PAUL SCHERRER INSTITUT

Zheqiao Geng :: LLRF Group :: Paul Scherrer Institut

Optimization Algorithms and Procedures for SwissFEL LLRF System

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

Outline

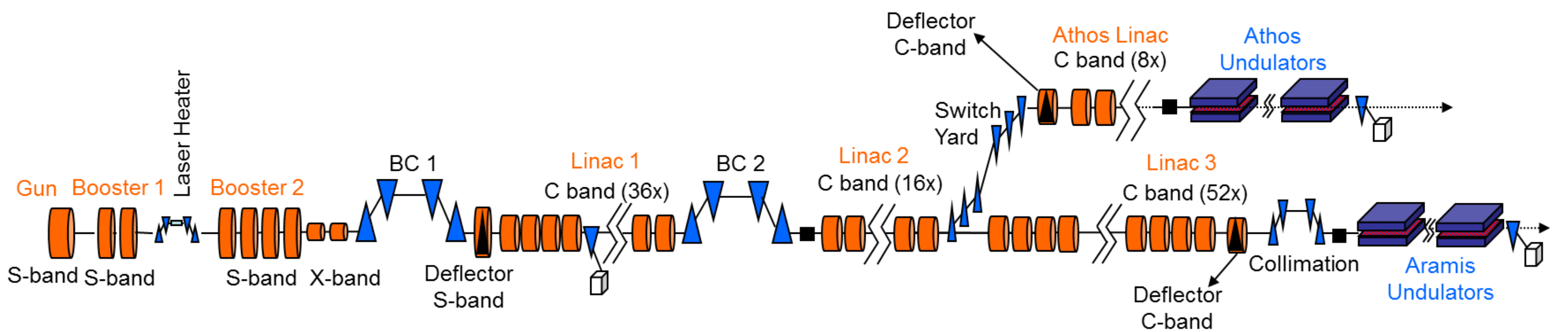
- Introduction
- LLRF Optimization Procedures
- Software Architecture
- Summary and Outlook

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:	~ 3.5 μs
▪ Num. of bunch per pulse:	up to 2

SwissFEL RF Systems



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

PAUL SCHERRER INSTITUT PSI

LLRF Commissioning

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

Phase 1 Procedures

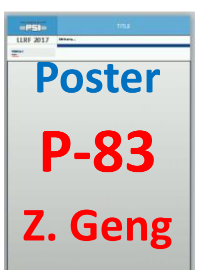
- ❑ Validate LLRF cabling
- ❑ Validate RF reference signal
- ❑ Power on hardware chassis
- ❑ Software installation and boot up
- ❑ Test interlock signals
- ❑ Calibrate RF signal power
- ❑ Validate base functions
- ❑ Validate basic performances
- ❑ Setup PV alarm limits
- ❑ Setup reference tracking

Phase 2 procedures

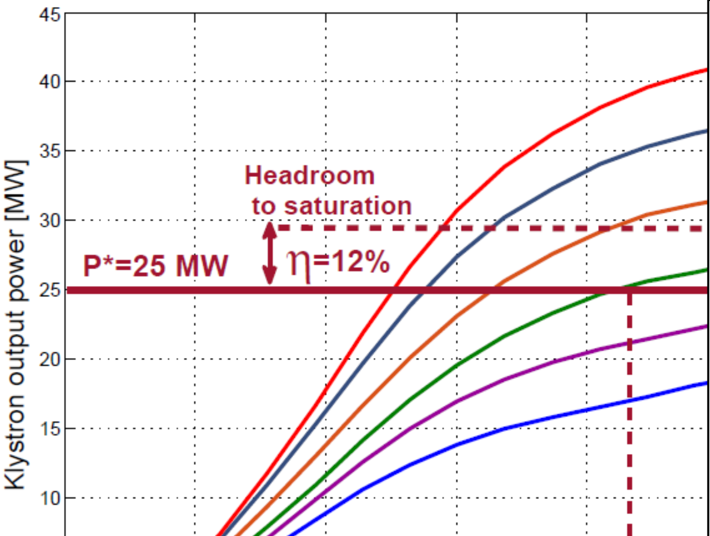
- ❑ Setup RF
- ❑ Optimize RF Performance
- ❑ Apply RF on Beam
- ❑ Optimize Beam Quality

