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Optimization Algorithms and Procedures for SwissFEL LLRF System

LLRF2017 Workshop, Barcelona , Spain, 16-19 October 2017

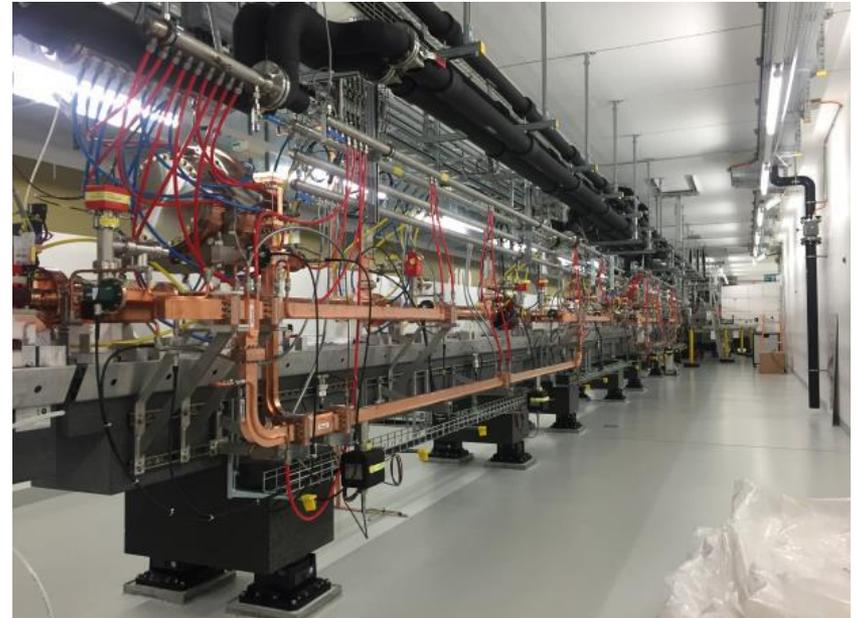
- Introduction
- LLRF Optimization Procedures
- Software Architecture
- Summary and Outlook

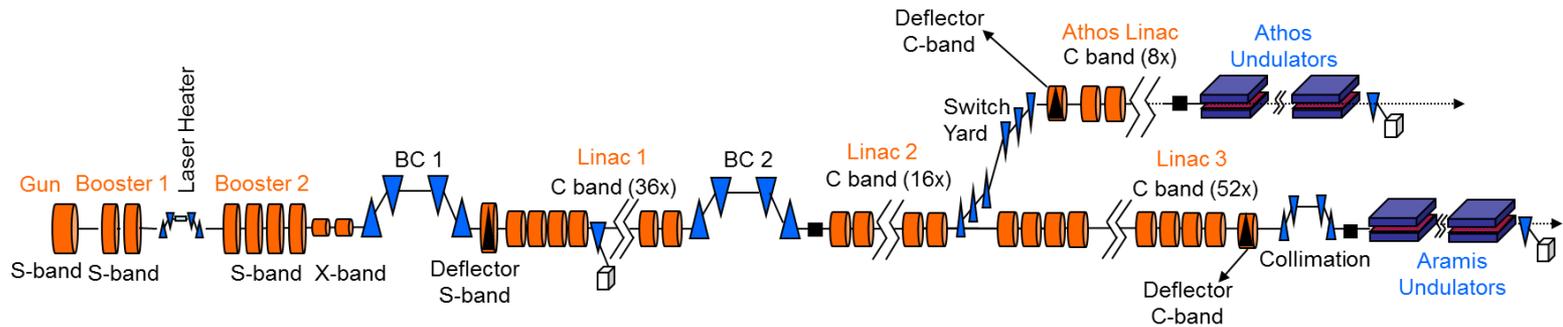


Introduction

SwissFEL is a free-electron laser under commissioning at PSI. Below are some key parameters related with RF system:

- Technology: Normal conducting
- Electron beam energy : up to 5.8 GeV
- RF repetition rate: up to 100 Hz
- RF pulse width: $\sim 3.5 \mu\text{s}$
- Num. of bunch per pulse: up to 2





SwissFEL consists of 6 S-band RF stations (1 for RF Gun, 4 with travelling wave structures and 1 for deflector cavity), 1 X-band RF station and 26 C-band RF stations (phase 1 of SwissFEL with Aramis beam line).

RF Station	Phase Tolerance (rms)	Voltage Tolerance (rms)
S-band (2998.8 MHz)	0.018 degS	0.018 %
C-band (5712 MHz)	0.036 degC	0.018 %
X-band (11.9952 GHz)	0.072 degX	0.018 %

LLRF Optimization Procedures

Phase 1:

- Started after installation finished
- Validate installation and signals
- Validate basic functionalities and performance
- *Milestone: ready for high power RF conditioning*

Phase 2 (LLRF Optimization):

- Started after high power RF conditioning finished
- Setup feedback controllers
- Apply RF on beam
- Calibrate accelerating voltage and beam phase
- Optimize RF and beam performance
- *Milestone: ready for stable beam operation*

- Validate LLRF cabling
- Validate RF reference signal
- Power on hardware chassis
- Software installation and boot up
- Test interlock signals
- Calibrate RF signal power
- Validate base functions
- Validate basic performances
- Setup PV alarm limits
- Setup reference tracking

Phase 1
Procedures

- Setup RF
- Optimize RF Performance
- Apply RF on Beam
- Optimize Beam Quality

Phase 2
procedures

Procedure: Setup RF

- Set default parameters
- Set RF signal average windows
- Calibrate vector sum
- Calibrate accelerating voltage from RF power measurement based on RF structure model
- Scan klystron non-linearity gain curves
- Fit OPD (**Operating Point Determination**) model



ROPT_Top.ui (on sf-1c6a-64-04)

Setup RF | Apply RF on Beam | Optimize RF Performance | Advanced Settings | LLRF C

Enable Set Default Parameters

Parameters to setup the LLRF system will be set to default values

- System status checking timers
- RF signal stability checking thresholds
- Tolerances for RF amplitude and phase settings
- Feedback loop settings
- Klystron power headroom
- Vector sum channel selection

Enable Set Avg Window, Group Delay

Ref. RF Station:

Average window and group delay settings will be copied from the selected station

Verify with Panels: LLRF Expert > LLRF > Tools > WF Timing (Timing) and "Show Average Windows"

Verify Vector Sum Calib

Vsum Calib Amplit Tol (rel):

Vsum Calib Phase Tol (deg):

Please do vector sum calibration directly with LLRF HLA and HPRF
Set with Panel: LLRF Expert > LLRF > Tools > Calib Vec Sum

Enable Model Based Acc Voltage Calib

Kly Output Power: Acc Voltage:

Klystron Nonlinearity Scanning

Please do klystron nonlinearity scanning directly with LLRF HLA and HPRF
Set with Panel: LLRF Expert > LLRF > Tools > Id Kly TF

OPD Fitting

Please do OPD fitting directly with the matlab tool!
Set with Panel: LLRF Expert > LLRF > RF Feedback > OPD ("Fit")

Klystron Working Point Setting

Please do klystron working point setting directly with LLRF HLA and HPRF
Set with Panel: LLRF Expert > LLRF > Tools > Set RF

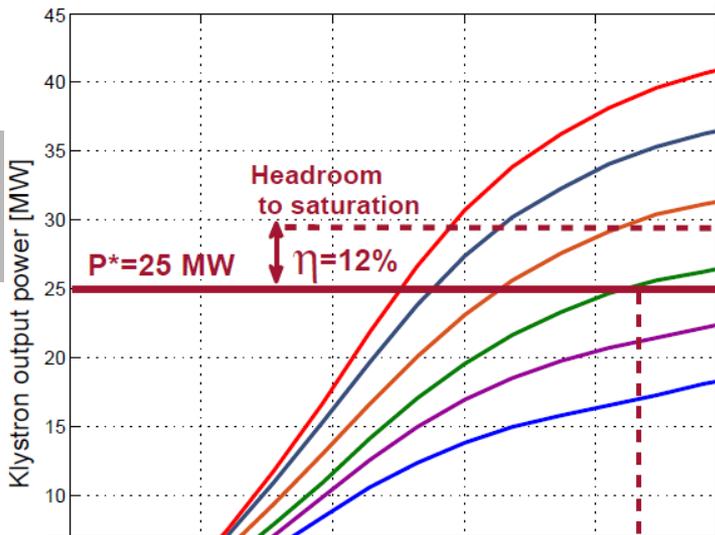
Procedure for klystron working point setting (the previous step should be completed)

1. Ask the operator (or HPRF people) the desired maximum power
2. Set the klystron power headroom (normally no less than 10%)
3. Set the "Klys Working Point Cond" to "Keep Headroom"
4. Input the max desired acc voltage or power and make sure the klystron is in saturation
5. Set the "Klys Working Point Cond" to "HVPS Fixed"
6. Close the amplitude and phase feedbacks by clicking "Off"

If it is determined that the klystron works at saturation without the feedbacks, the "Klys Working Point Cond" should be set to "Saturation". If not, the "Klys Working Point Cond" should be set to "Keep Headroom" and in step 6 only close phase feedback.

