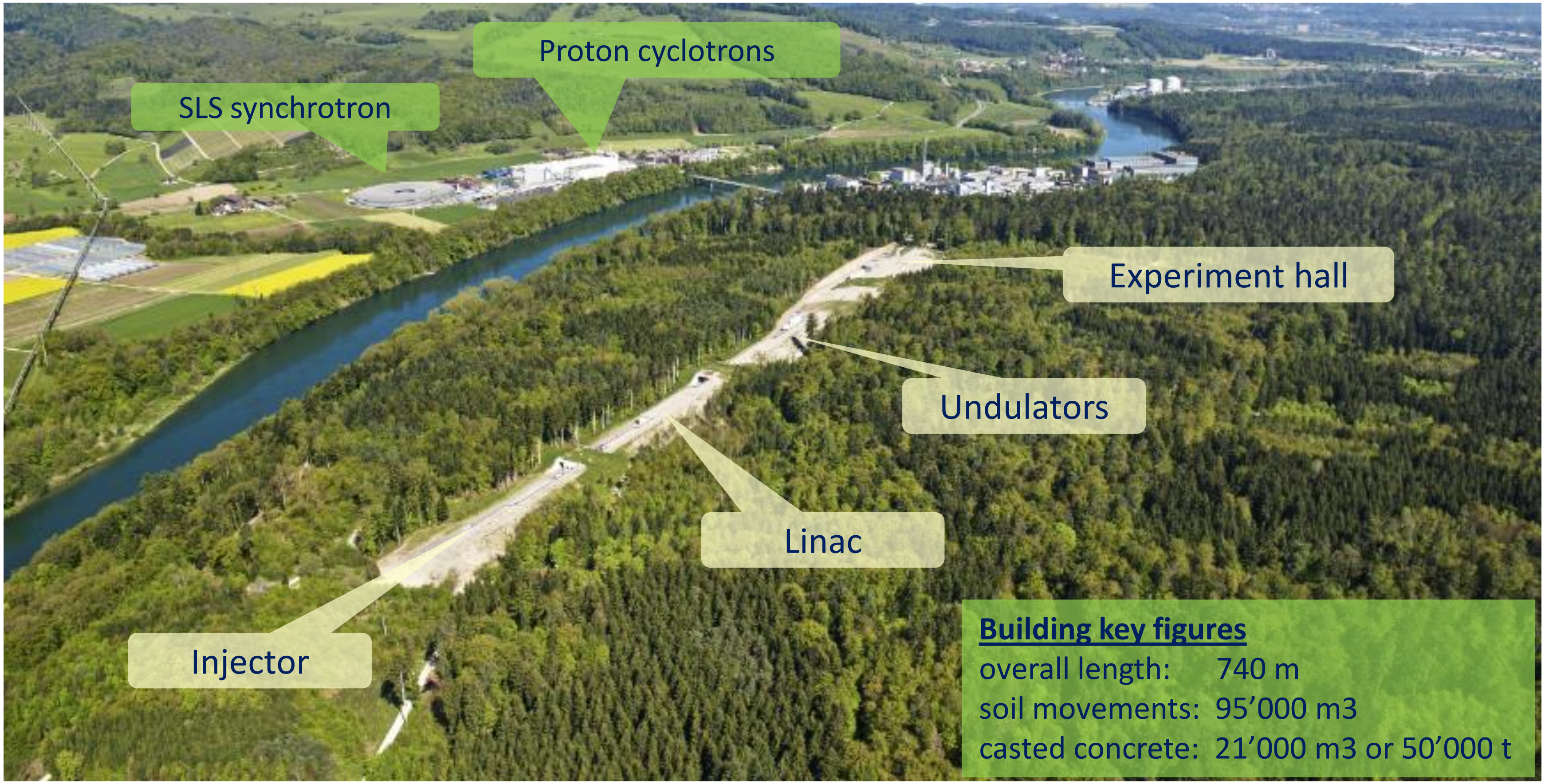
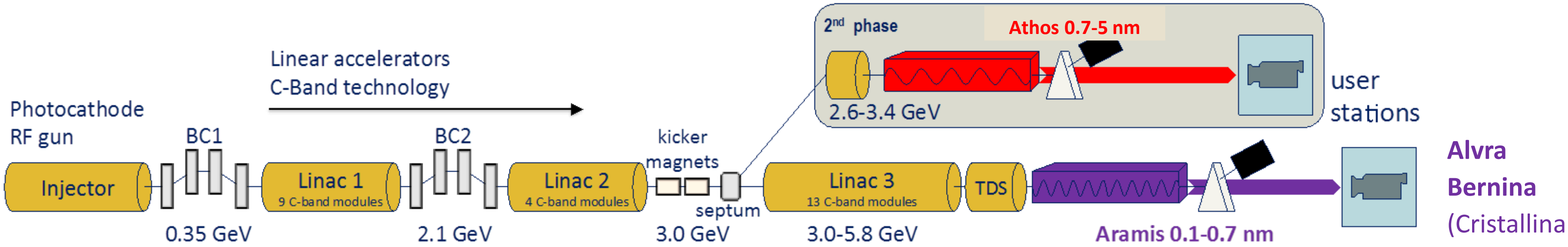
SwissFEL RF System Overview

SwissFEL Site



SwissFEL Overview



Main parameters

Wavelength from	0.1 - 5 nm
Photon energy	0.2 - 12 keV
Pulse duration (rms)	1 - 20 fs
e^- Energy (0.1 nm)	5.8 GeV
e^- Bunch charge	10 - 200 pC

ARAMIS

Hard X-ray FEL, λ=0.1 - 0.7 nm (12 - 2 keV),
First users 2018.

ATHOS

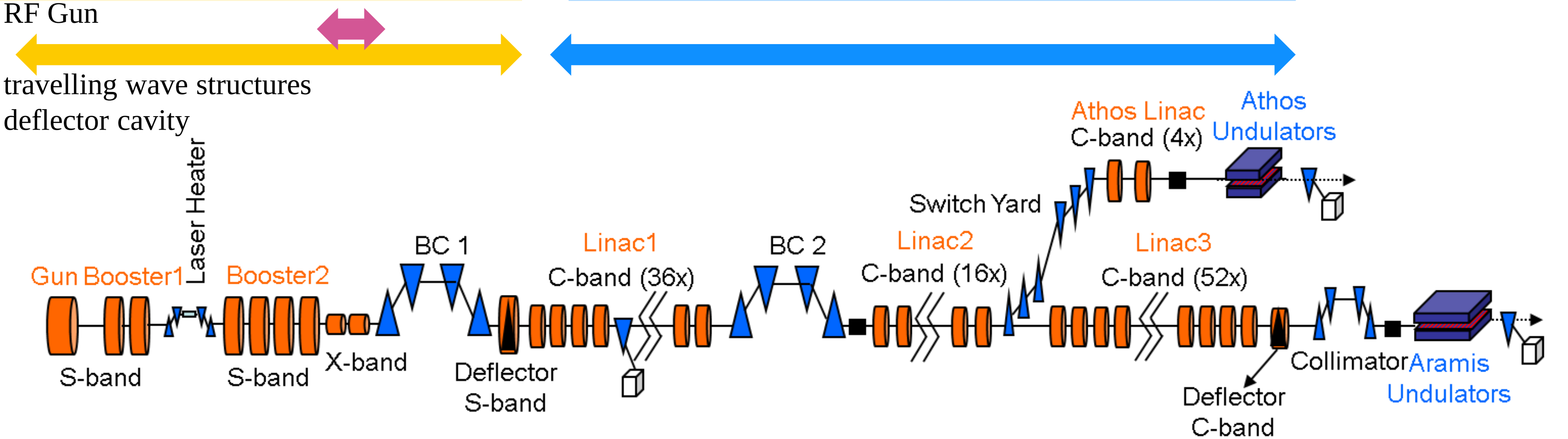
Beam Energy 2.7 - 3.3 GeV,
Soft X-ray FEL, λ=0.65 - 5.0 nm (2 - 0.2 keV),
2nd construction phase 2017 – 2021.

SwissFEL RF System Overview

6x S-band (2998.8 MHz)	1x X-band (11.9952 GHz)	26x C-band (5712 MHz) (phase 1 without Athos beam line)	RF stations

1x RF Gun

4x travelling wave structures
1x deflector cavity



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

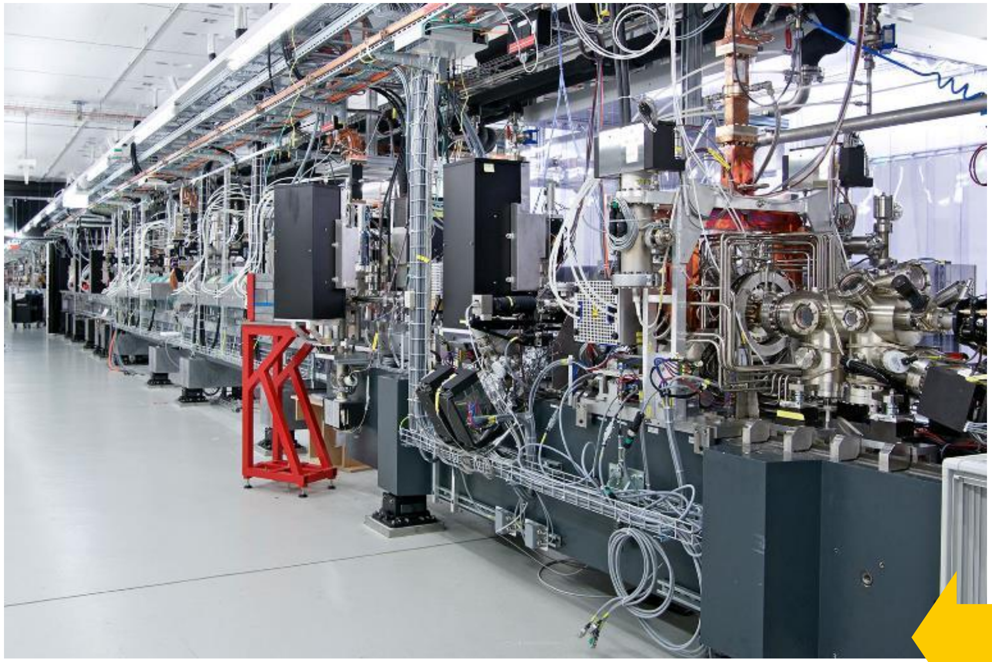
Aramis beam stability requirements (RMS):

- Peak current (bunch length): < 5 %
- Beam arrival time: < 20 fs
- Beam energy: < 5e-4

RF stability requirements (RMS):

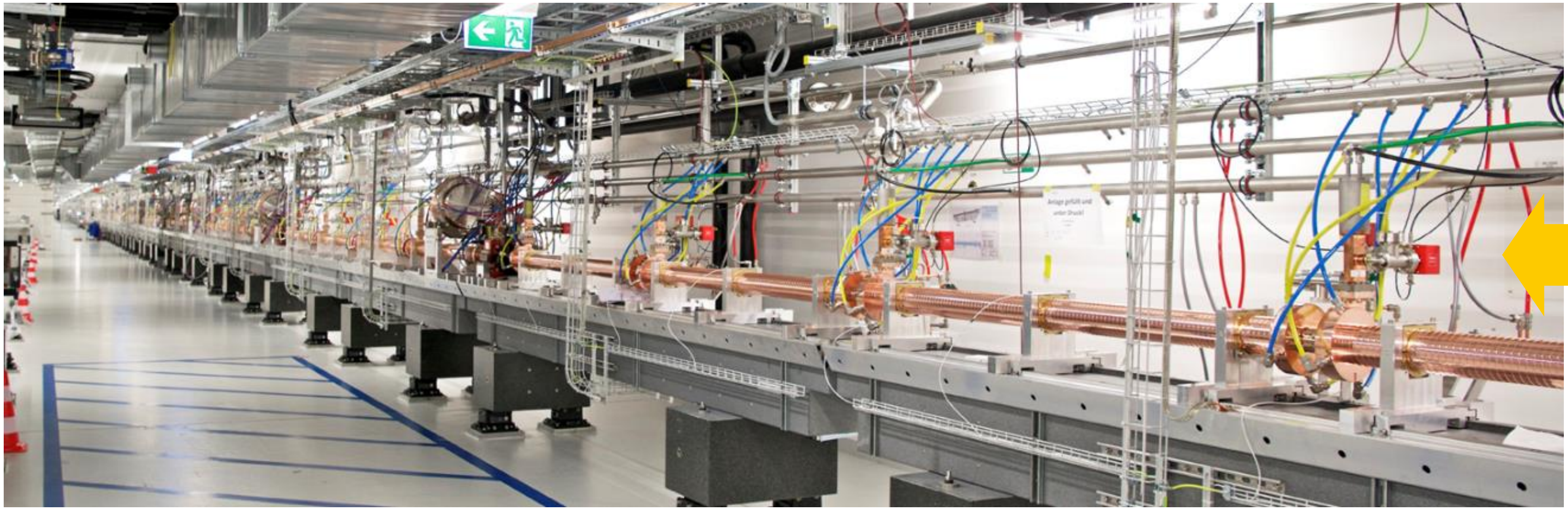
- S-band amplitude: < 1.8e-4
- C-band amplitude: < 1.8e-4
- X-band amplitude: < 1.8e-4
- S-band phase: < 0.018 degS
- C-band phase: < 0.036 degC
- X-band phase: < 0.072 degX