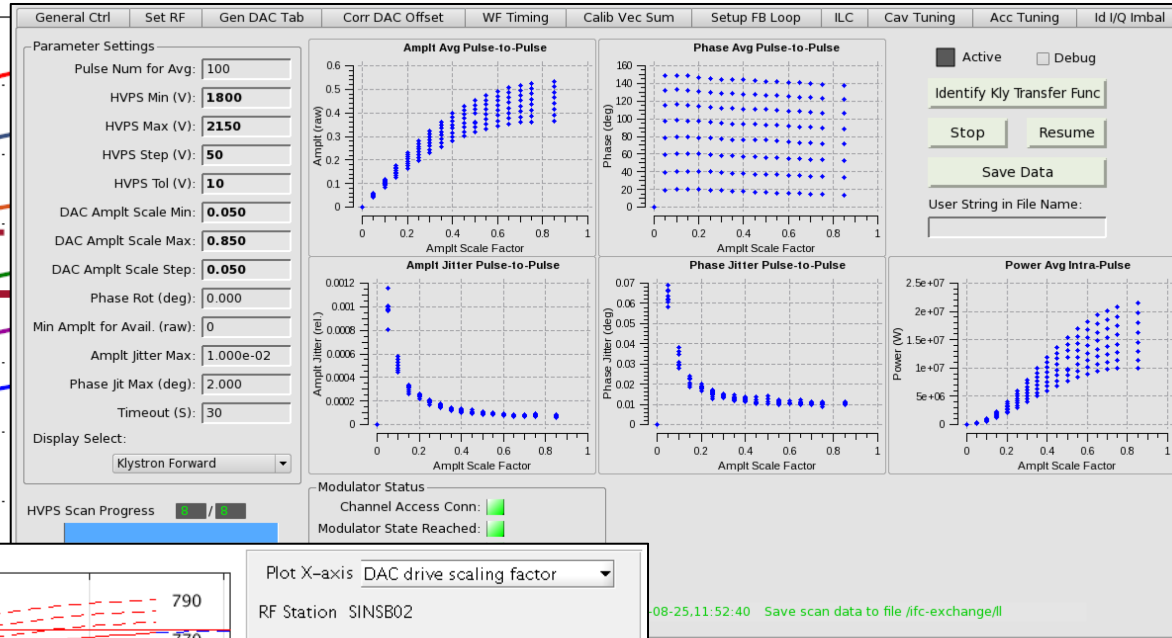
Procedure: Setup RF

- 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

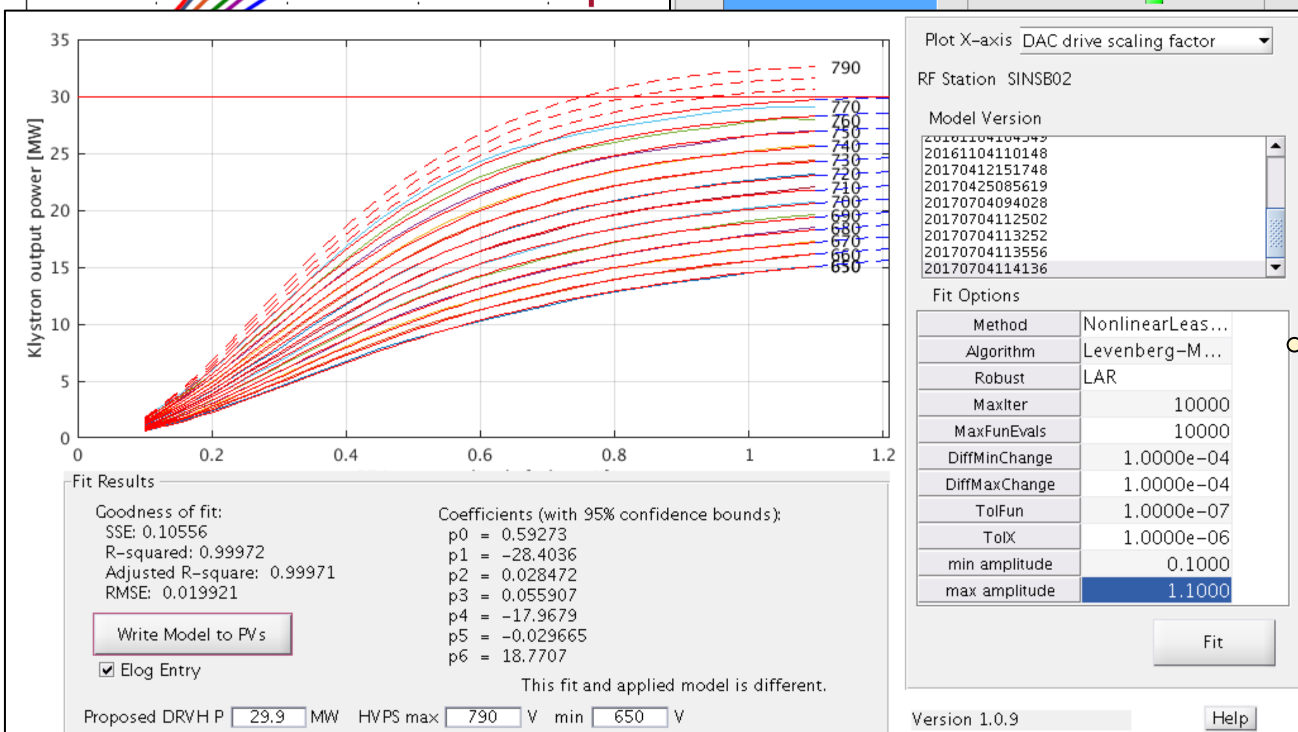


Algorithms and Tools for Klystron Linearization





Software tool to scan klystron gain curves

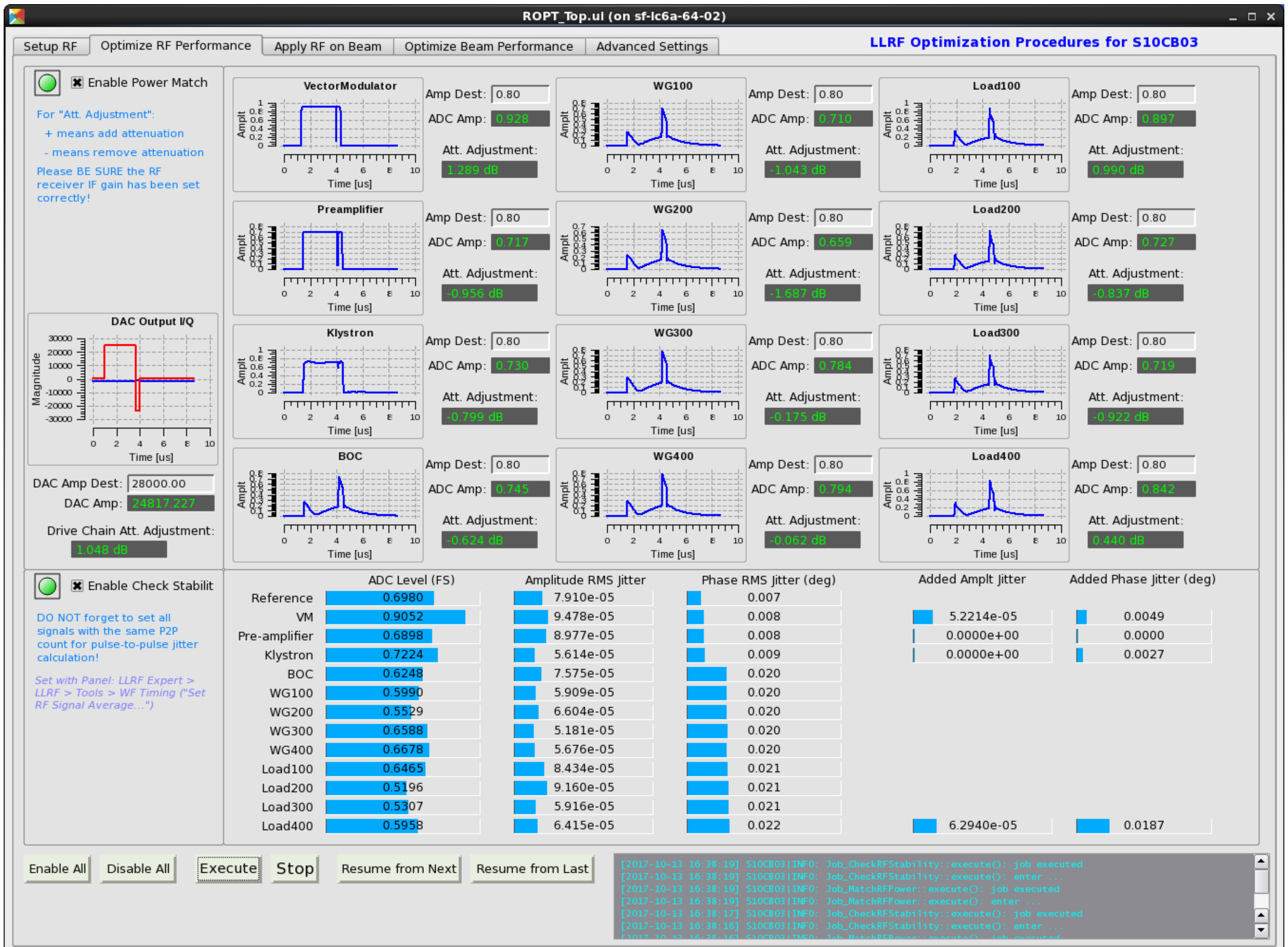


Courtesy:
Amin
Rezaeizadeh