Enable All | Disable All | Execute | Stop | Resume from Next | Resume from Last

```
[2017-09-09 15:47:50] S10C001 [INFO] Job_CheckRFStab
[2017-09-09 15:47:50] S10C001 [INFO] Job_CheckRFStab
[2017-09-09 15:47:50] S10C001 [INFO] Job_MatchRFPower
[2017-09-09 15:47:49] S10C001 [INFO] Job_MatchRFPower
[2017-09-09 15:47:49] S10C001 [INFO] Job_CheckRFStab
[2017-09-09 15:47:49] S10C001 [INFO] Job_CheckRFStab
[2017-09-09 15:47:49] S10C001 [INFO] Job_CheckRFStab
[2017-09-09 15:47:49] S10C001 [INFO] Job_MatchRFPower
```



General Ctrl | Set RF | Gen DAC Tab | Corr DAC Offset | WF Timing | Calib Vec Sum | Setup FB Loop | ILC | Cav Tuning | Acc Tuning | Id I/Q Imbal

Parameter Settings

- Pulse Num for Avg: 100
- HVPS Min (V): 1800
- HVPS Max (V): 2150
- HVPS Step (V): 50
- HVPS Tol (V): 10
- DAC Amplt Scale Min: 0.050
- DAC Amplt Scale Max: 0.850
- DAC Amplt Scale Step: 0.050
- Phase Rot (deg): 0.000
- Min Amplt for Avail. (raw): 0
- Amplt Jitter Max: 1.000e-02
- Phase jit Max (deg): 2.000
- Timeout (S): 30

Display Select: Klystron Forward

HVPS Scan Progress /

Amplt Avg Pulse-to-Pulse

Phase Avg Pulse-to-Pulse

Amplt Jitter Pulse-to-Pulse

Phase Jitter Pulse-to-Pulse

Power Avg Intra-Pulse

Active Debug

Identify Kly Transfer Func

Stop Resume

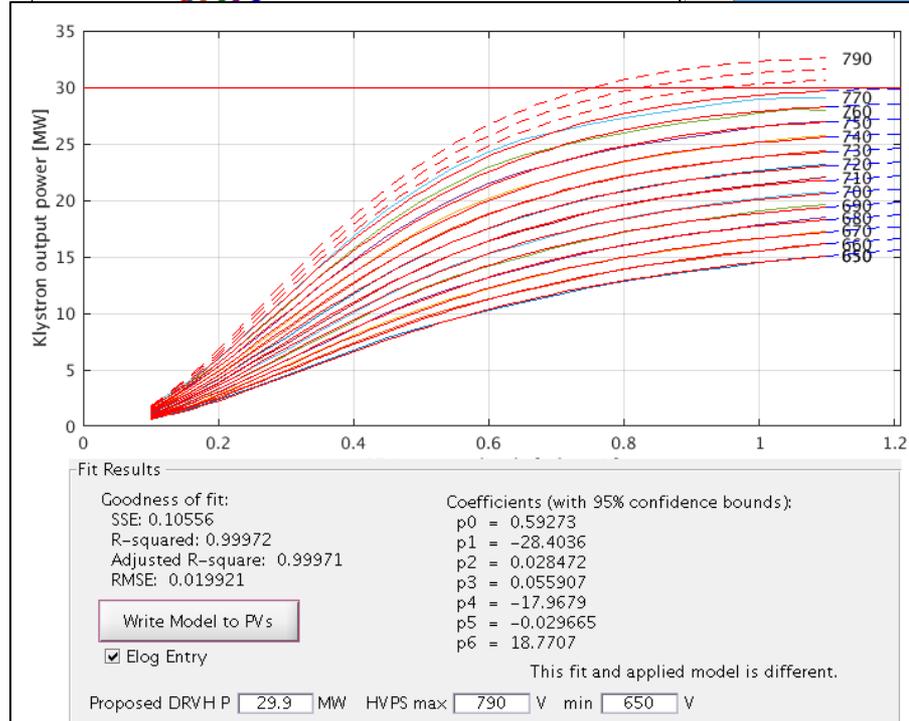
Save Data

User String in File Name:

Modulator Status

Channel Access Conn: ■

Modulator State Reached: ■



Plot X-axis DAC drive scaling factor

RF Station SINSB02

Model Version

- 20161104104349
- 20161104110148
- 20170412151748
- 20170425085619
- 20170704094028
- 20170704112502
- 20170704113252
- 20170704113556
- 20170704114136

Fit Options

Method	NonlinearLeas...
Algorithm	Levenberg-M...
Robust	LAR
MaxIter	10000
MaxFunEvals	10000
DiffMinChange	1.0000e-04
DiffMaxChange	1.0000e-04
TolFun	1.0000e-07
TolX	1.0000e-06
min amplitude	0.1000
max amplitude	1.1000

Fit

Version 1.0.9 Help

08-25,11:52:40 Save scan data to file /ifc-exchange/ll

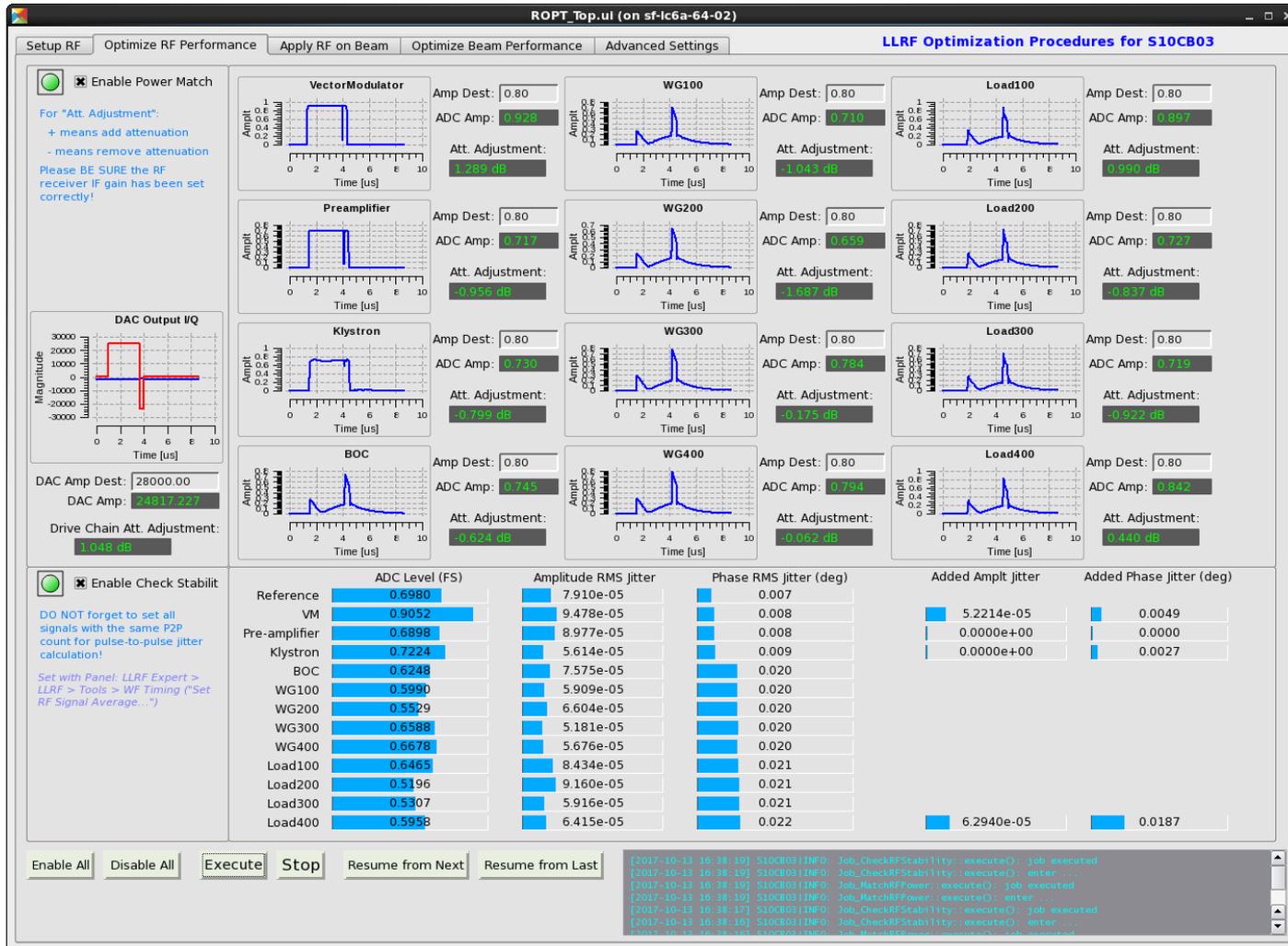
Software tool to scan klystron gain curves