SwissFEL RF System in Tunnel



RF Gun

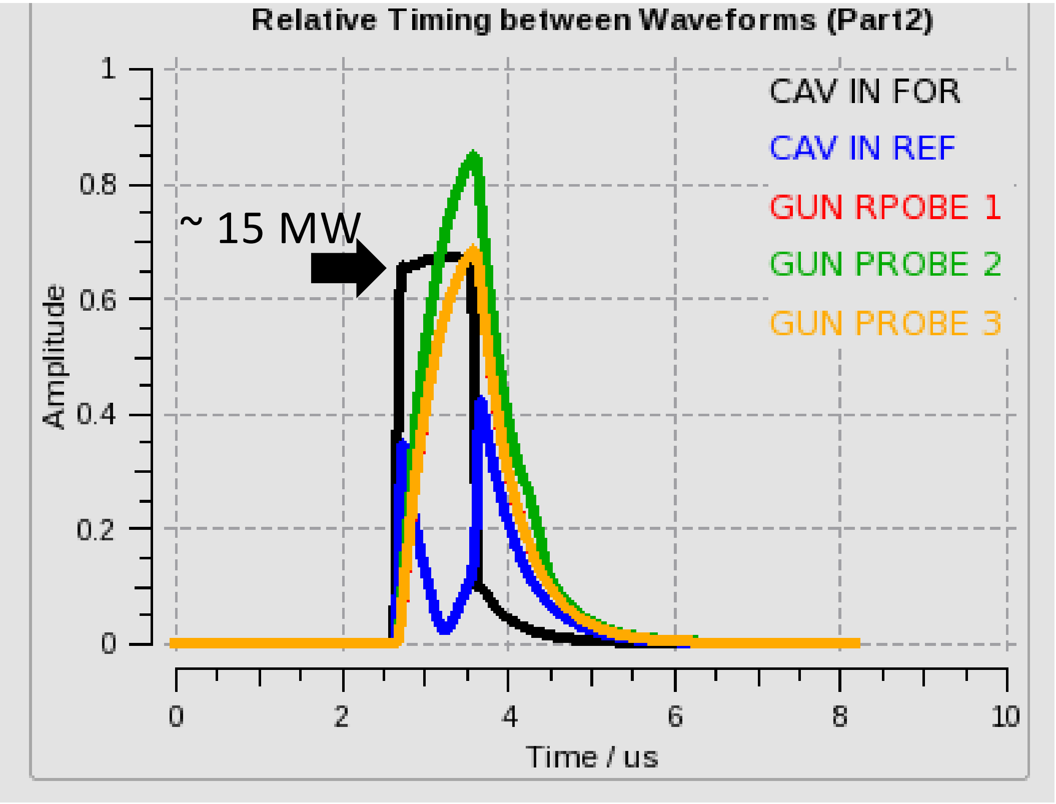
Injector S-band

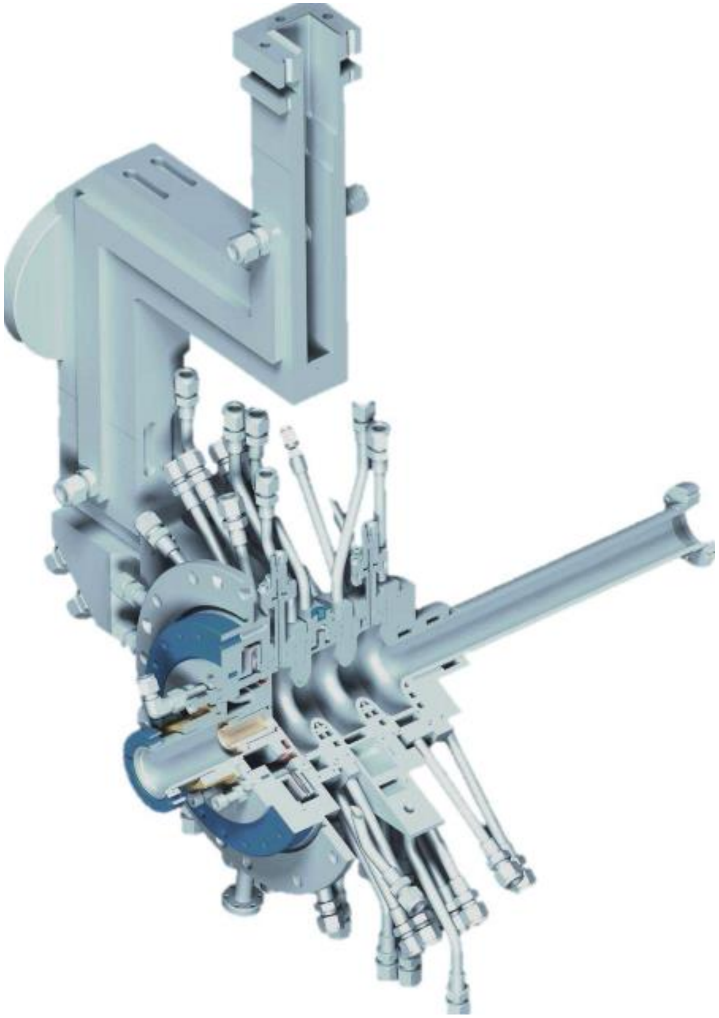


Linac
C-band

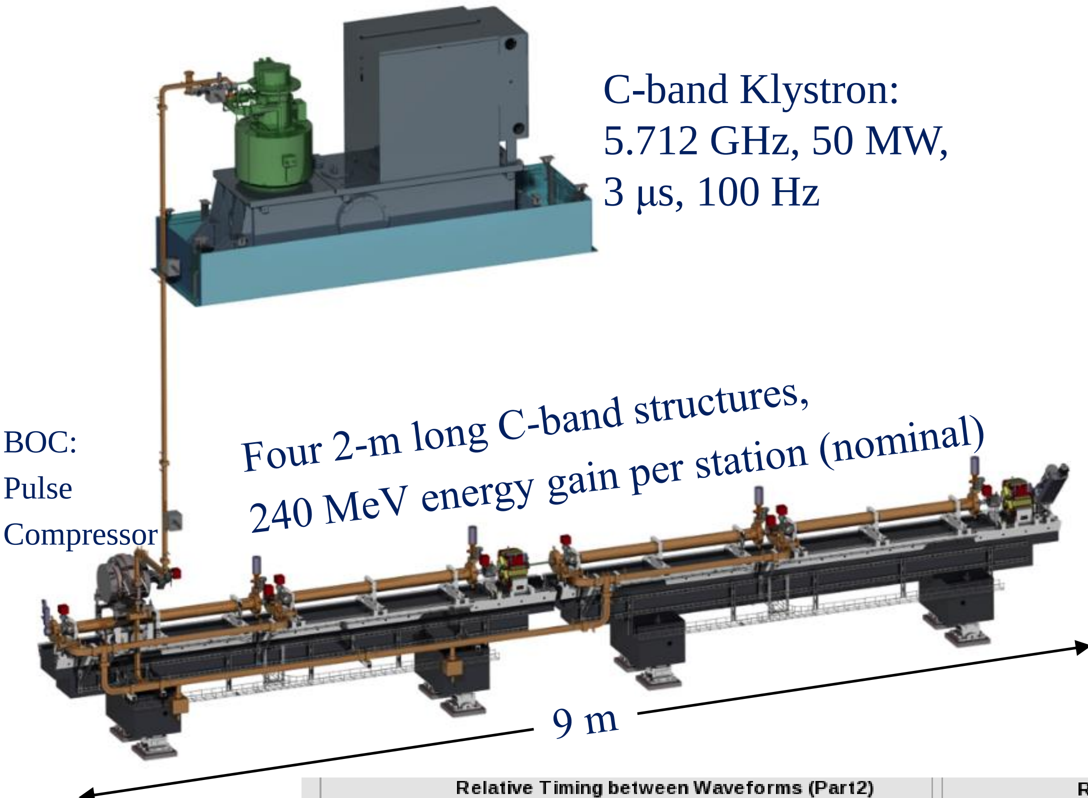
RF Gun

- RF Gun (PSI development):
  - 2.6-cell standing wave cavity (S-band)
  - 7.1 MeV nominal energy
- Standard operating procedure for routine gun-laser check – fundamental for stability and reproducibility of the facility!





C-band RF Station

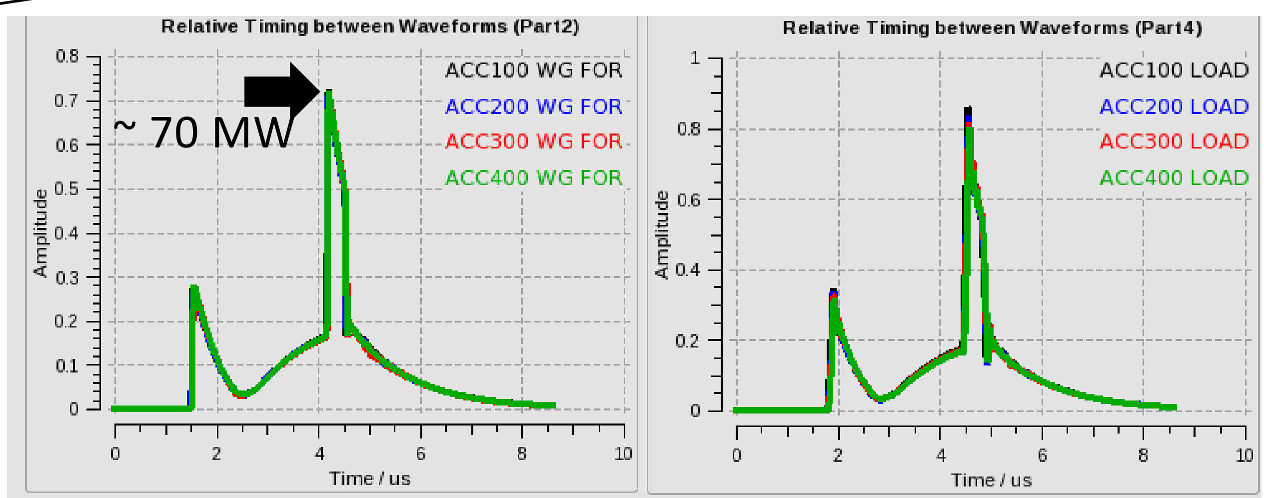


Status

- 26 RF stations available on beam:
  - Linac1: all of the 9 stations;
  - Linac2: all of the 4 stations;
  - Linac3: all of the 13 stations.
- All modules run at 100 Hz.
- Nominal beam energy of 5.8 GeV achieved

Station	Status	MV	deg
SINEG01	RF on beam	7.1	90.0
SINSB01	RF on beam	70.5	90.0
SINSB02	RF on beam	62.4	90.0
SINSB03	RF on beam	98.0	70.3
SINSB04	RF on beam	98.0	70.2
SINXB01	RF on beam	20.5	270.2
SINDI01	RF on delay	4.9	181.5
S10CB01	RF on beam	229.9	68.4
S10CB02	RF on beam	225.1	92.9
S10CB03	RF on beam	250.4	43.8
S10CB04	RF on beam	230.0	93.0
S10CB05	RF on beam	245.1	43.8
S10CB06	RF on beam	250.1	92.9
S10CB07	RF on beam	209.7	43.7
S10CB08	RF on beam	240.1	92.9
S10CB09	RF on beam	243.0	43.9

Station	Status	MV	deg
S20CB01	RF on beam	245.0	90.0
S20CB02	RF on beam	250.0	90.0
S20CB03	RF on beam	240.0	90.0
S20CB04	RF on beam	245.0	90.0
S30CB01	RF on beam	230.3	80.3
S30CB02	RF on beam	247.9	99.7
S30CB03	RF on beam	246.8	80.3
S30CB04	RF on beam	242.9	99.7
S30CB05	RF on beam	247.1	80.3
S30CB06	RF on beam	245.0	99.7
S30CB07	RF on beam	240.2	80.3
S30CB08	RF on beam	241.8	99.7
S30CB09	RF on beam	242.9	80.3
S30CB10	RF on beam	240.5	99.7
S30CB11	RF on beam	248.8	80.3
S30CB12	RF on beam	240.3	99.7
S30CB13	RF on beam	245.3	90.1



Solid-state Modulators

- Two types of solid-state modulators are used in SwissFEL Linac.
- **50 MW / 3μs RF, 370kV / 344A.**

AMPEGON

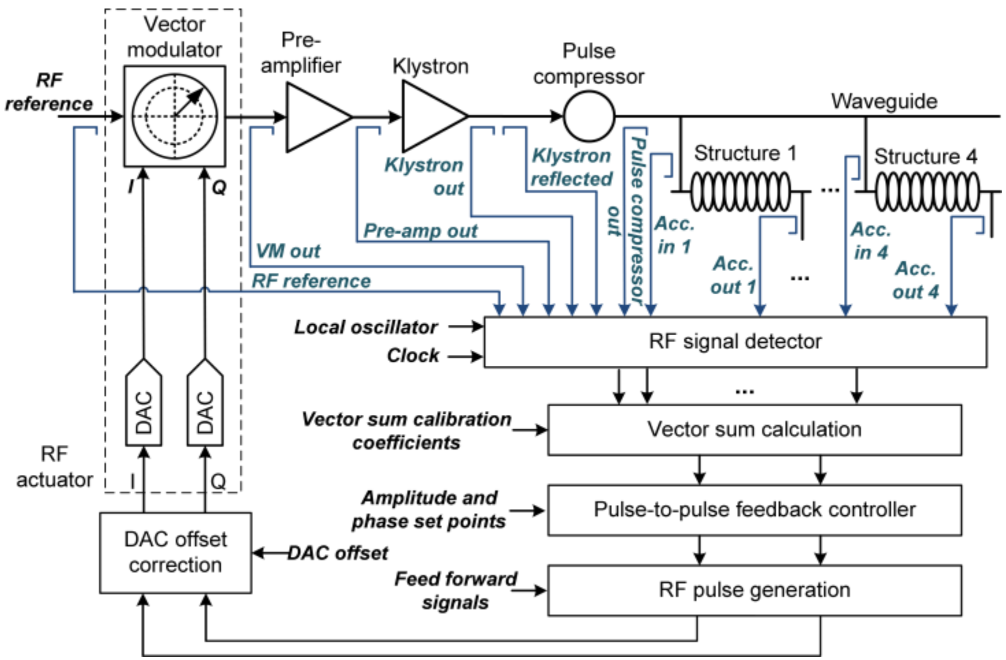
13 modulators (Linac1, Linac2)

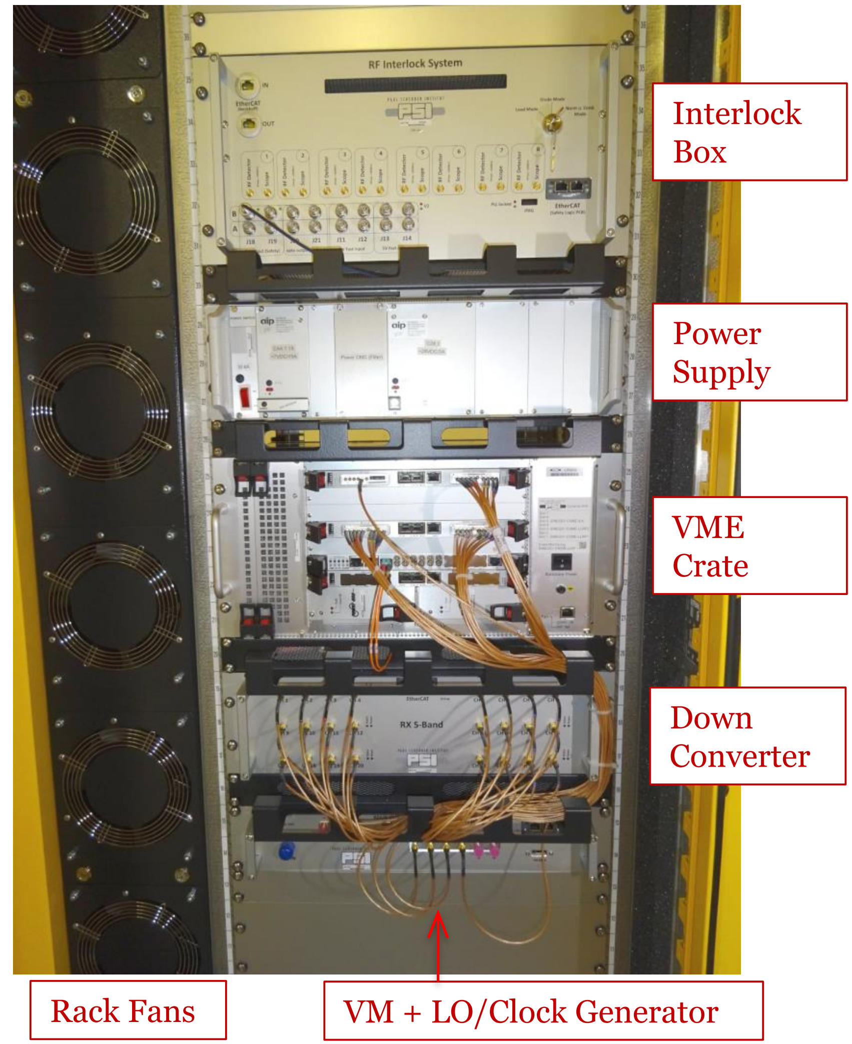
ScandiNova

13 modulators (Linac3)

Measured klystron HV pulse to pulse stability at 100 Hz < 15 ppm.