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

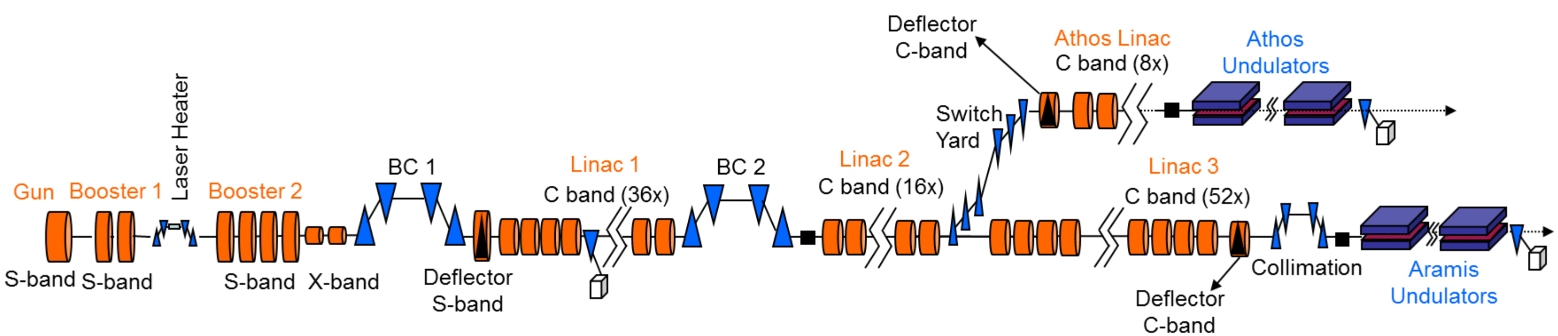
Procedure: Optimize RF Performance

- 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

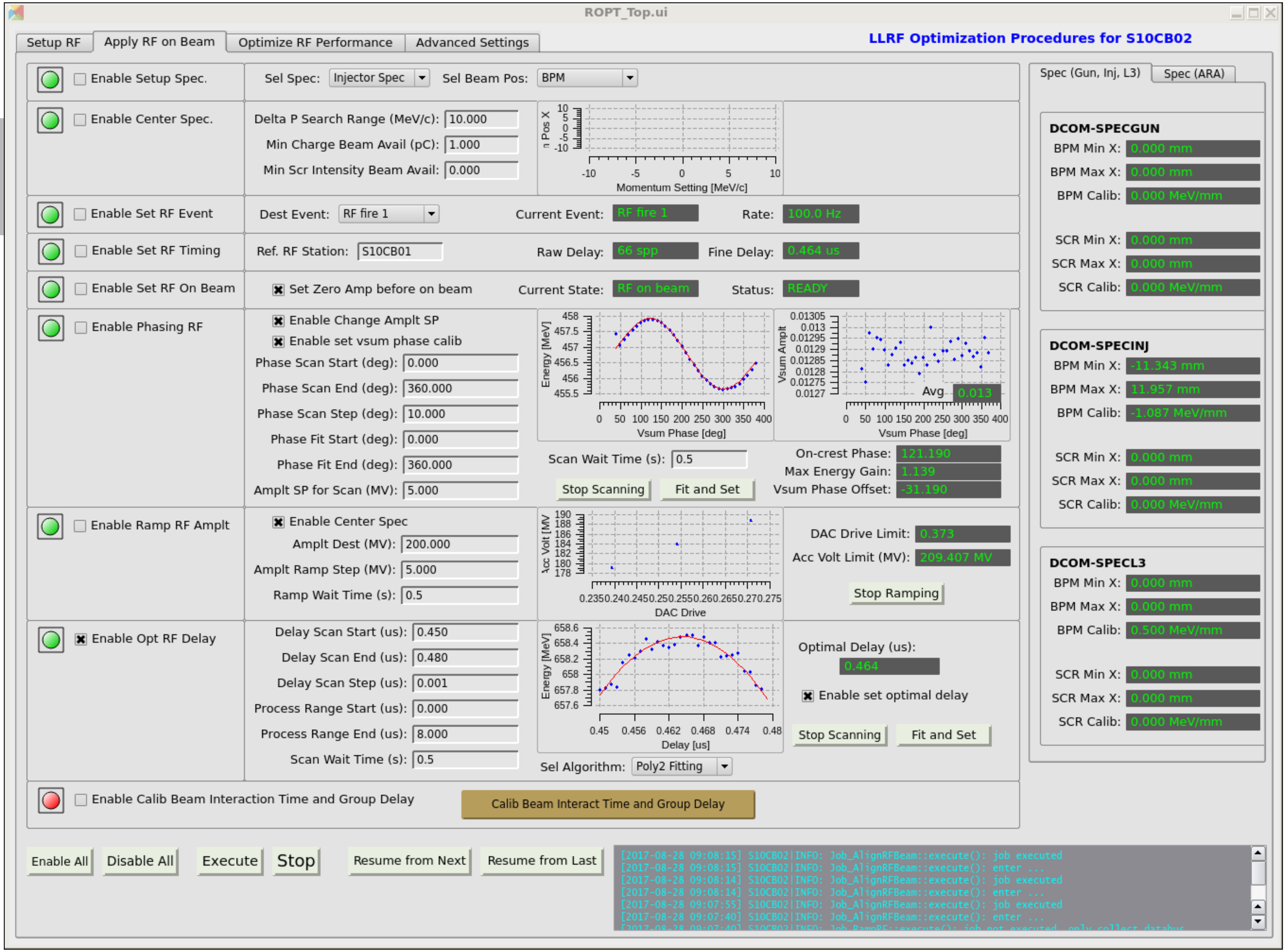


Procedure: Apply RF on Beam

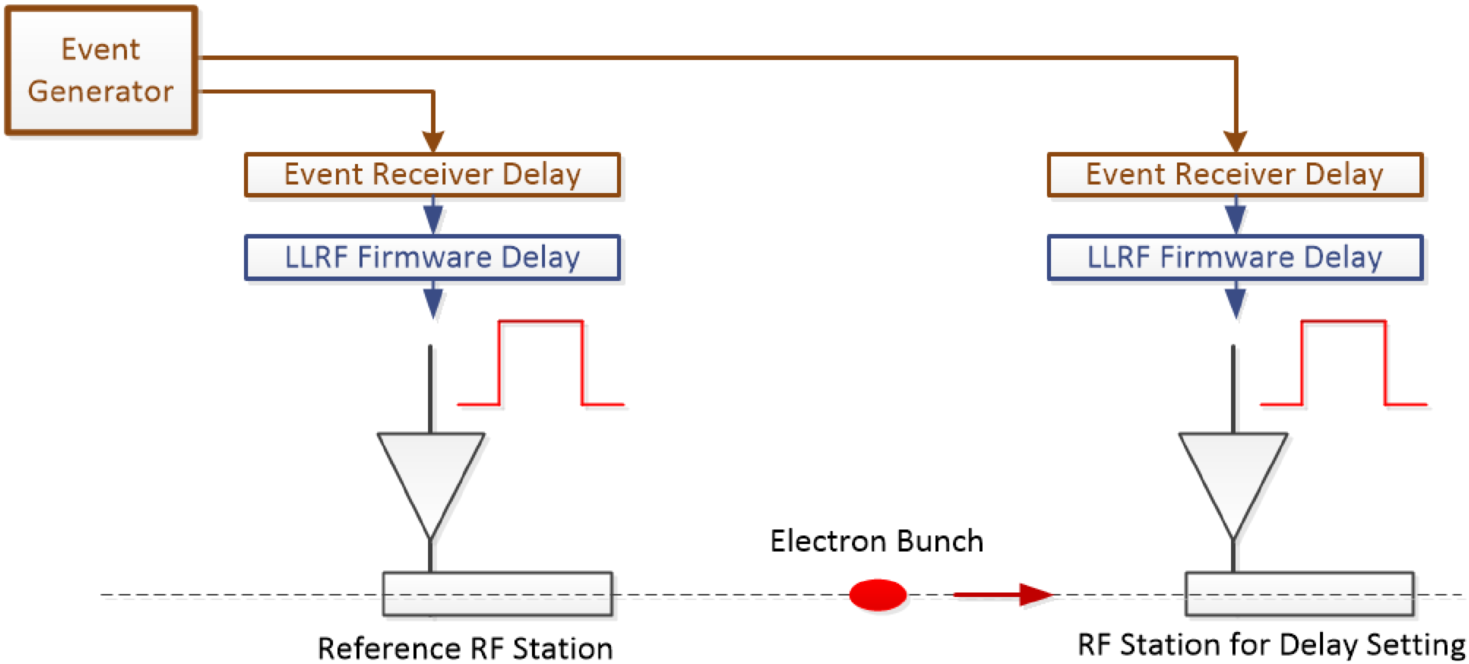
- Setup a downstream spectrometer according to the beam energy estimation with all upstream RF stations
- Center the beam position after the spectrometer by adjusting the dipole current with an algorithm similar as orbit feedback
- Set the timing event of the RF station to the one for beam acceleration
- 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.