Matlab tool to fit the klystron non-linearity model (OPD)

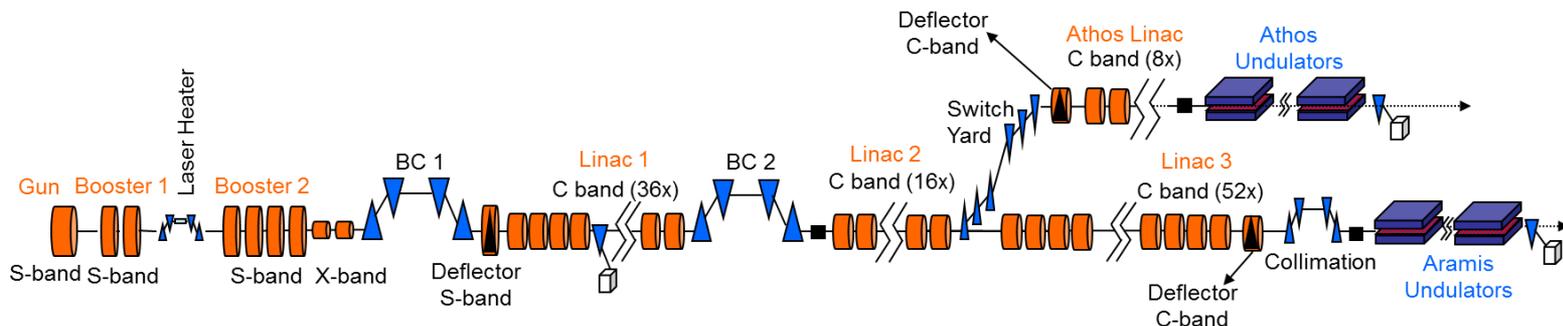
Procedure: Optimize RF Performance

- Adjust DAC drive level to maximize the SNR of RF actuator (for clean RF drive)
- Adjust RF signal level to maximize the SNR of RF detector (for better measurement resolution)
- On-line RF stability analysis



Procedure: Apply RF on Beam

- Setup a downstream spectrometer according to the beam energy estimation with all upstream RF stations
- Center the beam position after the spectrometer by adjusting the dipole current with an algorithm similar as orbit feedback
- Set the timing event of the RF station to the one for beam acceleration
- Set the timing delay of the RF station to overlap the RF with beam in time
- Apply the RF station on beam (**with reduced amplitude to avoid beam loss**)
- Calibrate the on-crest phase for maximum beam acceleration
- Ramp the RF power while keeping the spectrometer follows
- Further optimize the RF delay to maximize the beam energy
- Identify the RF-beam interaction region on the pulse for accurate RF field measurement (**measure the RF field seen by beam**)



Procedure: Apply RF on Beam – cont.

ROPT_Top.ui
LLRF Optimization Procedures for S10CB02

Setup RF
Apply RF on Beam
Optimize RF Performance
Advanced Settings

Enable Setup Spec.

Enable Center Spec.

Enable Set RF Event

Enable Set RF Timing

Enable Set RF On Beam

Enable Phasing RF

Enable Ramp RF Amplt

Enable Opt RF Delay

Enable Calib Beam Interaction Time and Group Delay

Sel Spec: Injector Spec Sel Beam Pos: BPM

Delta P Search Range (MeV/c): 10.000
 Min Charge Beam Avail (pC): 1.000
 Min Scr Intensity Beam Avail: 0.000

Dest Event: RF fire 1 Current Event: RF fire 1 Rate: 100.0 Hz

Ref. RF Station: S10CB01 Raw Delay: 9K 5pp Fine Delay: 0.464 us

Set Zero Amp before on beam Current State: RF on beam Status: READY

Enable Change Amplt SP
 Enable set vsum phase calib

Phase Scan Start (deg): 0.000
 Phase Scan End (deg): 360.000
 Phase Scan Step (deg): 10.000
 Phase Fit Start (deg): 0.000
 Phase Fit End (deg): 360.000
 Amplt SP for Scan (MV): 5.000

Enable Center Spec
 Amplt Dest (MV): 200.000
 Amplt Ramp Step (MV): 5.000
 Ramp Wait Time (s): 0.5

Delay Scan Start (us): 0.450
 Delay Scan End (us): 0.480
 Delay Scan Step (us): 0.001
 Process Range Start (us): 0.000
 Process Range End (us): 8.000
 Scan Wait Time (s): 0.5

Spec (Gun, Inj, L3) Spec (ARA)

DCOM-SPECGUN
 BPM Min X: 0.000 mm
 BPM Max X: 0.000 mm
 BPM Calib: 0.000 MeV/mm
 SCR Min X: 0.000 mm
 SCR Max X: 0.000 mm
 SCR Calib: 0.000 MeV/mm

DCOM-SPECINJ
 BPM Min X: -11.343 mm
 BPM Max X: 11.957 mm
 BPM Calib: -1.087 MeV/mm
 SCR Min X: 0.000 mm
 SCR Max X: 0.000 mm
 SCR Calib: 0.000 MeV/mm

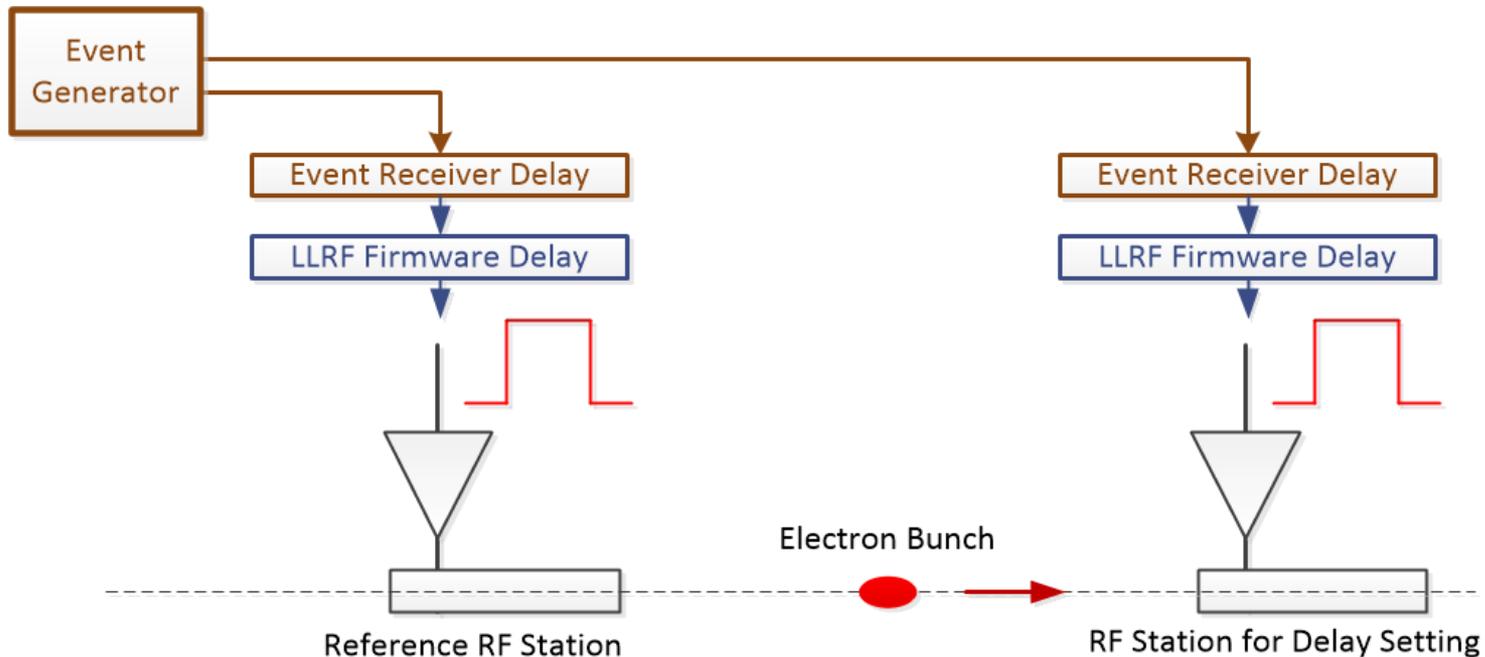
DCOM-SPECL3
 BPM Min X: 0.000 mm
 BPM Max X: 0.000 mm
 BPM Calib: 0.000 MeV/mm
 SCR Min X: 0.000 mm
 SCR Max X: 0.000 mm
 SCR Calib: 0.000 MeV/mm