LLRF System





LLRF system provides:

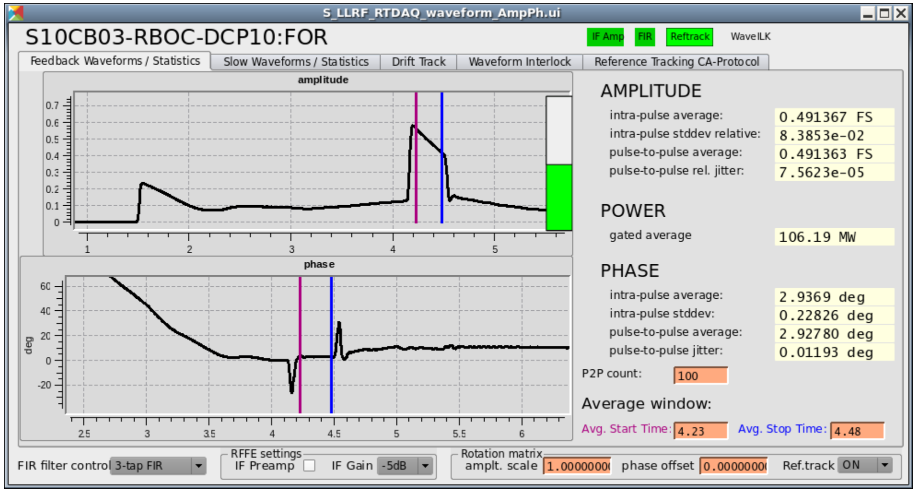
- Precise and accurate phase and amplitude measurements.
- Pulse-to-pulse feedback for suppression of RF field drifts.
- Facilitation for RF system setup and operation.

RF System Stability

RF Amplitude and Phase Measurements

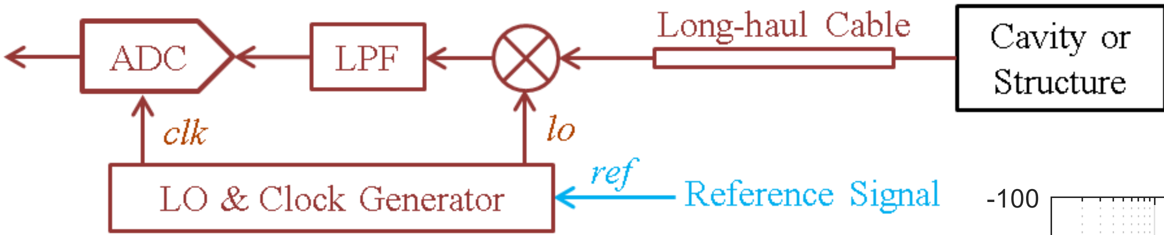
- Amplitude and phase are calculated for each RF pulse by averaging in the filling time of accelerating structures.
- The measurement bandwidth is limited by the effective bandwidth of the structures in the table on right side.
- The pulse-to-pulse feedback loops can compensate for fluctuations slower than 1 Hz (drifts).

Cavity / Structure	Frequency (MHz)	Effective Bandwidth (kHz)
RF Gun Cavity	2998.8	330.8
S-band Structure	2998.8	475.8
C-band Structure	5712	1346.5
X-band Structure	11995.2	4219.0



With feedbacks on, the amplitude and phase RMS jitter contains noise power from 1 Hz to the bandwidth of the cavity/structure.

LLRF/RF Detector added Noise



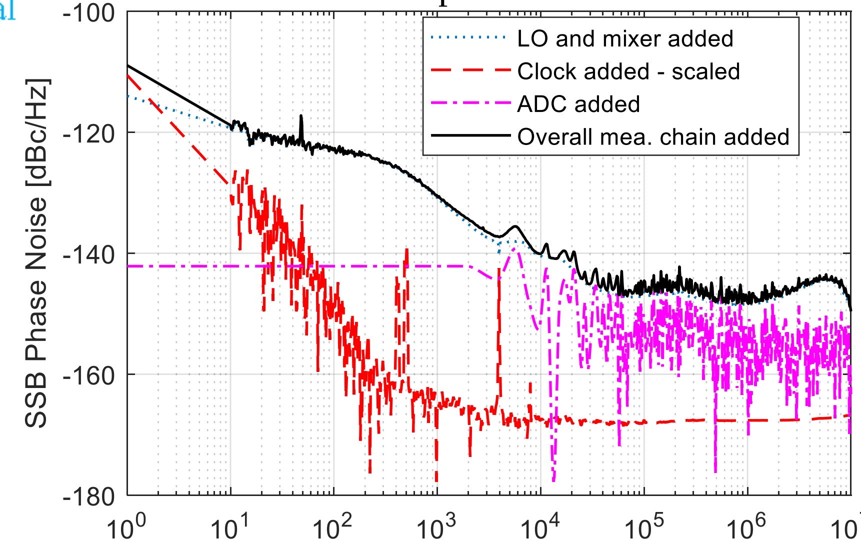
Added noise by RF measurement chain:

$$\Delta\varphi_{mea} = -\Delta\varphi_{LO,added} - \frac{f_{IF}}{f_{CLK}}\Delta\varphi_{CLK,added} + \Delta\varphi_{cable,added} + \Delta\varphi_{mixer,added} + \Delta\varphi_{ADC,added}$$

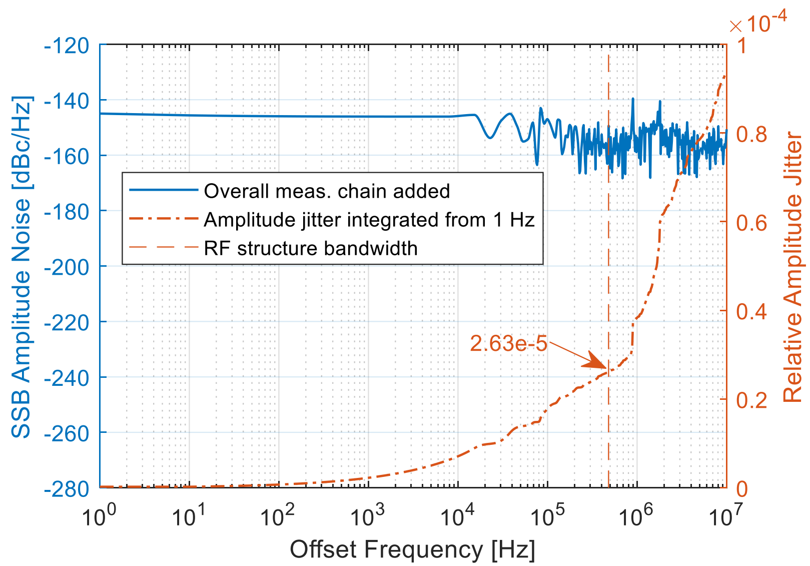
$$\Delta\alpha_{mea} = \Delta\alpha_{cable,added} + \Delta\alpha_{mixer,added} + \Delta\alpha_{ADC,added}$$

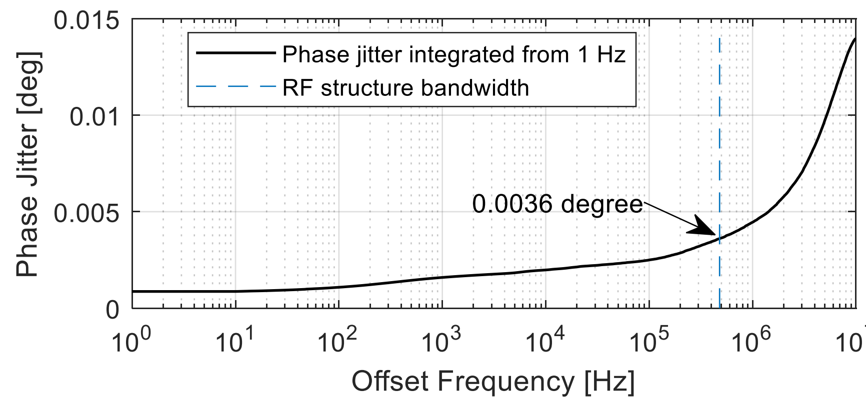
$$\Delta\alpha = \frac{\Delta A}{A}$$

SwissFEL S-band RF detector added phase noise



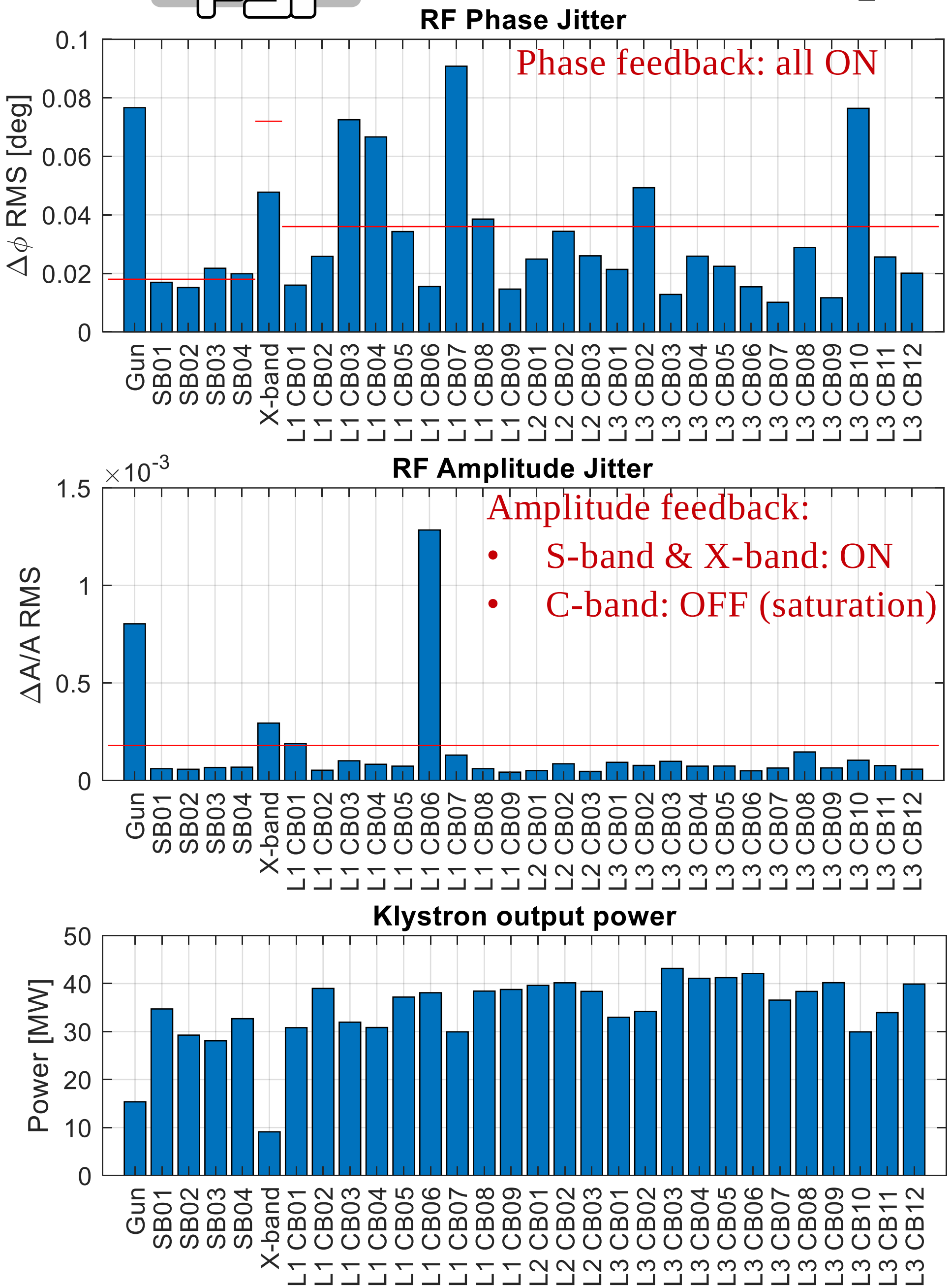
SwissFEL S-band RF detector added amplitude noise





RF detector added noise can be neglected when studying the RF system jitter.

Station Pulse-to-pulse Amplitude and Phase Jitter

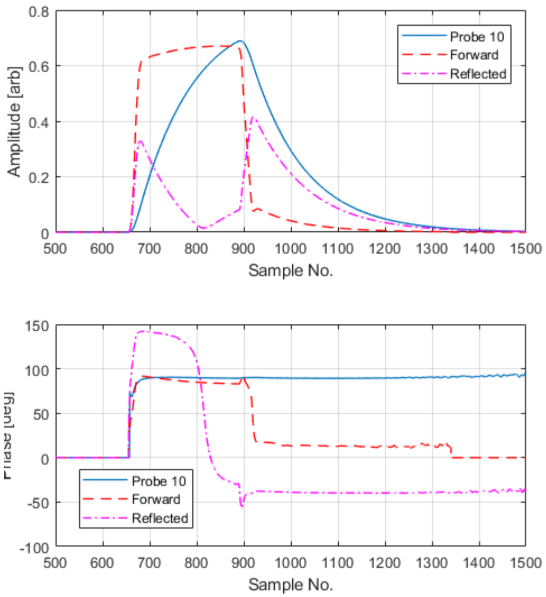


RF Station	Phase Tolerance (rms)	Voltage Tolerance (rms)
S-band (2.9988 GHz)	0.018 degS	0.018 %
C-band (5.7120 GHz)	0.036 degC	0.018 %
X-band (11.9952 GHz)	0.072 degX	0.018 %

- RMS jitter is calculated with the 10-min amplitude/phase data with beam in presence (RF rate 100 Hz, statistics with beam rate 25 Hz).
- Gun measurement problem:
  - Contains high-frequency noise (not averaged in pulse) and other passband mode (π/2-mode): **beam feels less jitter**.
  - Problematic cavity probes.
- Linac1 C-band #6 pre-amplifier failed and resulted in large amplitude drift in open loop operation.
- Large phase jitter in several C-band stations – BOC multipacting.