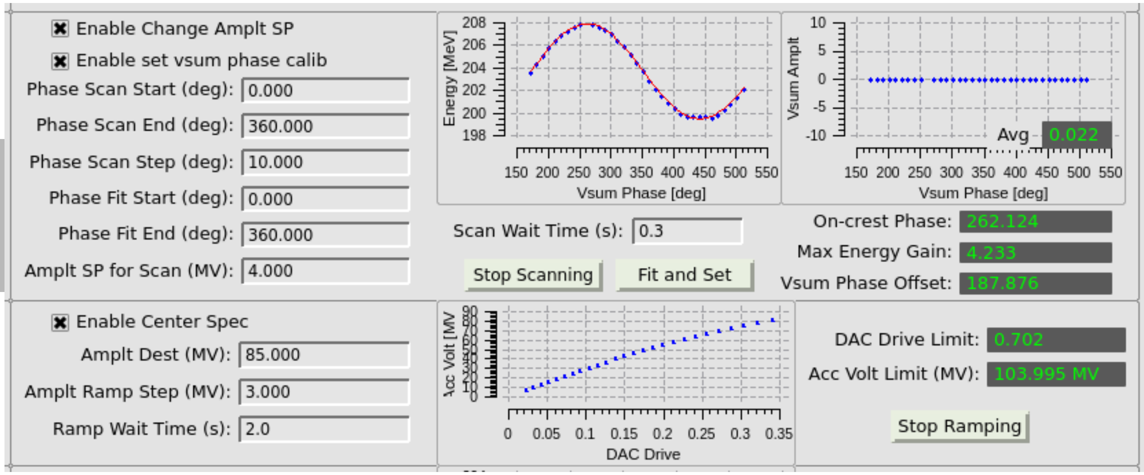


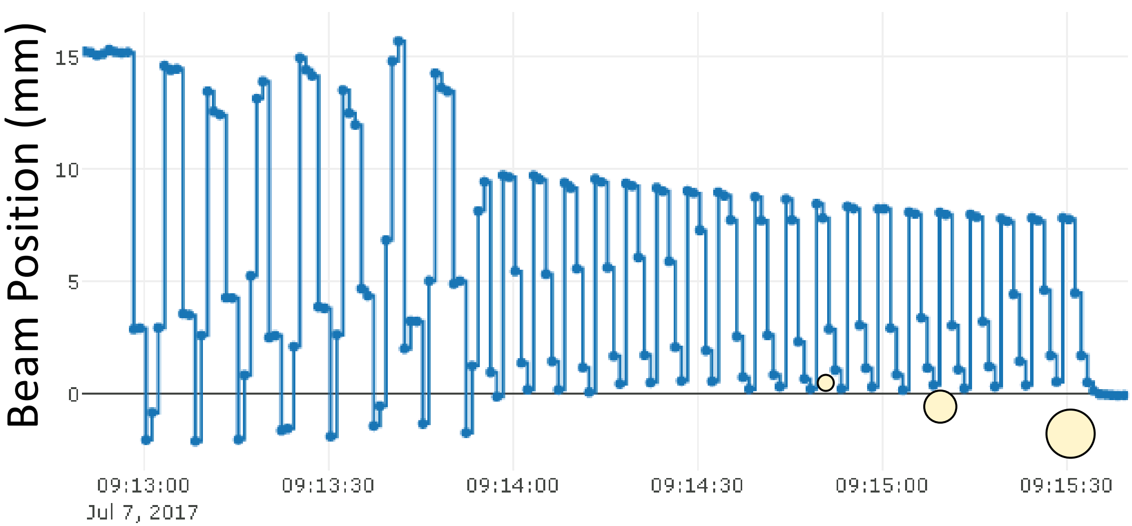
Algorithms to Set RF Station Timing Delay