Enable All
Disable All
Execute
Stop
Resume from Next
Resume from Last

```

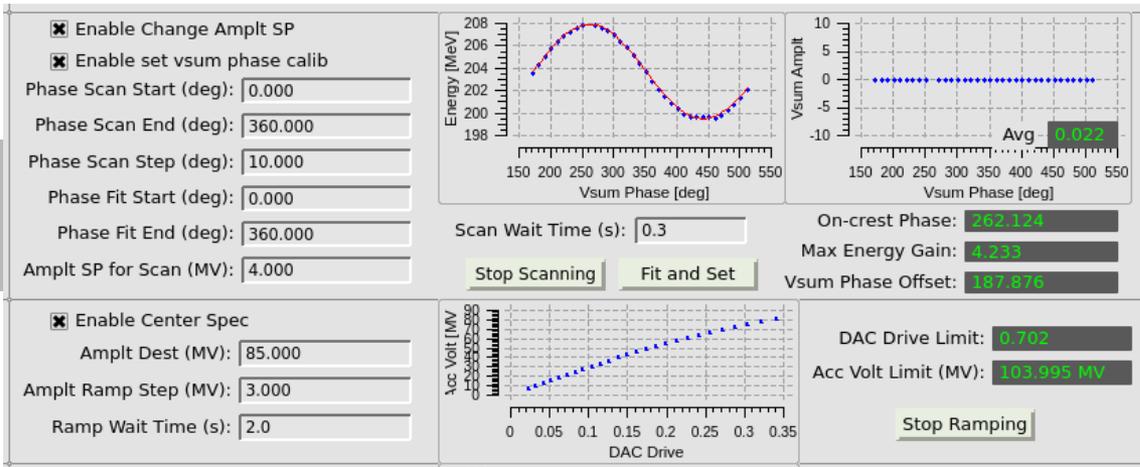
[2017-08-28 09:08:15] S10CB02|INFO: Job_AlignRFBeam::execute(): job executed
[2017-08-28 09:08:15] S10CB02|INFO: Job_AlignRFBeam::execute(): enter ...
[2017-08-28 09:08:14] S10CB02|INFO: Job_AlignRFBeam::execute(): job executed
[2017-08-28 09:08:14] S10CB02|INFO: Job_AlignRFBeam::execute(): enter ...
[2017-08-28 09:07:55] S10CB02|INFO: Job_AlignRFBeam::execute(): job executed
[2017-08-28 09:07:40] S10CB02|INFO: Job_AlignRFBeam::execute(): enter ...
[2017-08-28 09:07:40] S10CB02|INFO: Job_RampRF::execute(): job not executed, only collect data bus
                
```

Algorithms to Set RF Station Timing Delay

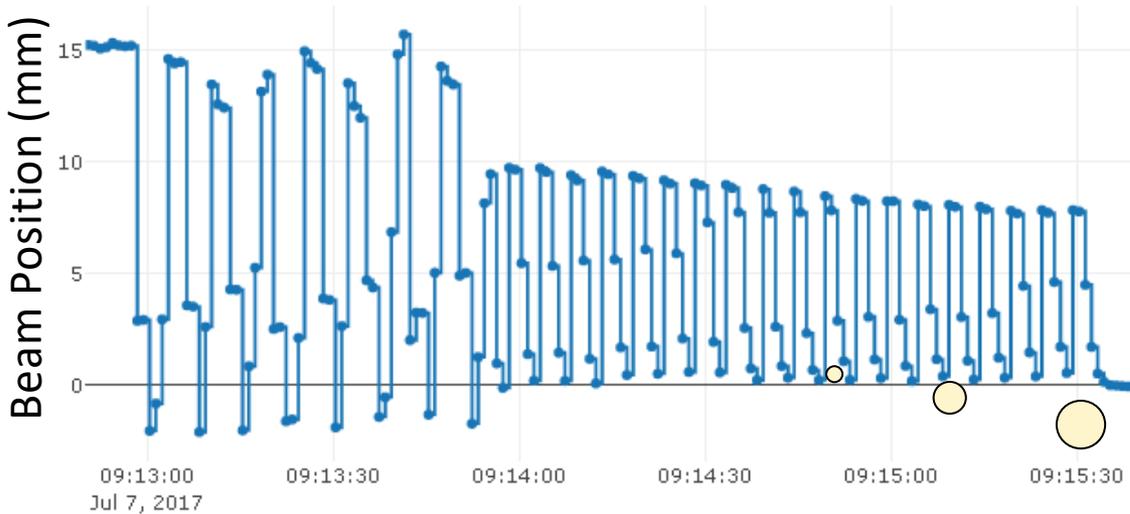


- A reference RF station that has been applied on beam.
- The desired total delay of the RF station under setting is estimated by comparing with the reference RF station taking into account the flight-time of the electron bunch. And then the “Event Receiver Delay” (raw delay) and “LLRF Firmware Delay” (fine delay) can be adjusted.

Tools to Perform RF Phasing and Ramping

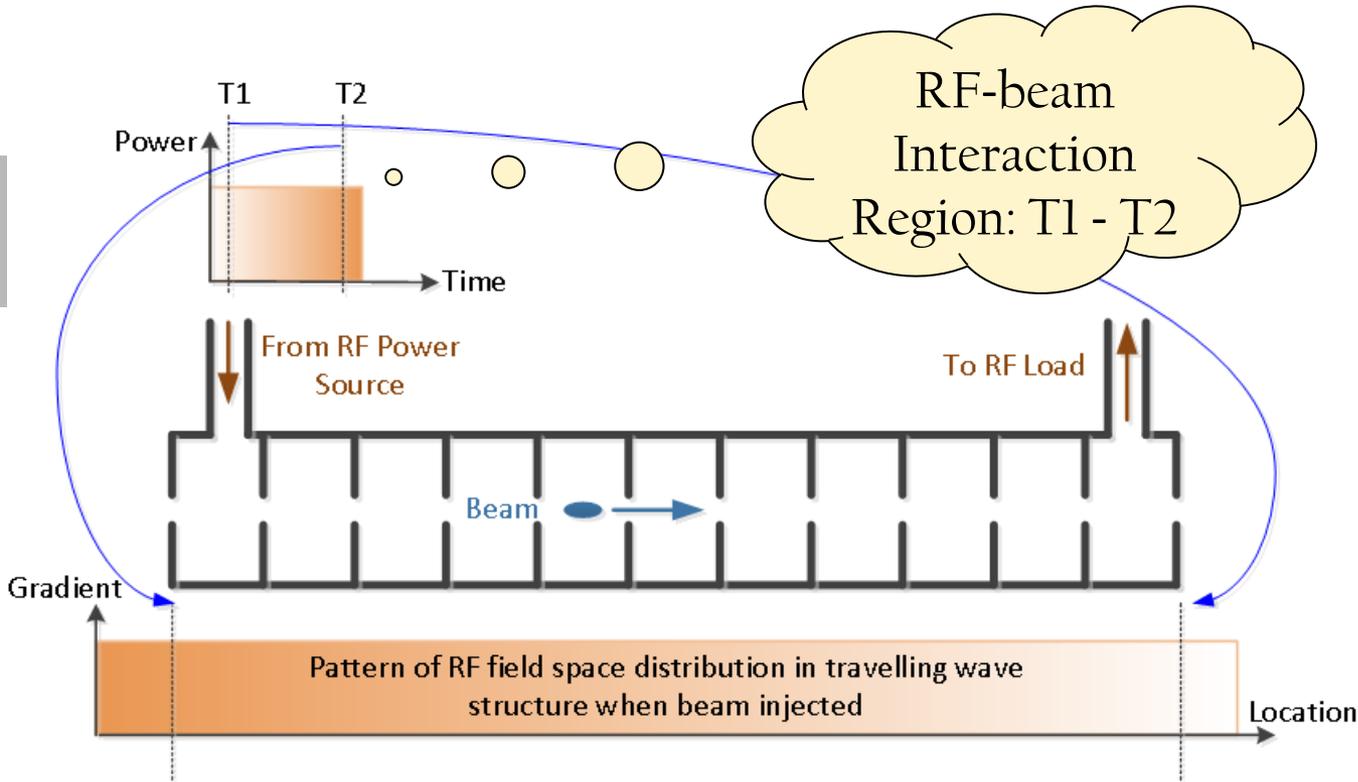


- **Phasing:** scan RF phase in full cycle with low accelerating voltage and fit the energy-phase relation with a sine function (results: on-crest phase).
- **RF Ramping:** ramp the accelerating voltage in steps, after each step, automatically adjust the spectrometer to center the beam.