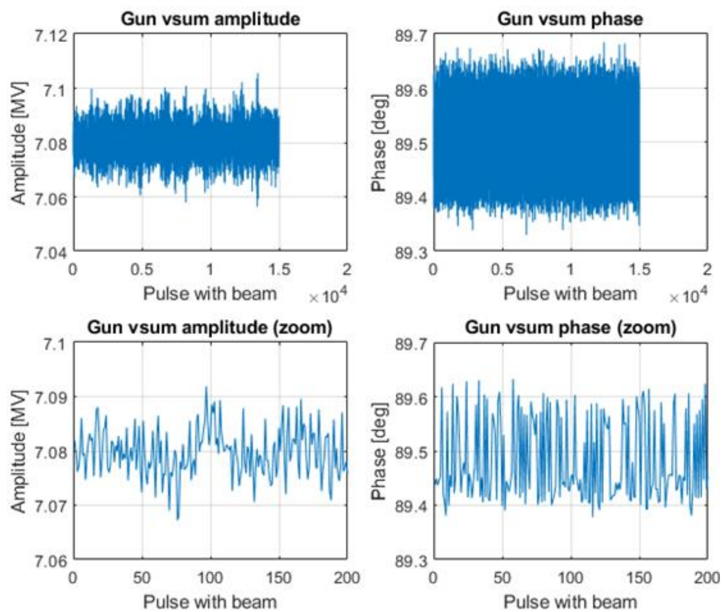
Data collected from SwissFEL at July 13, 2019 13:44–13:54

Example: RF Gun Amplitude and Phase Jitter

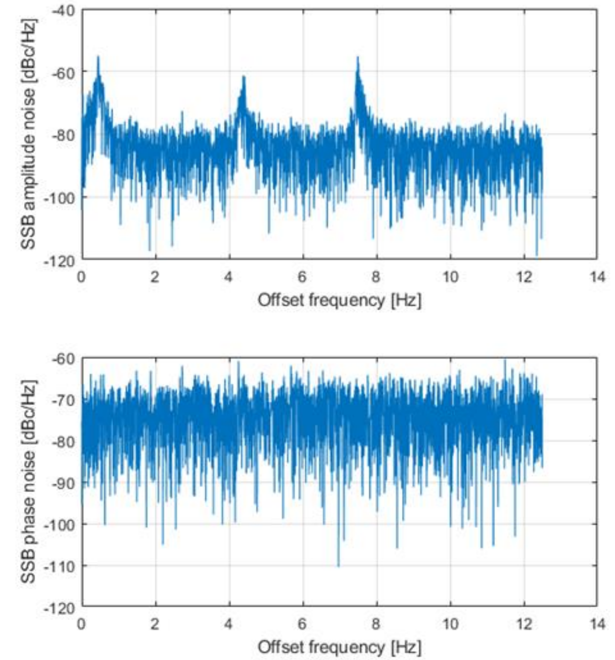


Gun probe, forward and reflected waveforms.

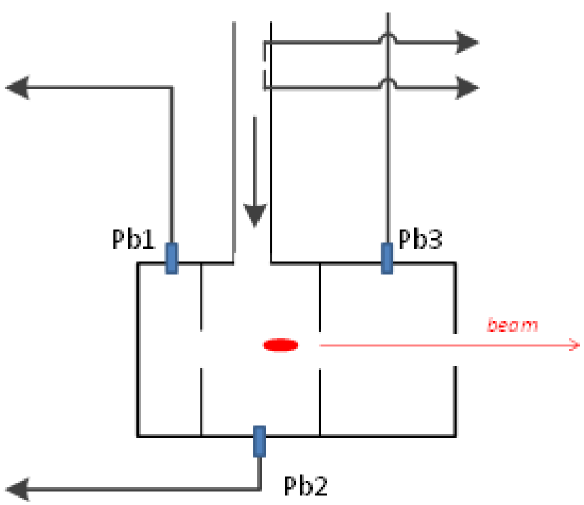
Data collected 2019.07.13 13:44 to 13:54



Amplitude and phase pulse-to-pulse data of Gun cavity field (vector sum of probe signals).



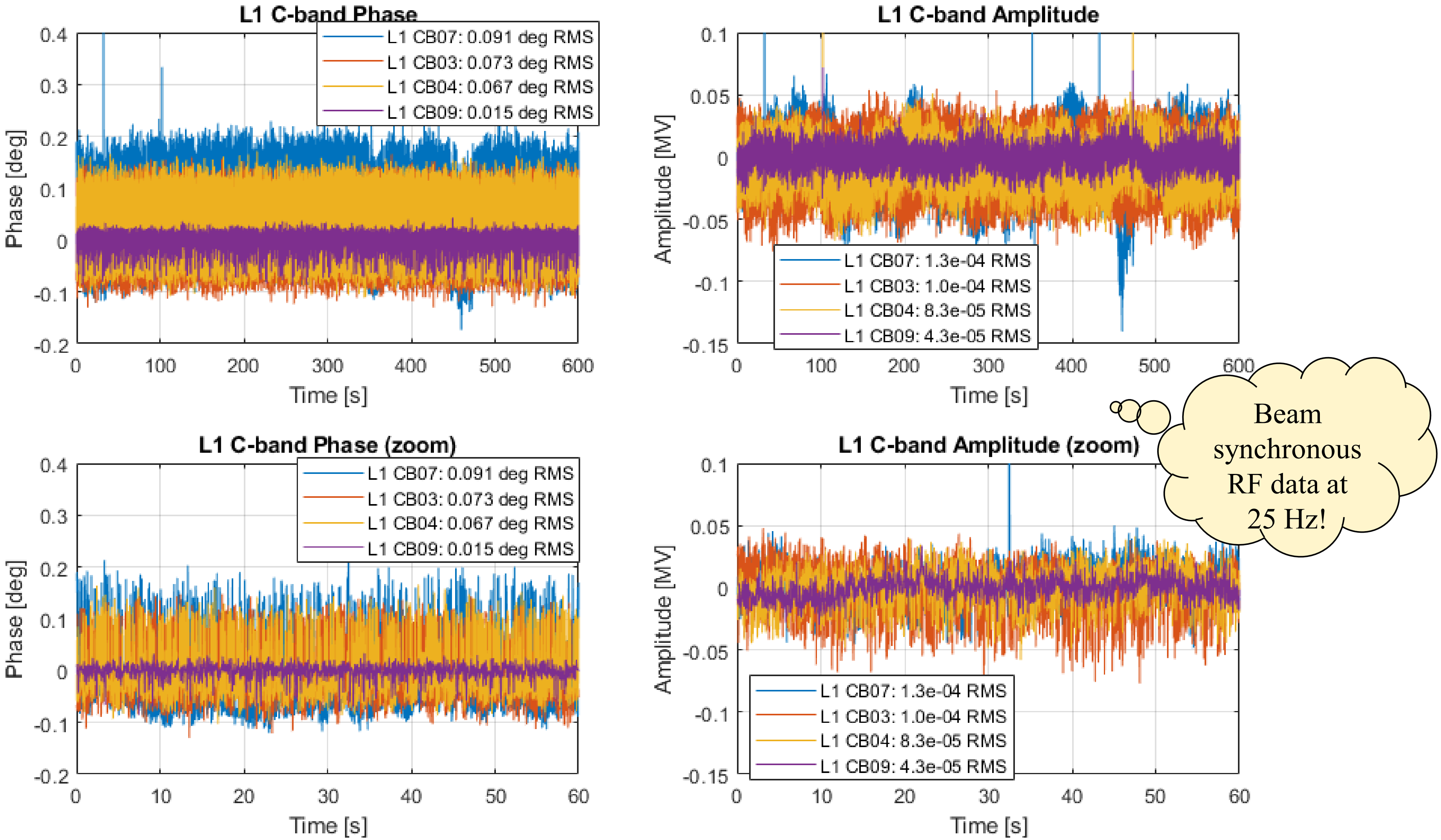
Spectrum of amplitude and phase pulse-to-pulse data.



Possible sources of resonant peaks:

- Cavity probe is sensitive to the mechanical vibration major caused by cooling water flows.
- Pass-band mode signal aliased back to the Nyquist band of beam repetition rate (25 Hz).

Example: C-band Amplitude and Phase Jitter



- ❑ Linac1 C-band #9 was well controlled – as a reference.
- ❑ Linac1 C-band #3, #4 and #7 had wideband phase jumps. Introduced by BOCs.

Data collected from SwissFEL at July 13, 2019 13:44–13:54

Procedure for Measurement of RF Driving Component added Phase Jitter

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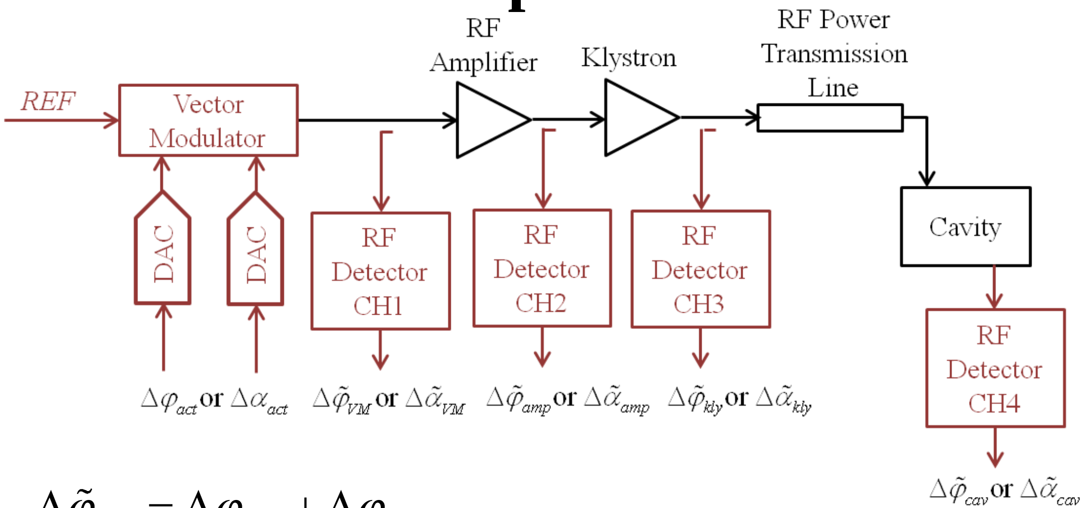


The phase of the input and output of a component are compared for each RF pulse to estimate the added phase jitter.

Here shows an example to measure the added phase jitter by the S-band pre-amplifier:

$$\Delta\tilde{\varphi}_{VM} = \Delta\varphi_{VM} + \Delta\varphi_{mea1,added}$$

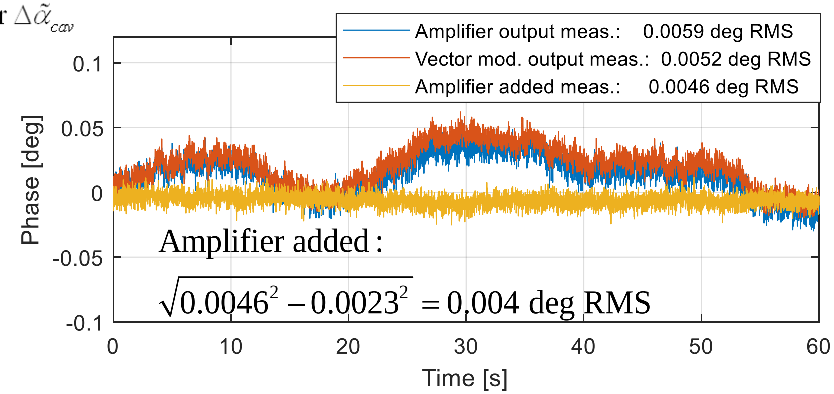
$$\Delta\tilde{\varphi}_{amp} = \Delta\varphi_{amp} + \Delta\varphi_{mea2,added}$$

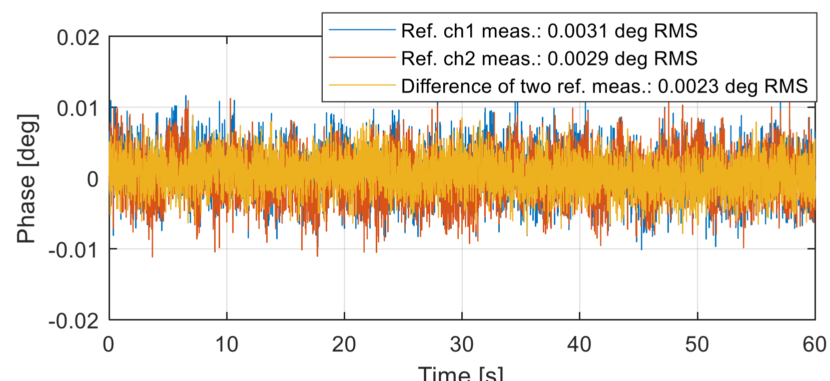
$$\Delta\varphi_{amp,added} = \Delta\varphi_{amp} - \Delta\varphi_{VM}$$

$$\Delta\tilde{\varphi}_{amp} - \Delta\tilde{\varphi}_{VM} = \Delta\varphi_{amp,added} + \left(\Delta\varphi_{mea2,added} - \Delta\varphi_{mea1,added}\right)$$

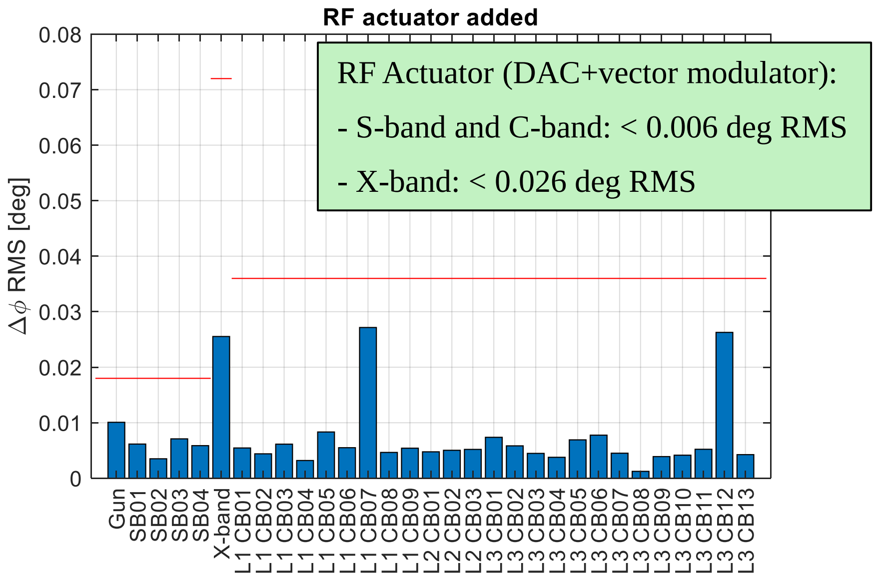
$$RMS^2\{\Delta\varphi_{amp,added}\} = RMS^2\{\Delta\tilde{\varphi}_{amp} - \Delta\tilde{\varphi}_{VM}\} - RMS^2\{\Delta\varphi_{mea2,added} - \Delta\varphi_{mea1,added}\}$$