- 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

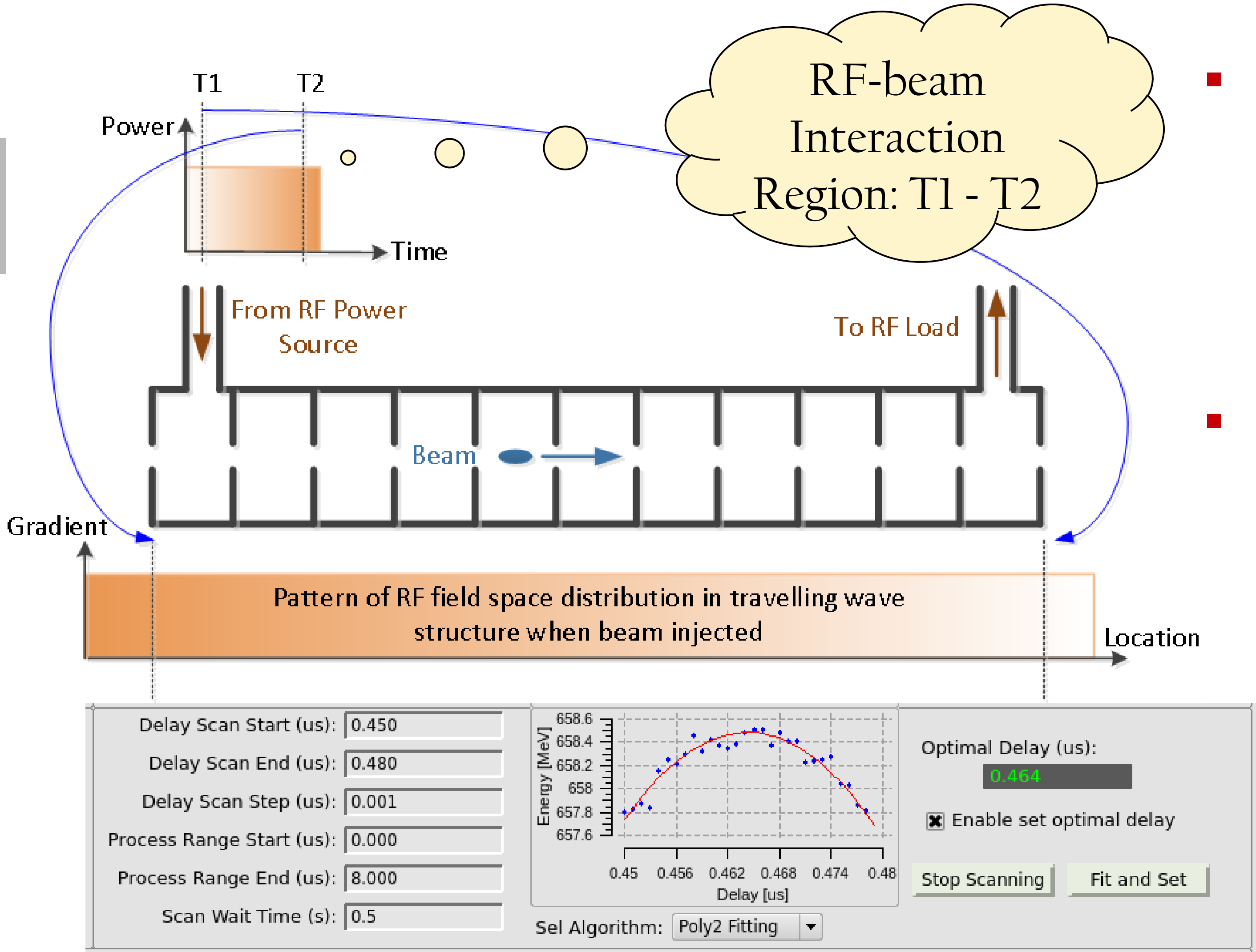




- **Phasing**: scan RF phase in full cycle with low accelerating voltage and fit the energy-phase relation with a sine function (results: on-crest phase).
- **RF Ramping**: ramp the accelerating voltage in steps, after each step, automatically adjust the spectrometer to center the beam.

Beam position after spectrometer when ramping RF power.