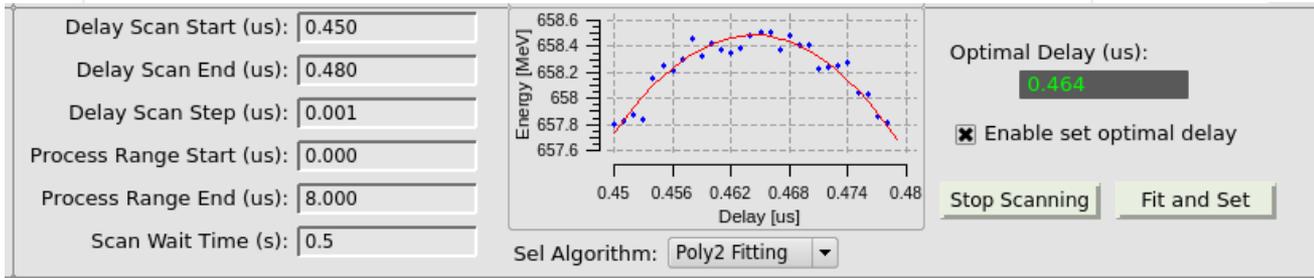


Beam position after spectrometer when ramping RF power.

RF-beam Interaction Optimization



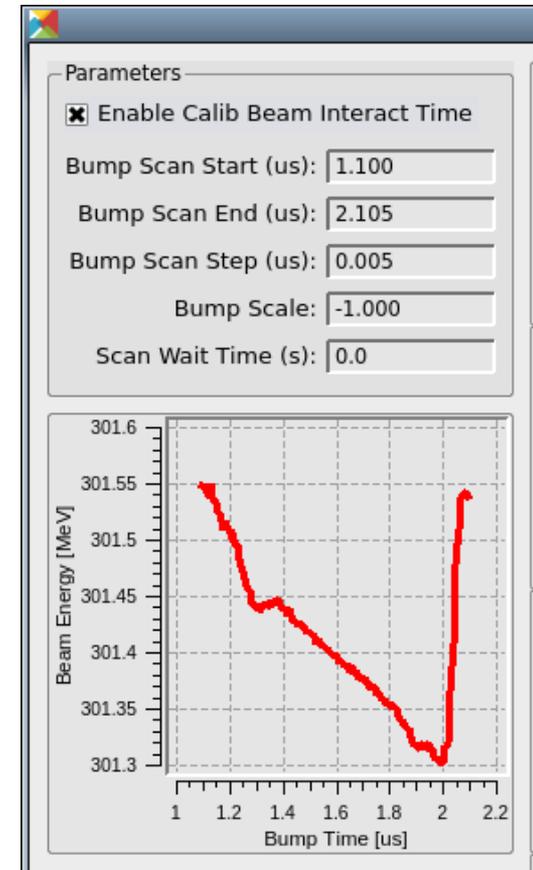
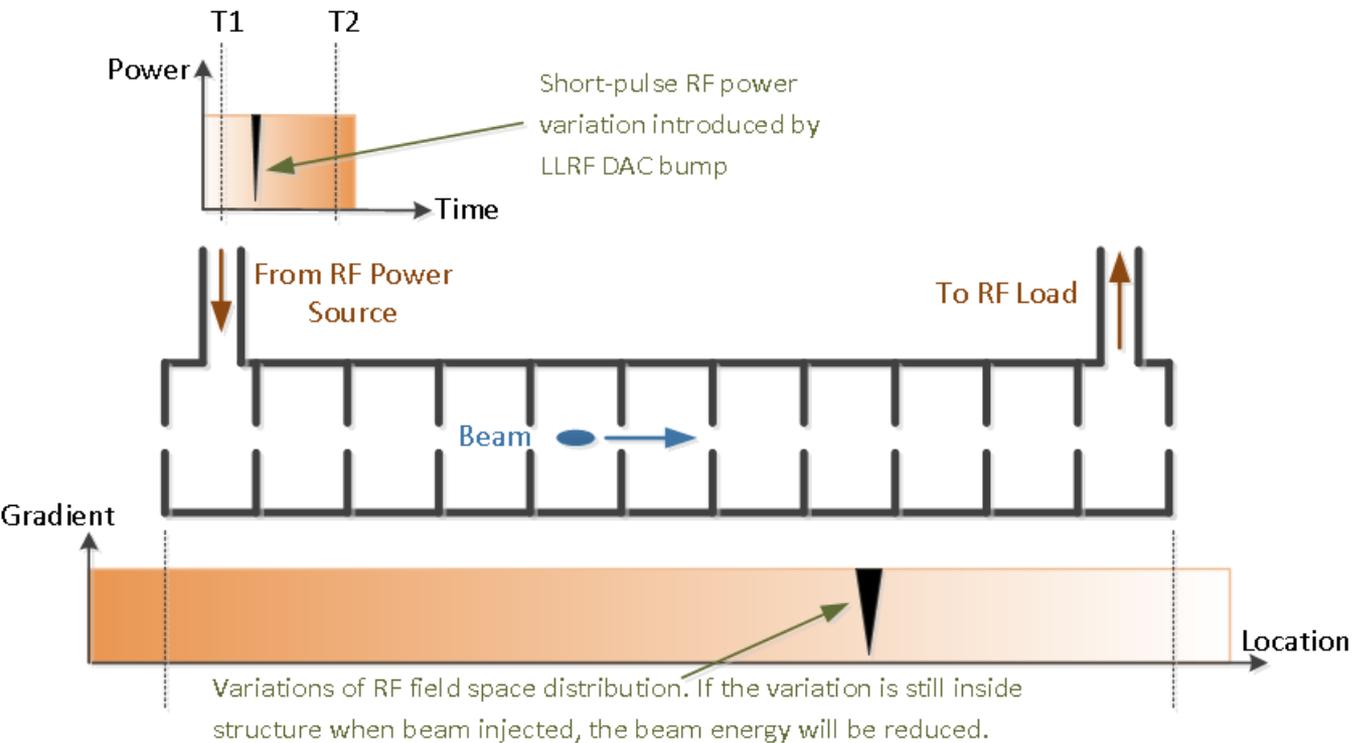
- Optimize RF pulse delay so that the structure is fully filled when beam injected.
- Identify the time region in the RF pulse that fills the structure and interacts with beam.