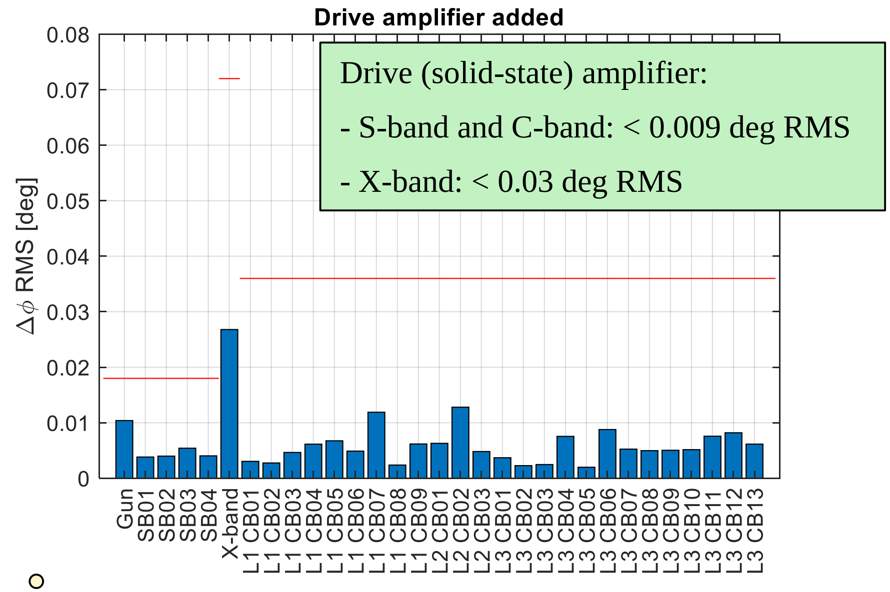
In this talk, the RF detector added noise is very small and is neglected.

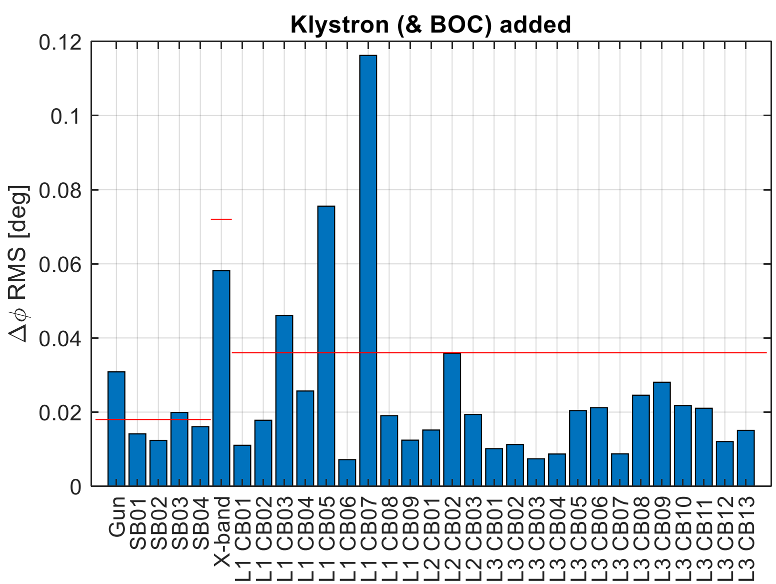


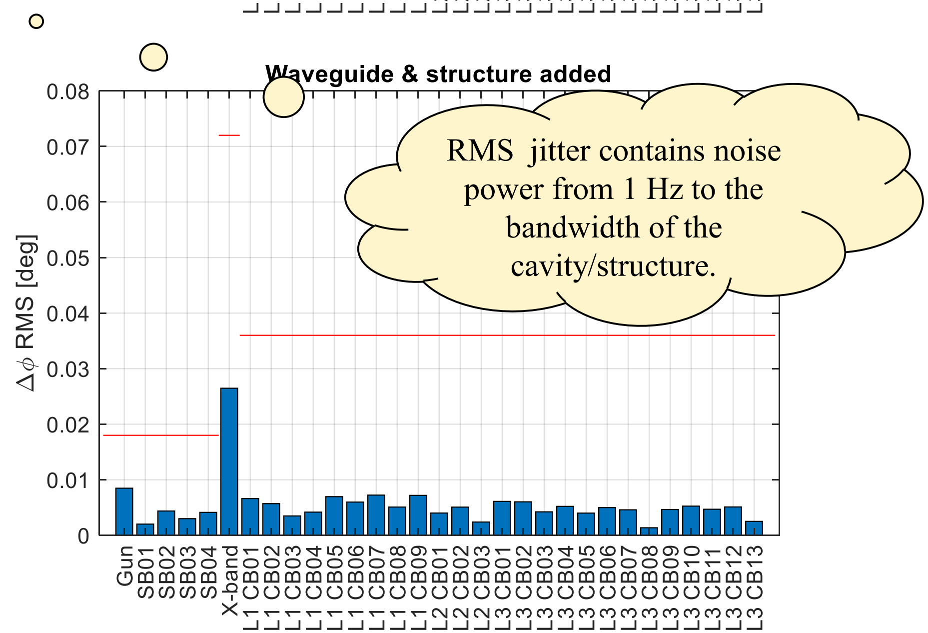


Summary RF Driving Components added Phase Jitter









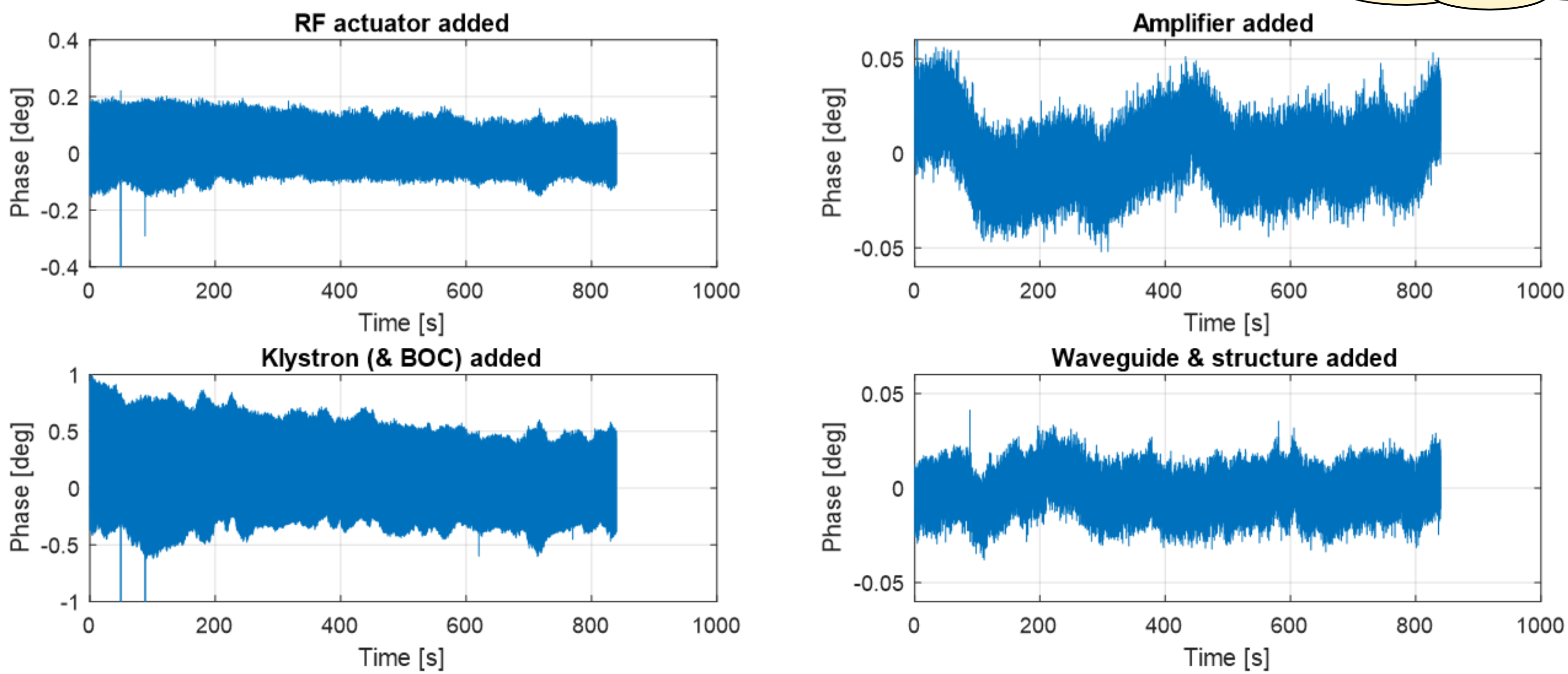
Data collected from SwissFEL at Jan. 11, 2019 12:03–12:17

Did not remove RF detector measurement added noise in these figures

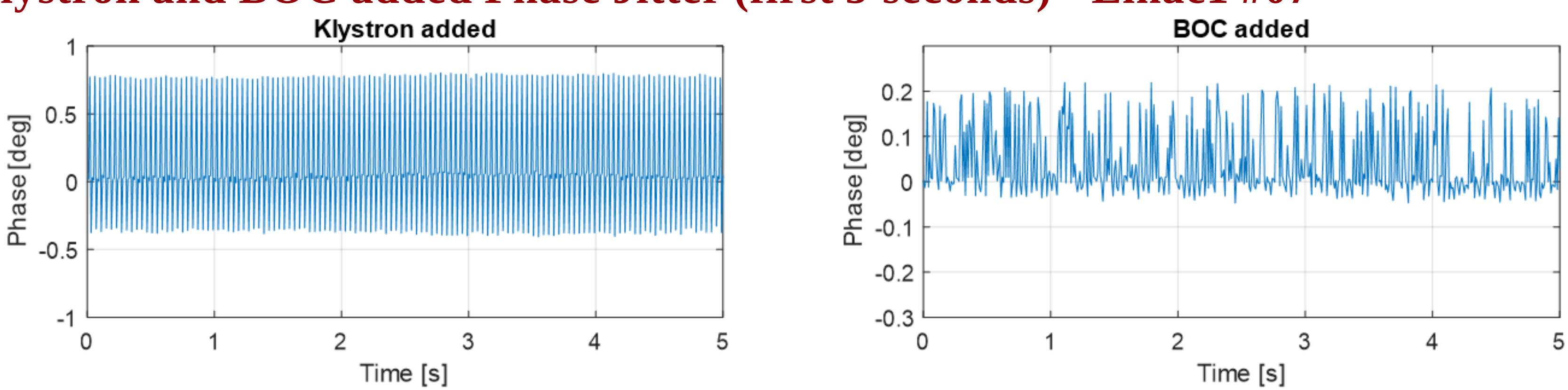
Example: RF Driving Components added Phase Jitter

RF Components added Phase Jitter - Linac1 #07

100 Hz RF data!



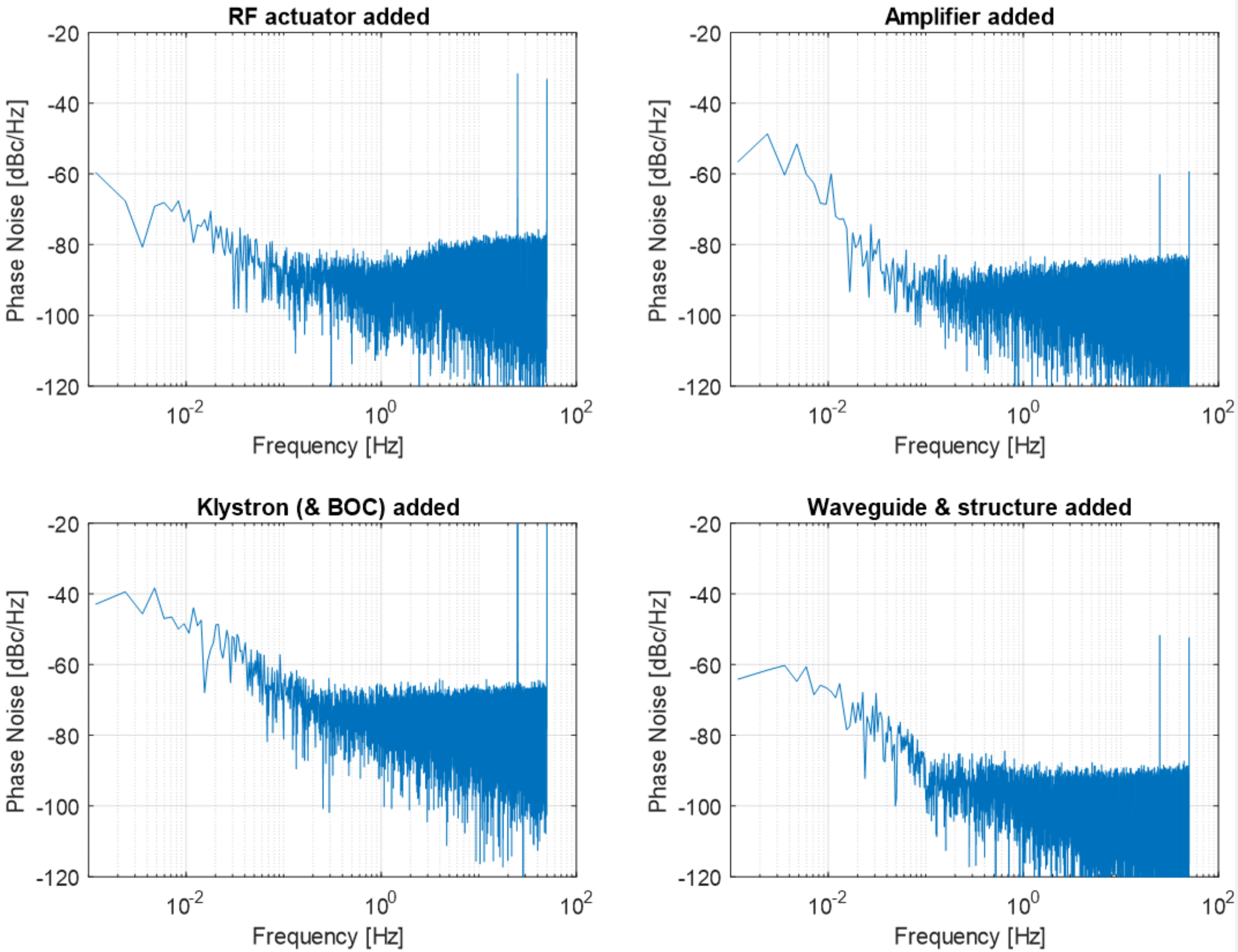
Klystron and BOC added Phase Jitter (first 5 seconds) - Linac1 #07