RF-beam Interaction Optimization

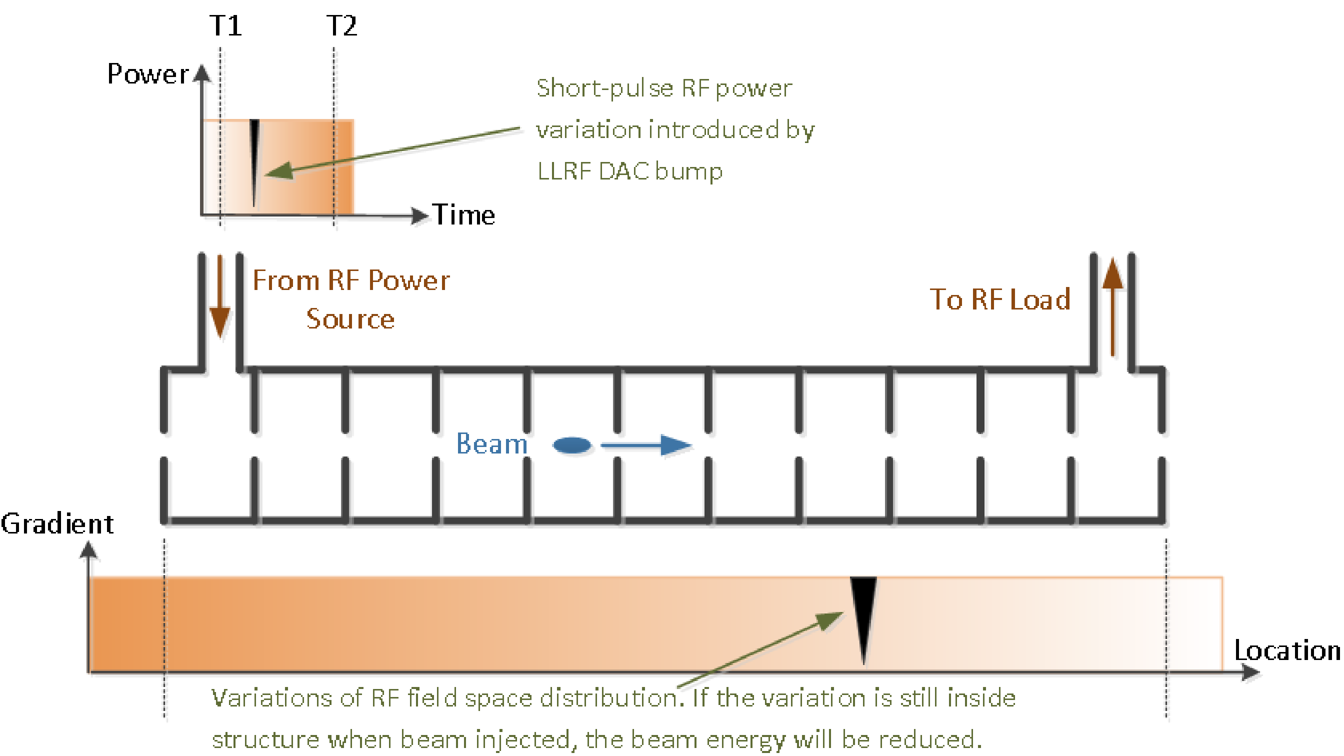


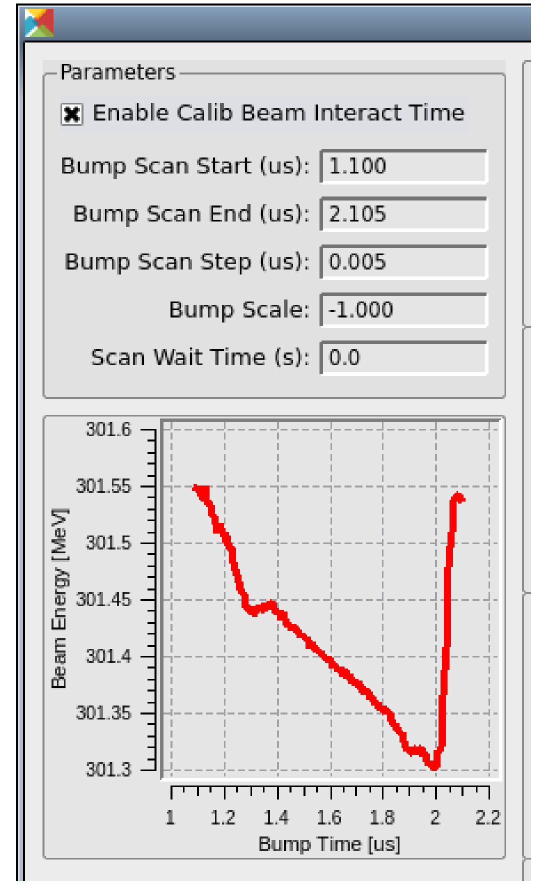
- Optimize RF pulse delay so that the structure is fully filled when beam injected.
- Identify the time region in the RF pulse that fills the structure and interacts with beam.

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

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

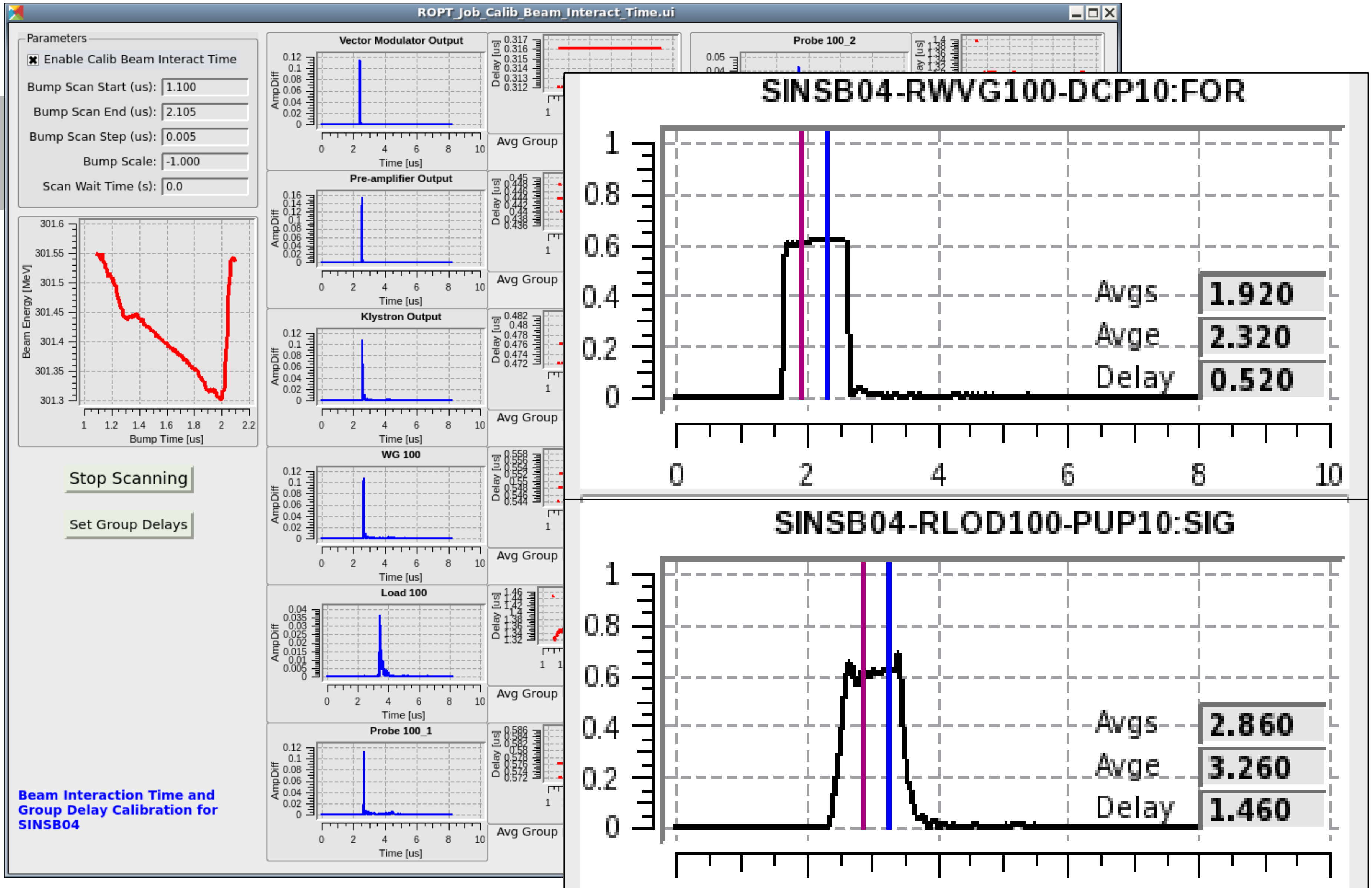
Algorithms to Identify RF-beam Interaction Region