$$\mathbf{v}_{acc} \sim \int_{T_1}^{T_2} \mathbf{v}_{RF}(t) dt$$

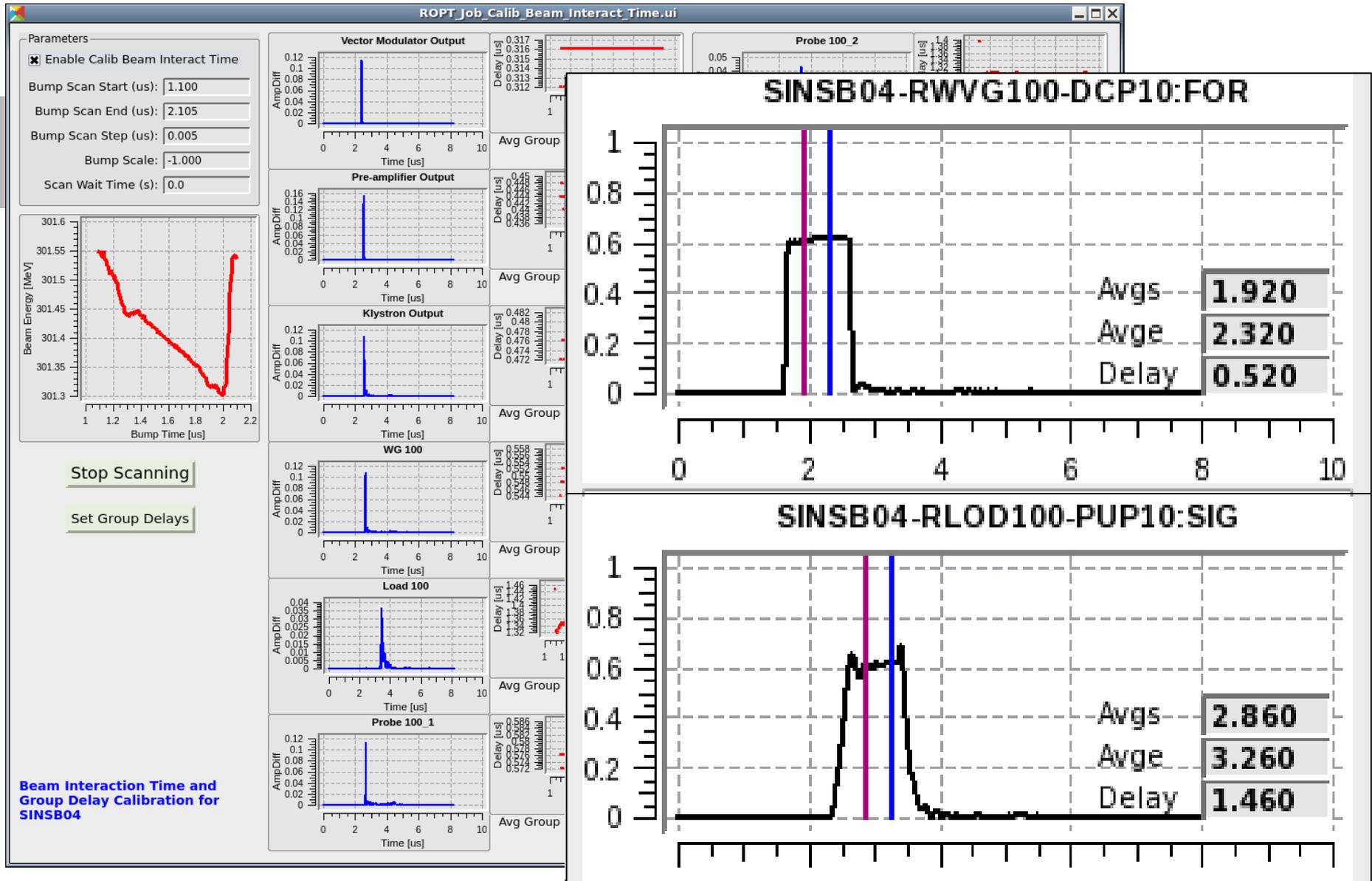
T2-T1 is the filling time of the structure (S-band: 930 ns, C-band: 330 ns, X-band: 105 ns)

Algorithms to Identify RF-beam Interaction Region



- Generate a negative bump in the RF pulse by varying a single DAC point (DACs of SwissFEL LLRF system work at ~ 250 MSPS).
- Scan the time of DAC bump and correlate with the beam energy. The time range of the bump that reduces the beam energy is the RF-beam interaction region in the RF pulse.

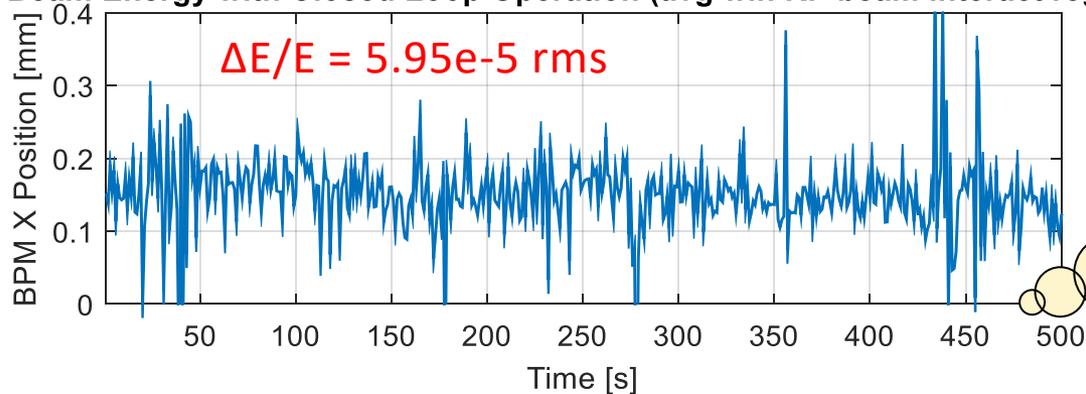
Settings of RF Average Windows and Group Delays



Verification of RF-beam Interaction Region

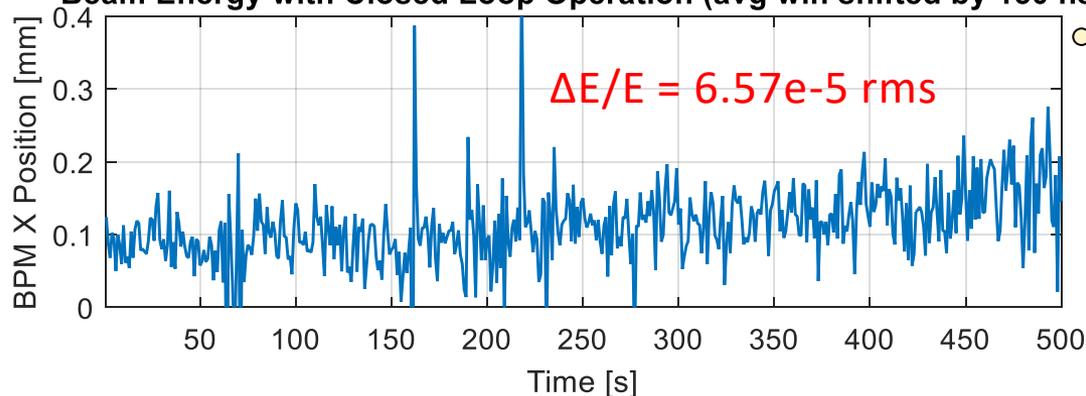
- To verify the RF-beam interaction region, the beam energy stability was measured with RF amplitude and phase feedbacks on, and the RF signals were measured with different average windows.

Beam Energy with Closed Loop Operation (avg win RF-beam interact region)



Pre-condition for good feedback:
Measure what really seen by beam!

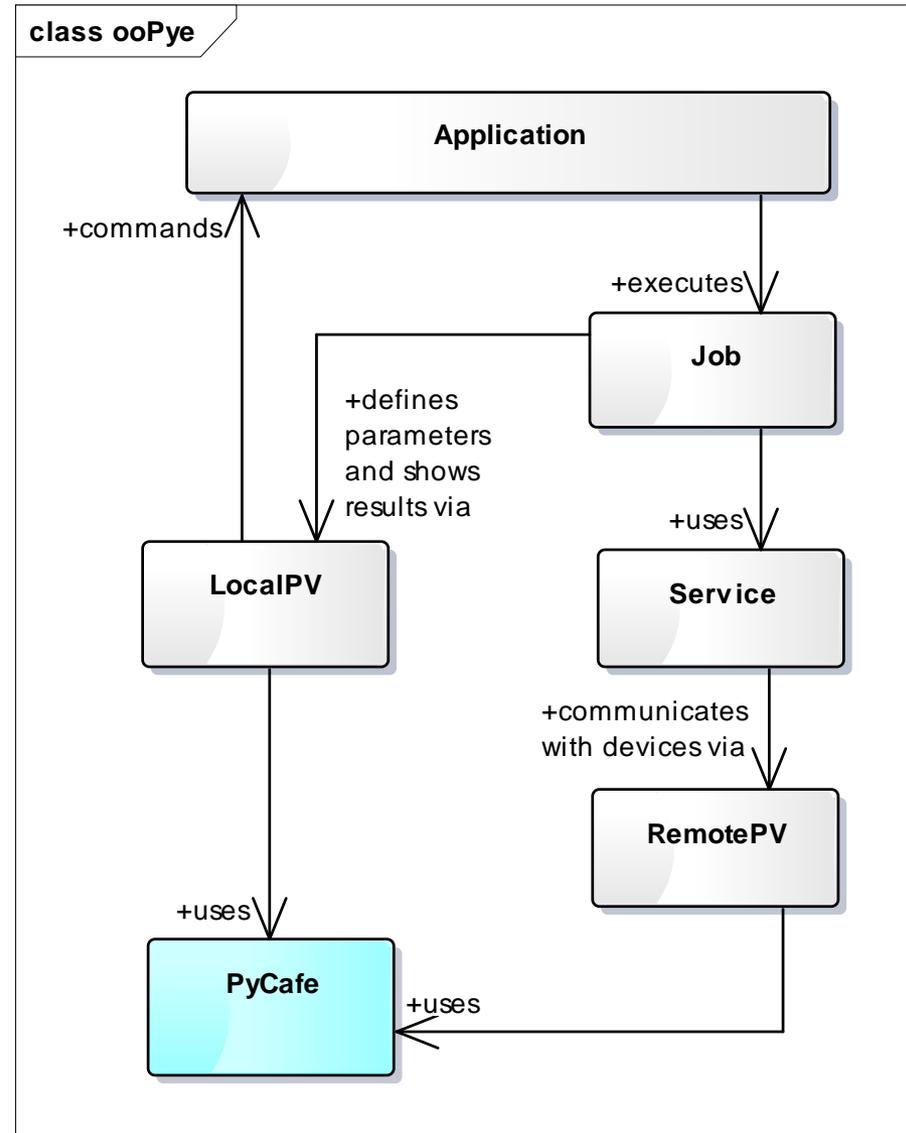
Beam Energy with Closed Loop Operation (avg win shifted by 150 ns)