Data collected from SwissFEL at Jan. 11, 2019 12:03–12:17

Example: RF Driving Components added Phase Jitter

RF Components added Phase Noise - Linac1 #07



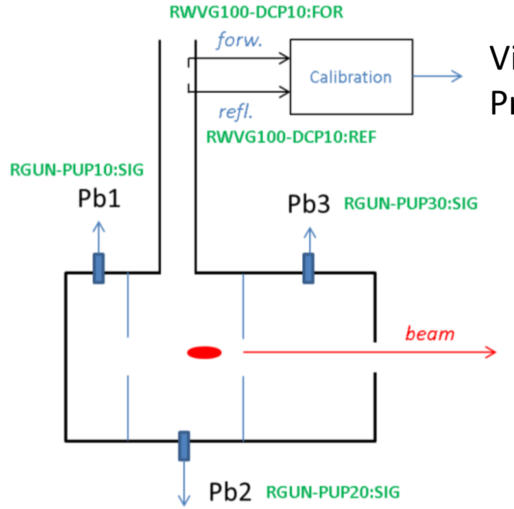
- Disturbance clearly visible at beam rate (25 Hz when collecting data) and its harmonics.
- Components downstream from amplifier contribute to low-frequency fluctuations.
- BOC contributes to high frequency noise due to the random jumps.
- **Noise slower than 1 Hz will be suppressed by LLRF phase feedback!**

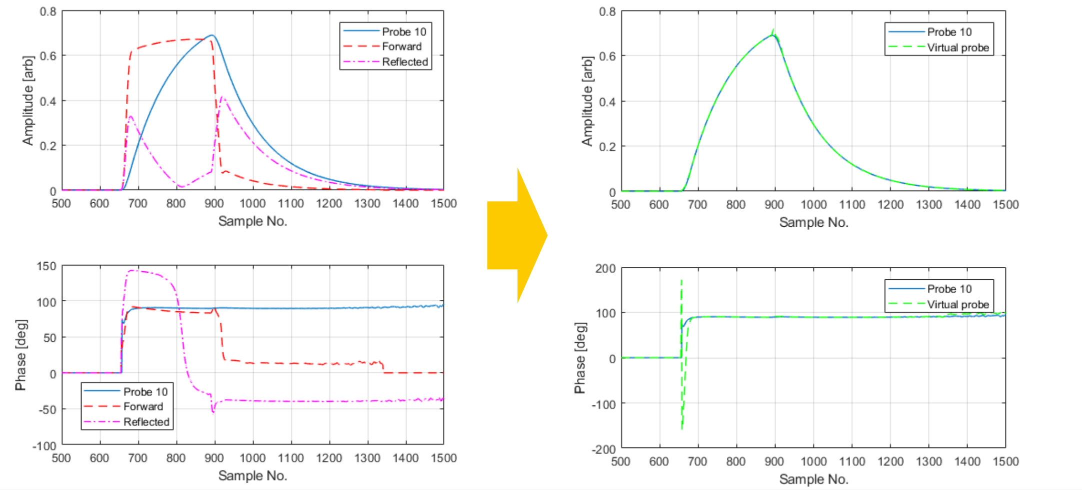
Data collected from SwissFEL at Jan. 11, 2019 12:03–12:17

RF Jitter Mitigation

Improvement of RF Gun Field Measurement

Use virtual probe to replace the probe signal.





Construction of virtual probe:

Vector sum of measured forward and reflected signals:

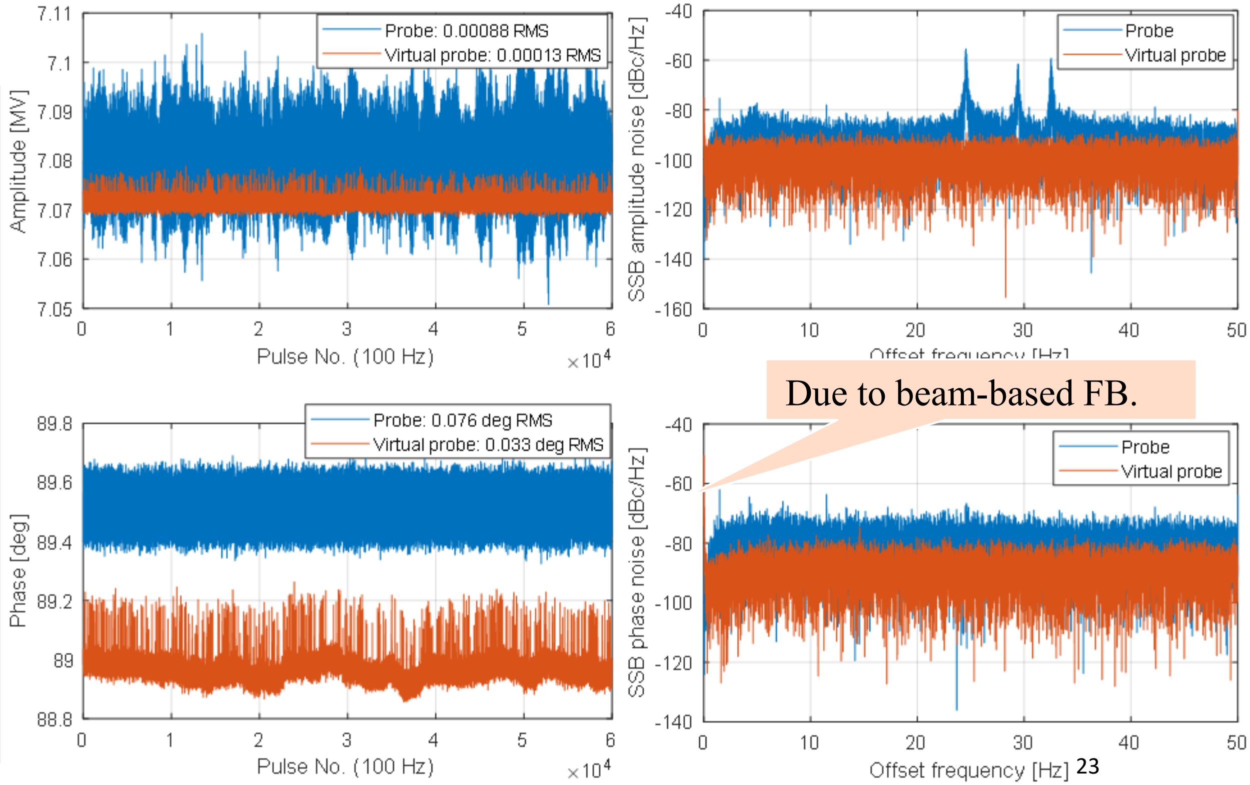
$$\left.\begin{aligned} \mathbf{v}_{for} &= \mathbf{a}\mathbf{v}_{for,mea} + \mathbf{b}\mathbf{v}_{ref,mea} \\ \mathbf{v}_{ref} &= \mathbf{c}\mathbf{v}_{for,mea} + \mathbf{d}\mathbf{v}_{ref,mea} \end{aligned}\right\} \Rightarrow$$

$$\mathbf{v}_{probe} = \mathbf{v}_{for} + \mathbf{v}_{ref} = \mathbf{m}\mathbf{v}_{for,mea} + \mathbf{n}\mathbf{v}_{ref,mea}$$

$$(\mathbf{m} = \mathbf{a} + \mathbf{c},\ \mathbf{n} = \mathbf{b} + \mathbf{d})$$

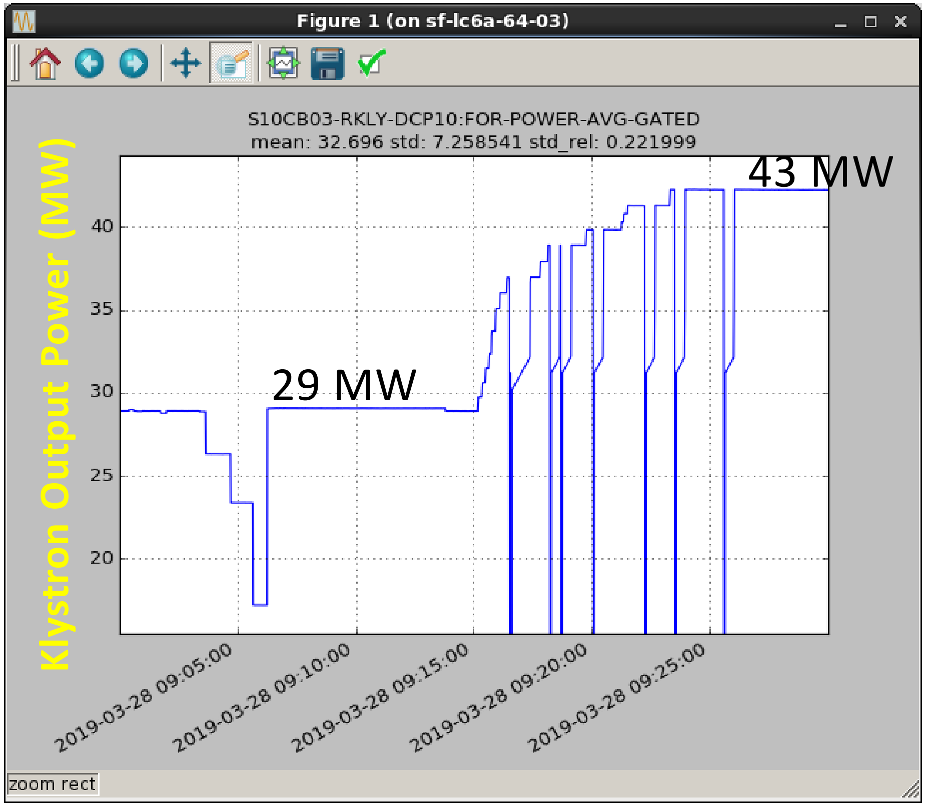
Calibration of m and n:

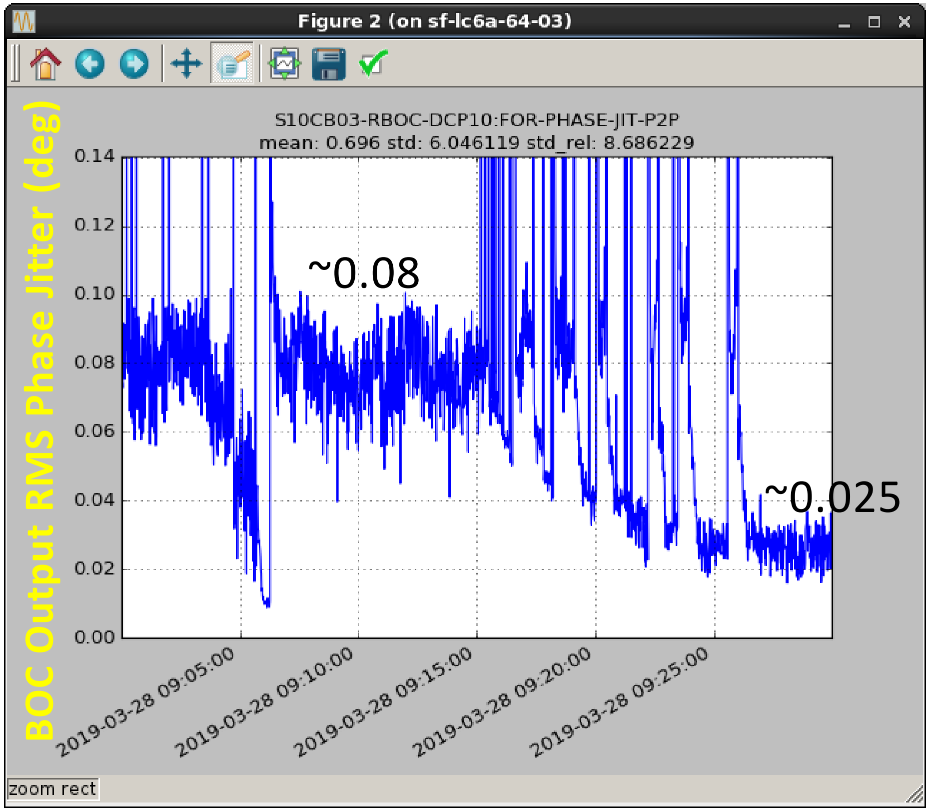
Linear fitting with the “Pb1” and measured forward and reflected signals.



BOC Multipacting

Study of BOC Multipacting (Example: Linac1 #3)



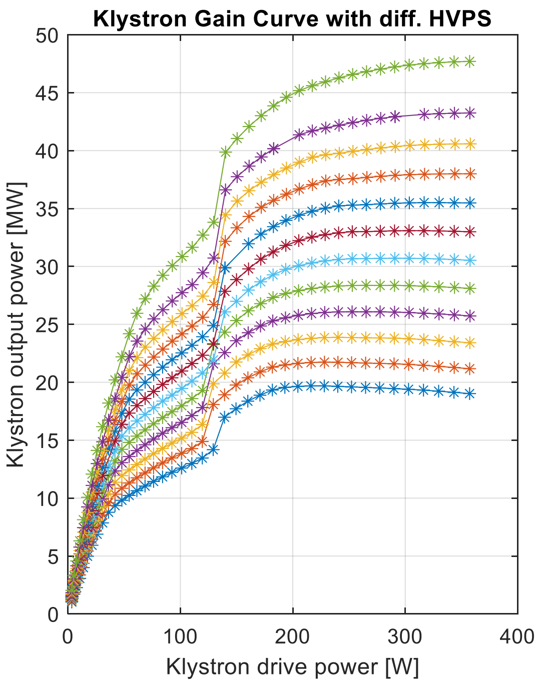


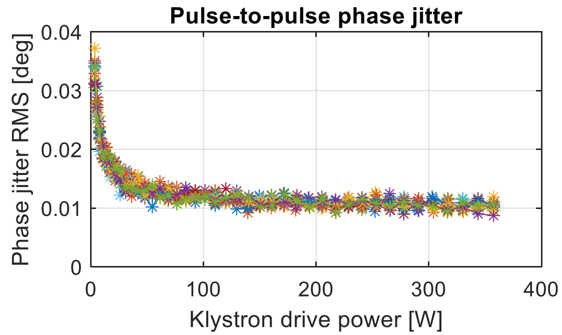
Mitigation Methods:

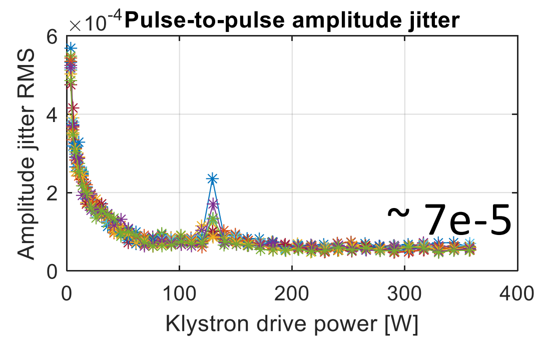
- ❑ Operate the C-band klystrons at a power level larger than 40 MW.