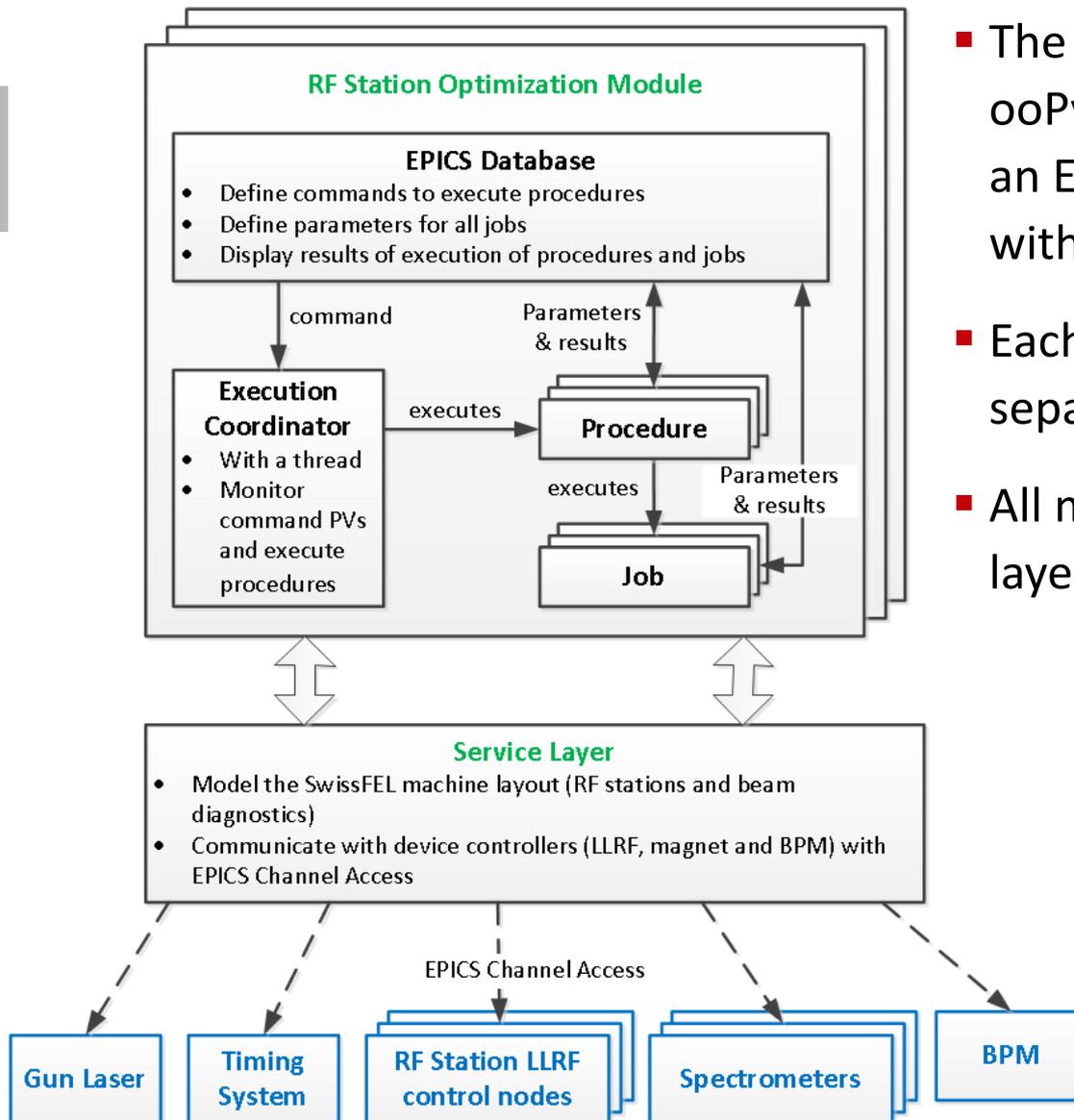


Dispersion
 $\eta = -0.85 \text{ m}$,
 $\Delta x = \eta \Delta E / E$

Software Architecture

- The class “Application” contains a thread.
- Local PVs and remote PVs are defined in user Python code. EPICS database and soft IOC can be automatically generated and installed.
- PyCafe is a Python based EPICS channel access client developed by Jan Chrin (PSI).
<https://ados.web.psi.ch/cafe/cython.html>





- The software is derived from the ooPy framework and designed as an EPICS soft IOC and implemented with Python.
- Each RF station is optimized by a separate module.
- All modules share the same service layer.

Summary and Outlook

Summary and Outlook

- ❑ The automated or semi-automated LLRF optimization procedures have been used in the commissioning of SwissFEL.
 - It significantly reduces the time to setup a fresh RF station for beam operation.
 - It provides very helpful guidelines and tools to optimize the LLRF system after shutdown or maintenance.
- ❑ The procedure to further optimize the beam quality (e.g. beam energy stability, fine tuning of two-bunch operation) will be developed in the near future.
- ❑ The experiences gained when developing and using the LLRF optimization procedures will be helpful for other systems (e.g. beam based feedback system).

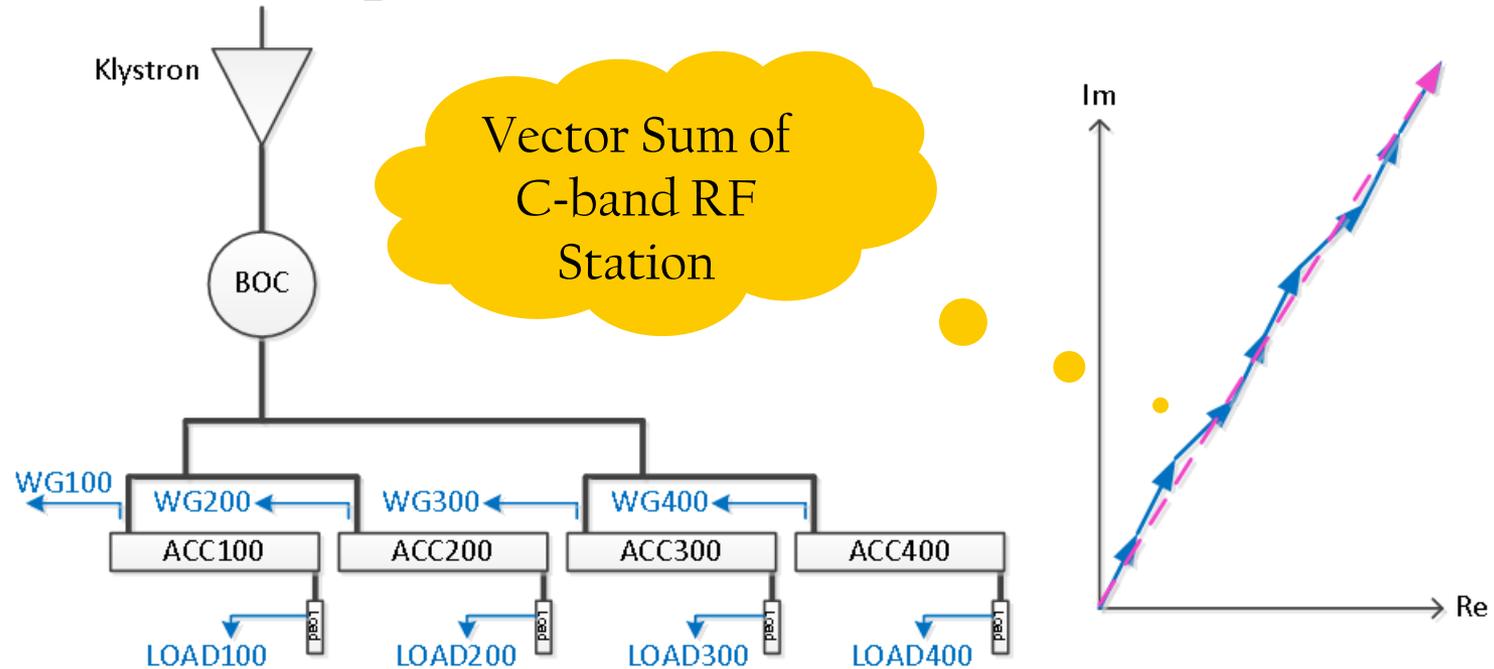
Thank you for
your attention!