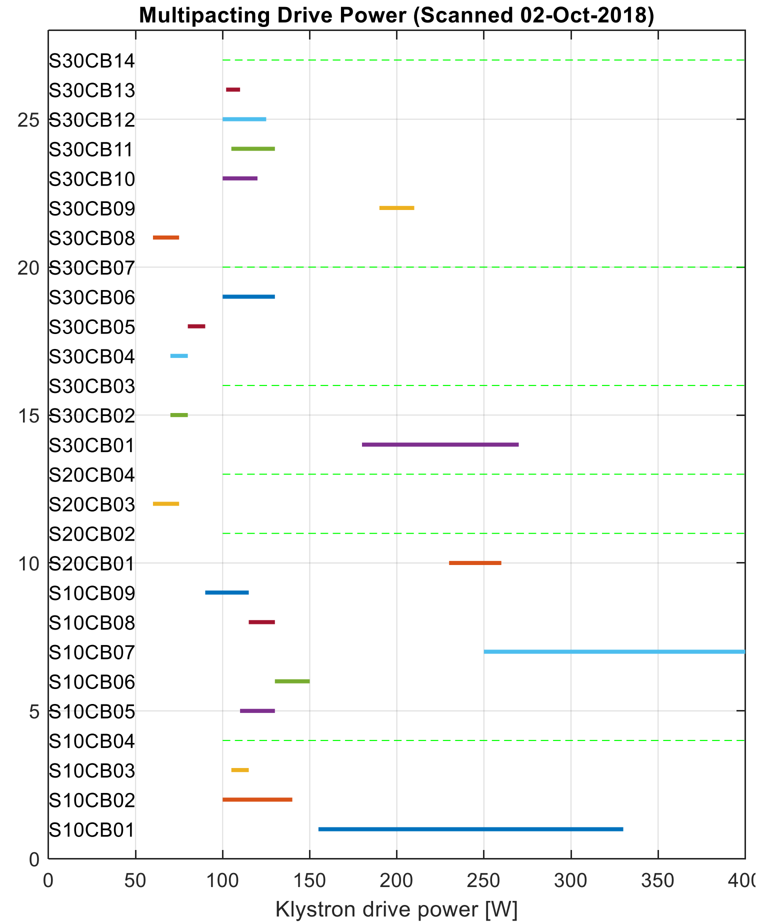
C-band Klystron Multipacting

Multipacting in C-band Klystron (Example: Linac1 #8)







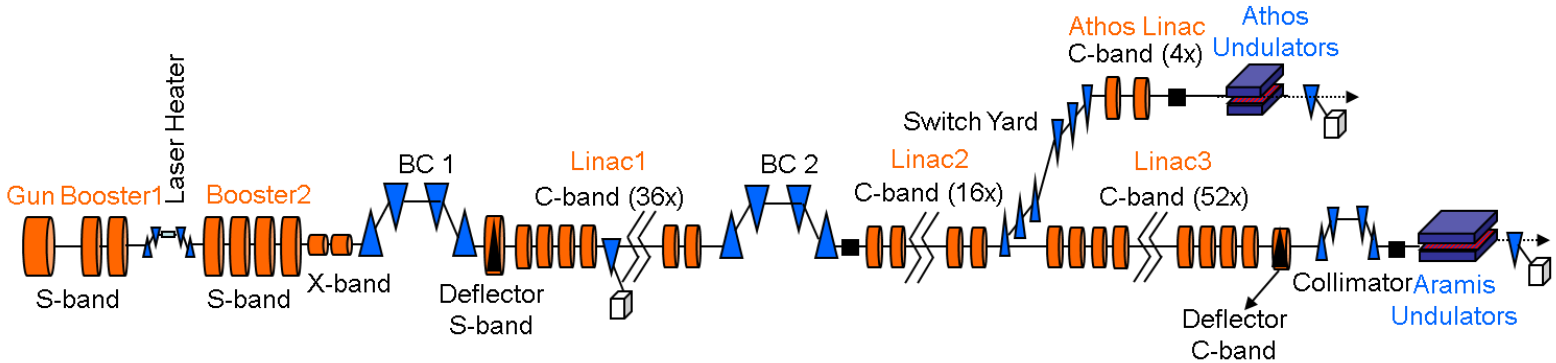


Mitigation Methods:

- Operate the C-band RF stations in saturation and adjust the drive power to avoid the multipacting region.
- Phases of multiple klystrons in the same Linac section are adjusted to achieve the desired vector-sum amplitude and phase changes.

Beam Stability

Beam Sensitivity to RF Noise



Courtesy: Sven Reiche

Sensitivity Matrix *M* converts the error sources to beam jitter:

$$\begin{bmatrix} (\Delta E/E)_{BC1} \\ \Delta\varphi_{BC1} \\ (\Delta L/L)_{BC1} \\ (\Delta E/E)_{BC2} \\ \Delta\varphi_{BC2} \\ (\Delta L/L)_{BC2} \\ (\Delta E/E)_{L3} \\ \Delta\varphi_{L3} \\ (\Delta L/L)_{L3} \end{bmatrix} = M \begin{bmatrix} (\Delta Q/Q)_{LH} \\ \Delta\varphi_{LH} \\ (\Delta E/E)_{LH} \\ (\Delta A/A)_{bst2} \\ \Delta\varphi_{bst2} \\ (\Delta A/A)_{X} \\ \Delta\varphi_{X} \\ (\Delta A/A)_{L1} \\ \Delta\varphi_{L1} \\ (\Delta A/A)_{L23} \\ \Delta\varphi_{L23} \end{bmatrix}$$

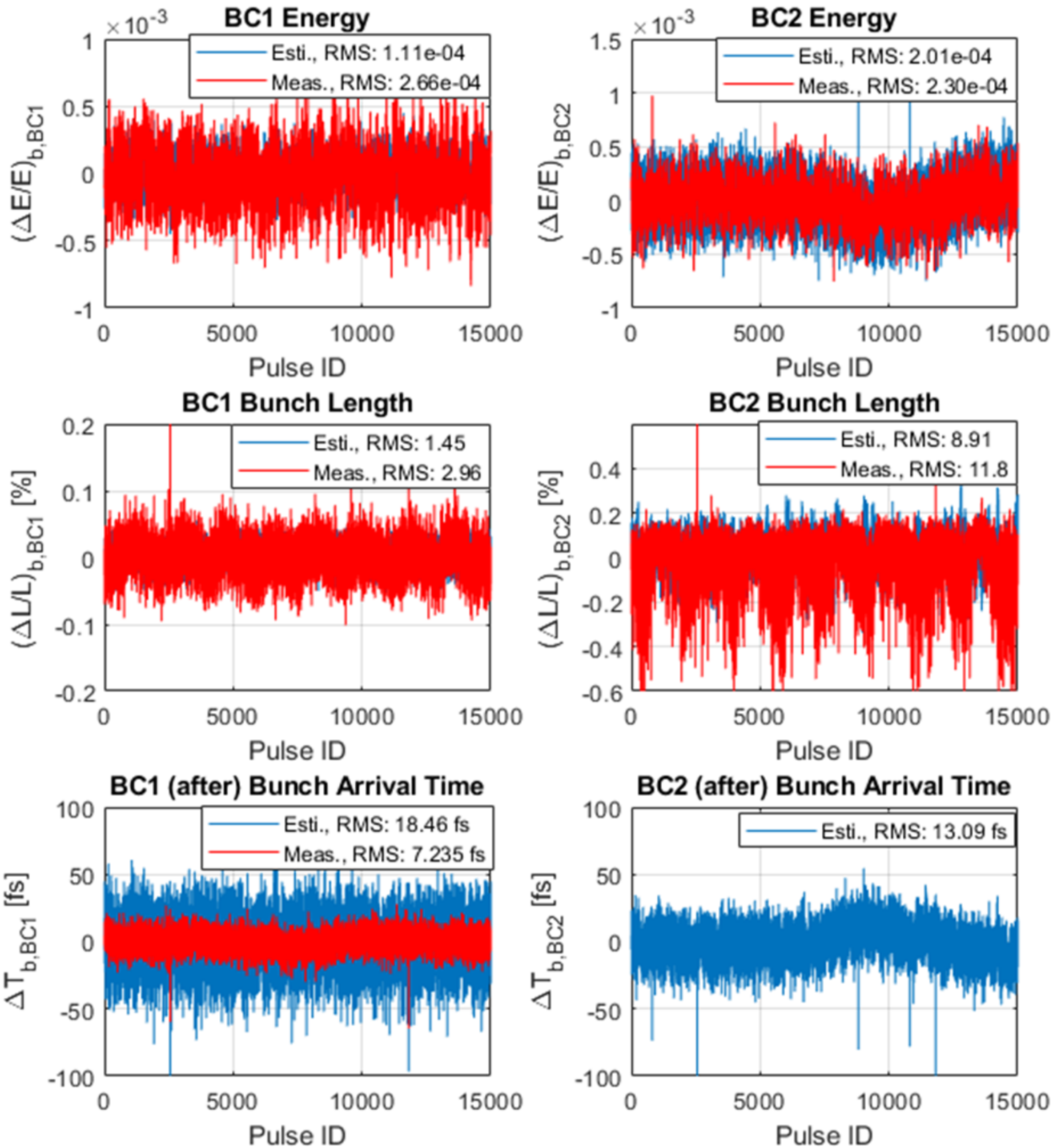
Error Source	Notation	Sensitivity
LH Bunch Charge	$(\Delta Q/Q)_{LH}$	5.733
LH Bunch Phase (deg)	$\Delta\varphi_{LH}$	68.079
LH Bunch Energy	$(\Delta E/E)_{LH}$	-36.768
Booster 2 Amplitude	$(\Delta A/A)_{bst2}$	-100.583
Booster 2 Phase (deg)	$\Delta\varphi_{bst2}$	94.446
X-band Amplitude	$(\Delta A/A)_{X}$	3.774
X-band Phase (deg)	$\Delta\varphi_{X}$	-56.055
Linac 1 Amplitude	$(\Delta A/A)_{L1}$	20.083
Linac 1 Phase (deg)	$\Delta\varphi_{L1}$	32.506

Example: Sensitivity of the BC2 relative bunch length deviation $(\Delta L/L)_{BC2}$ w.r.t. the error sources

Use Cases:

1) From measurements of jitter sources predict the beam parameter jitter.
2) From required beam parameter jitter determine the jitter budgets of the jitter sources.

Estimation and Measurement of Beam Jitters



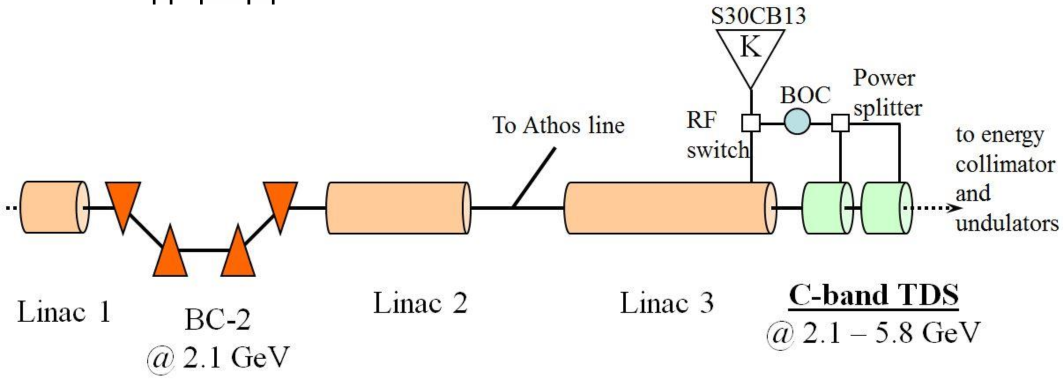
- Beam jitters can be predicted from RF measurements via the response matrix and directly measured with beam diagnostics.
- When collecting data, all longitudinal feedbacks **OFF**.

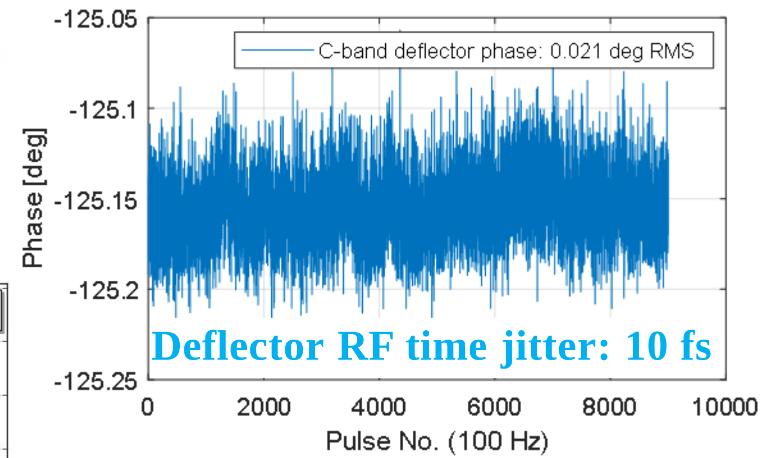
At BC2 Exit:

- Measured beam energy jitter: 2.3e-4 RMS (goal: 5e-4)
- Measured bunch length jitter: 11.8 % RMS (goal: 5 %)
- Measured arrival time jitter (see next page): 13 fs RMS (goal: 20 fs)

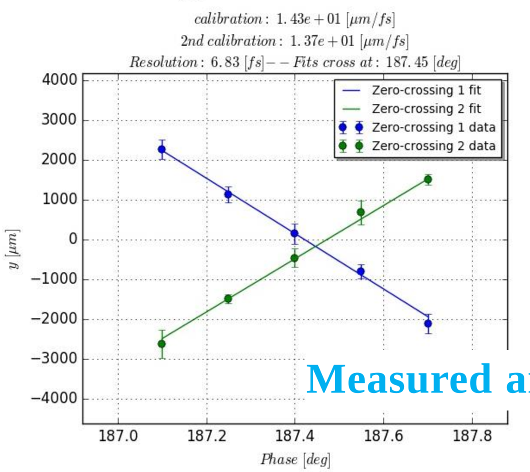
Data collected from SwissFEL at July 13, 2019 13:44–13:54