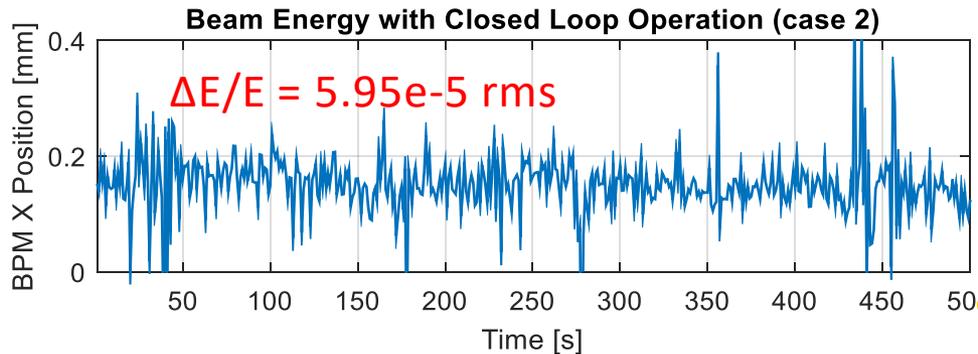
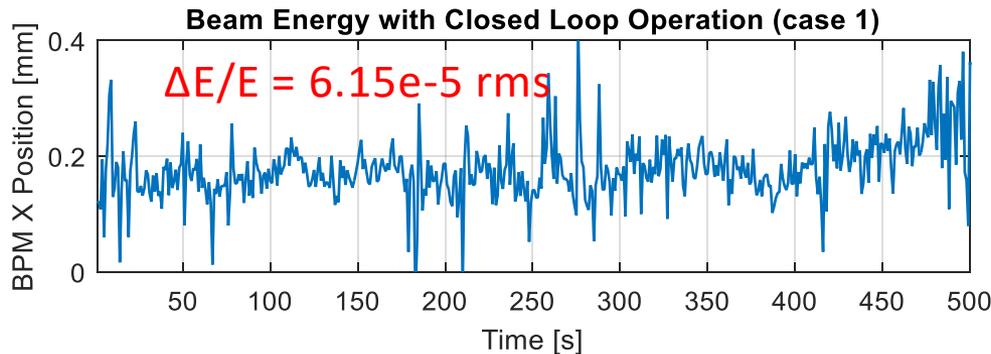
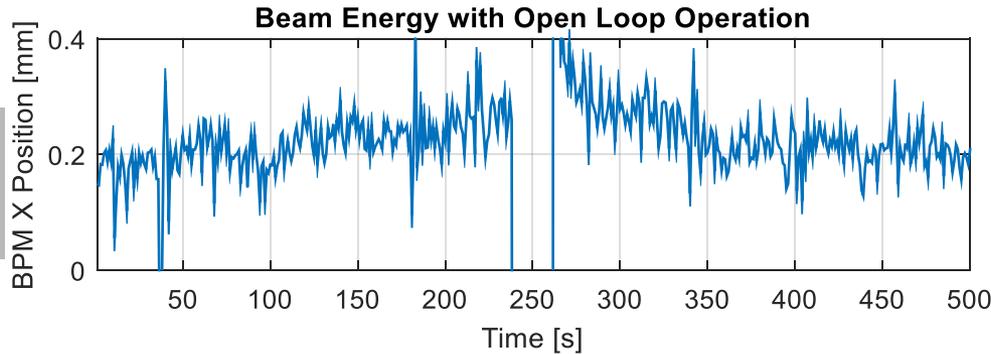
Backup

Setup RF: Vector Sum Calibration



- RF signals at the input (**waveguide**) and output (**load**) of travelling wave structures are summed up to represent the RF field seen by beam.
- The variations in vector sum amplitude and phase reflect the fluctuations in both RF power drive and structures.

Setup RF: Vector Sum Calibration – cont.



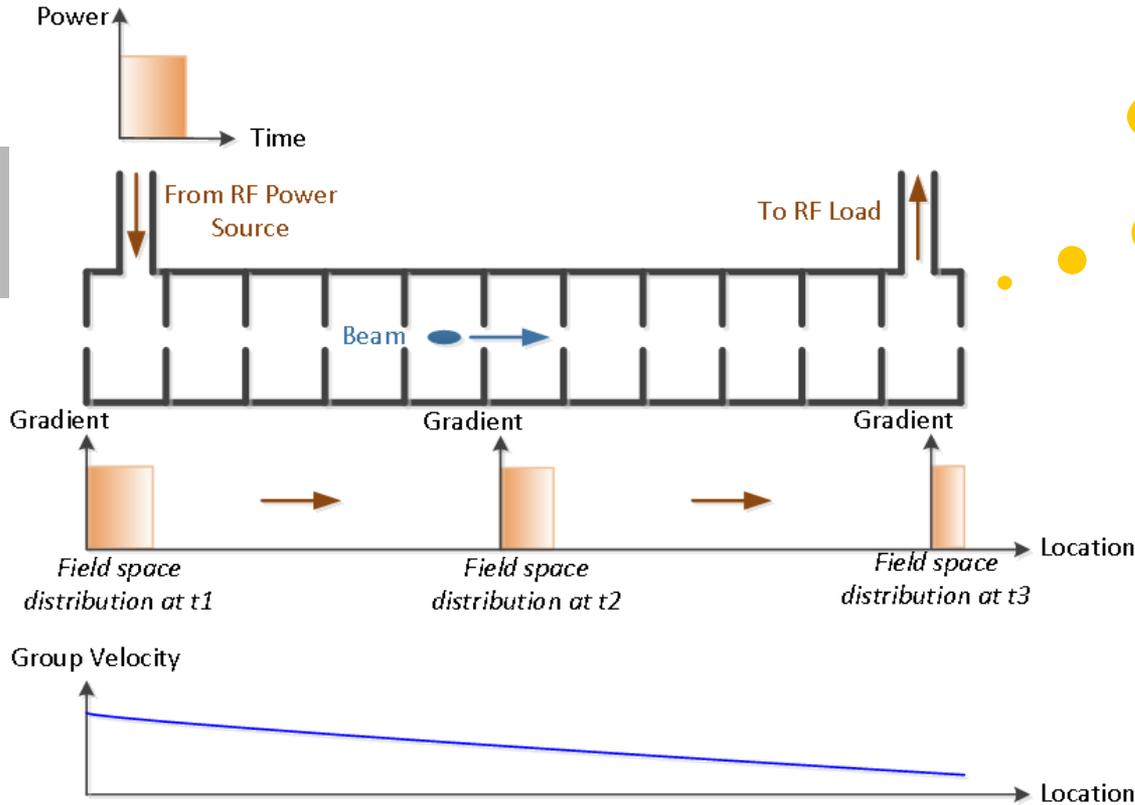
One S-band RF station before BC1 was used to test the vector sum calibration with amplitude and phase feedbacks. The beam energy jitter was measured with a BPM after the injector spectrometer.

Three tests:

- *Open loop operation*
- *Closed loop operation case 1:* vector sum only includes input signals of structures
- *Closed loop operation case 2:* vector sum includes both input and output signals of structures

Dispersion $\eta = -0.85$ m,
 $\Delta x = \eta \Delta E / E$

Apply RF on Beam: RF-beam Interaction – cont.



Constant Gradient Structures at SwissFEL

- Algorithm to calculate integrated RF fields seen by beam.

Future plan: weight function is related with distribution of group velocity.

Current Algorithm: $\mathbf{v}_{acc} \sim \int_{T_1}^{T_2} \mathbf{v}_{RF}(t) dt$

Expected Algorithm: $\mathbf{v}_{acc} \sim \int_{T_1}^{T_2} \mathbf{v}_{RF}(t) w(t) dt$