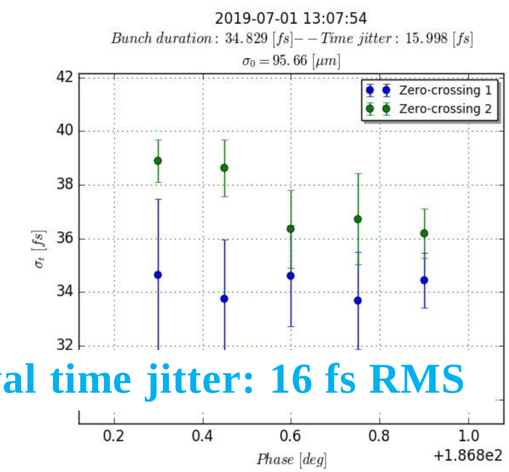
Bunch Arrival Time Mea. with C-band Deflector



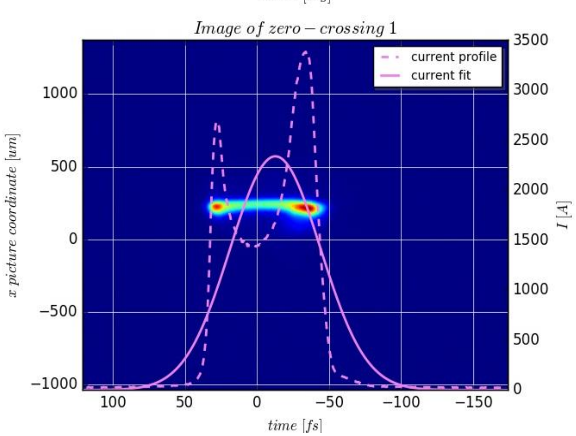


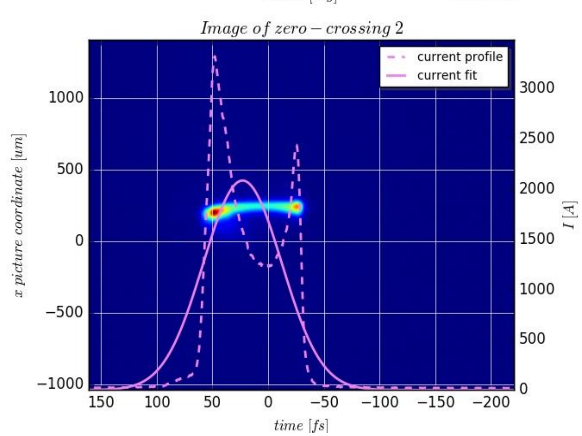
Deflector RF time jitter: 10 fs





Measured arrival time jitter: 16 fs RMS





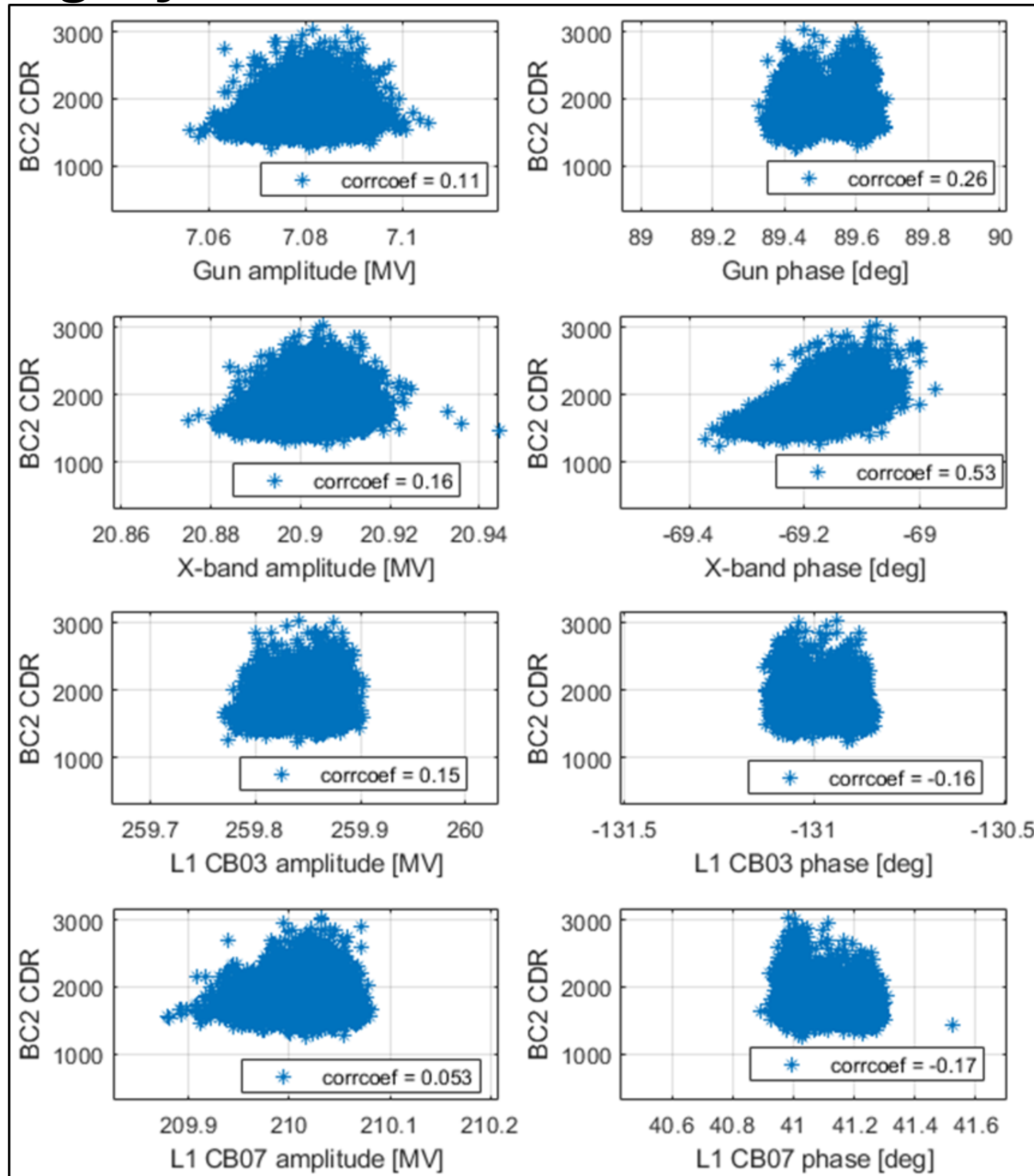
Estimated actual bunch arrival time at the end of Linac 3 of SwissFEL:

$$t_{b,RMS} = \sqrt{16^2 - 10^2} \approx 13 \text{ fs}$$

BC2 bunch-length jitter:RF-beam Jitter Correlation

Correlation between bunch length jitter measured with CDR and jitter sources.

- The correlation strength shows the potential RF stations that have large jitter and require improvements.
- Conclusion from the correlation on right side:
  - RF Gun stability need improvement;
  - X-band stability needs special focus – need to be improved even better than the original stability specification in CDR;
  - Linac 1 C-band phase stability (mainly due to BOC multipacting) needs improvement.



Data collected from SwissFEL at July 13, 2019 13:44–13:54

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Summary and Outlook

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Summary:

- SwissFEL RF system has reached its nominal working point: 5.8 GeV energy gain @ 100 Hz. Linac3 can provide 2 spare RF stations in hot-standby.
- Most RF stations satisfy the stability requirements. Improvements are needed for the RF Gun, X-band and several Linac 1 C-band stations. The X-band phase jitter is one of the major sources for the bunch length jitter and a tighter stability requirement should be applied.

Outlook for Future:

- Stability improvement:
  - Improve the X-band stability by improving the pre-amplifier and modulator;
  - Understand and mitigate the phase jitter synchronous to beam (e.g. Linac1 #7);
  - Mitigate all the C-band stations with BOC multipacting.
  - Evaluate the drifts in RF reference distribution system and LLRF system.
- Reliability and operability improvement:
  - Improve the software (LLRF, modulator, RF station master state machine, beam base feedback …) inter-operability and robustness.

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Special Thanks to:

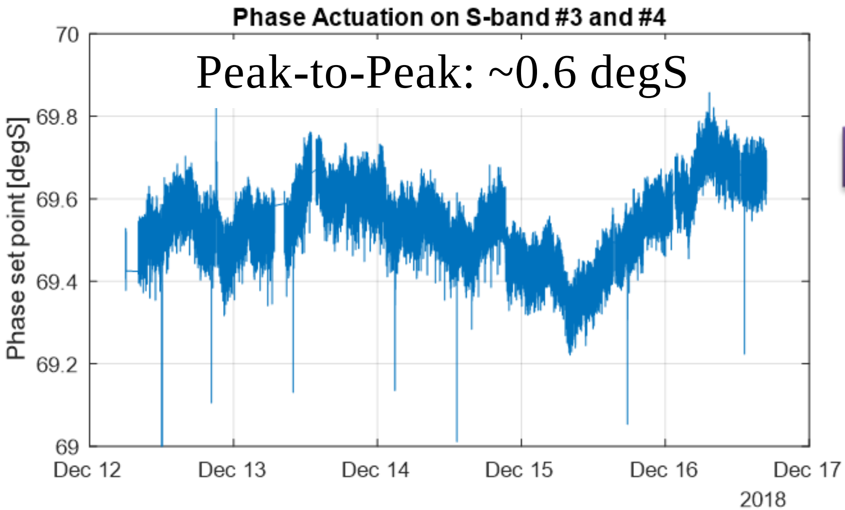
- ❑SwissFEL RF and LLRF team.
- ❑SwissFEL beam dynamics experts and operators.

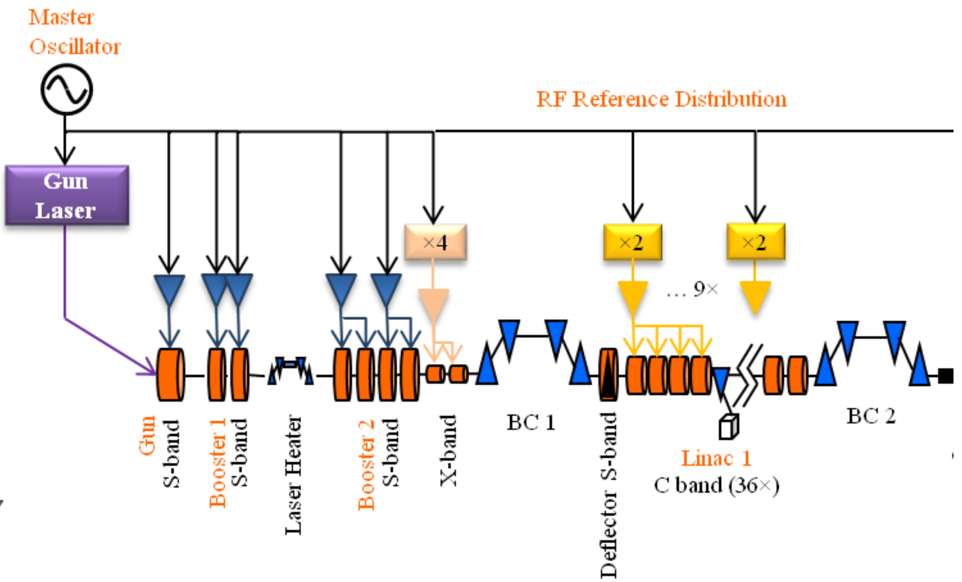
Thank you for your attention!

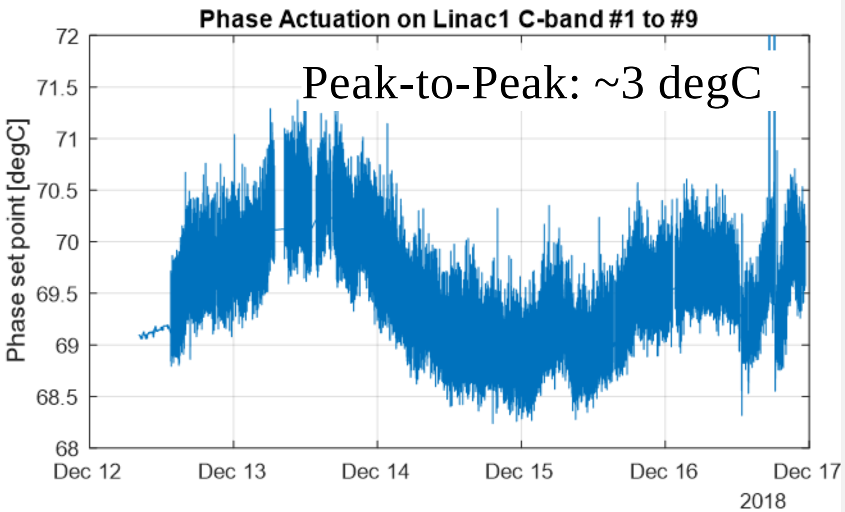
Backup Slides

(Drift)

Long-term Phase Drift



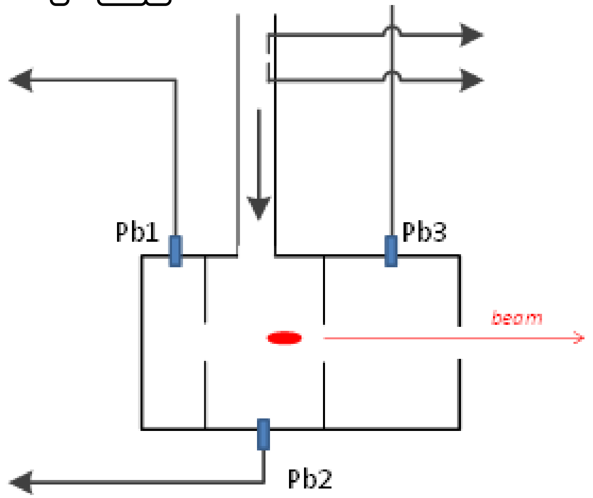




- Beam based feedback stabilizes the beam energy and compression at BC1 and BC2 by actuating on the RF phases.
- Phase actuations reflect the drifts in the machine.
- Possible sources of drifts:
  - RF reference distribution system
  - Gun laser system
  - RF detection in LLRF (pickup cable drifts or RF detector drifts)
- **The drifts are suppressed by the beam based feedback!**

Data collected from SwissFEL at Dec. 12-17, 2018 during the pilot user experiment.

Example: RF Gun Probe Drift



- ❑ Cavity probe coupling ratio is sensitive to temperature due to RF heat load change (e.g. after a interlock trip)
  - It takes minutes for the amplitude of probes to get stable.
  - PUP10 (Pb1) and PUP30 (Pb3) change in opposite directions.
- ❑ **Consequence**: RF feedback based on the measurement of probe signals cannot stabilize the cavity field during the transient time.