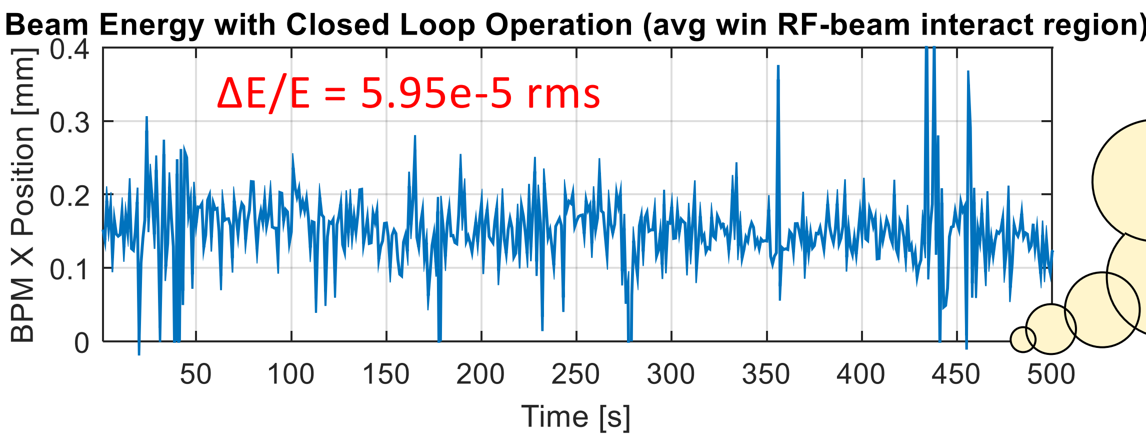
- Generate a negative bump in the RF pulse by varying a single DAC point (DACs of SwissFEL LLRF system work at ~250 MSPS).
- Scan the time of DAC bump and correlate with the beam energy. The time range of the bump that reduces the beam energy is the RF-beam interaction region in the RF pulse.

Settings of RF Average Windows and Group Delays

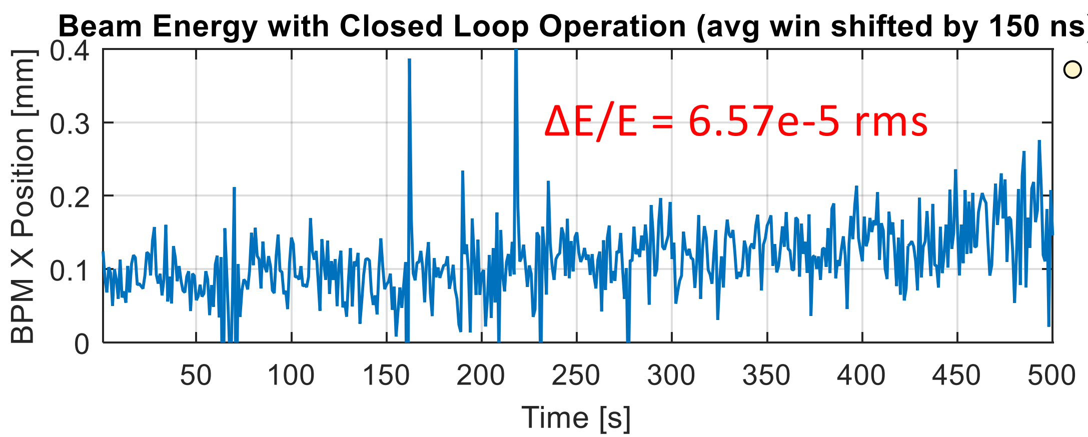


Verification of RF-beam Interaction Region

- 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.



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

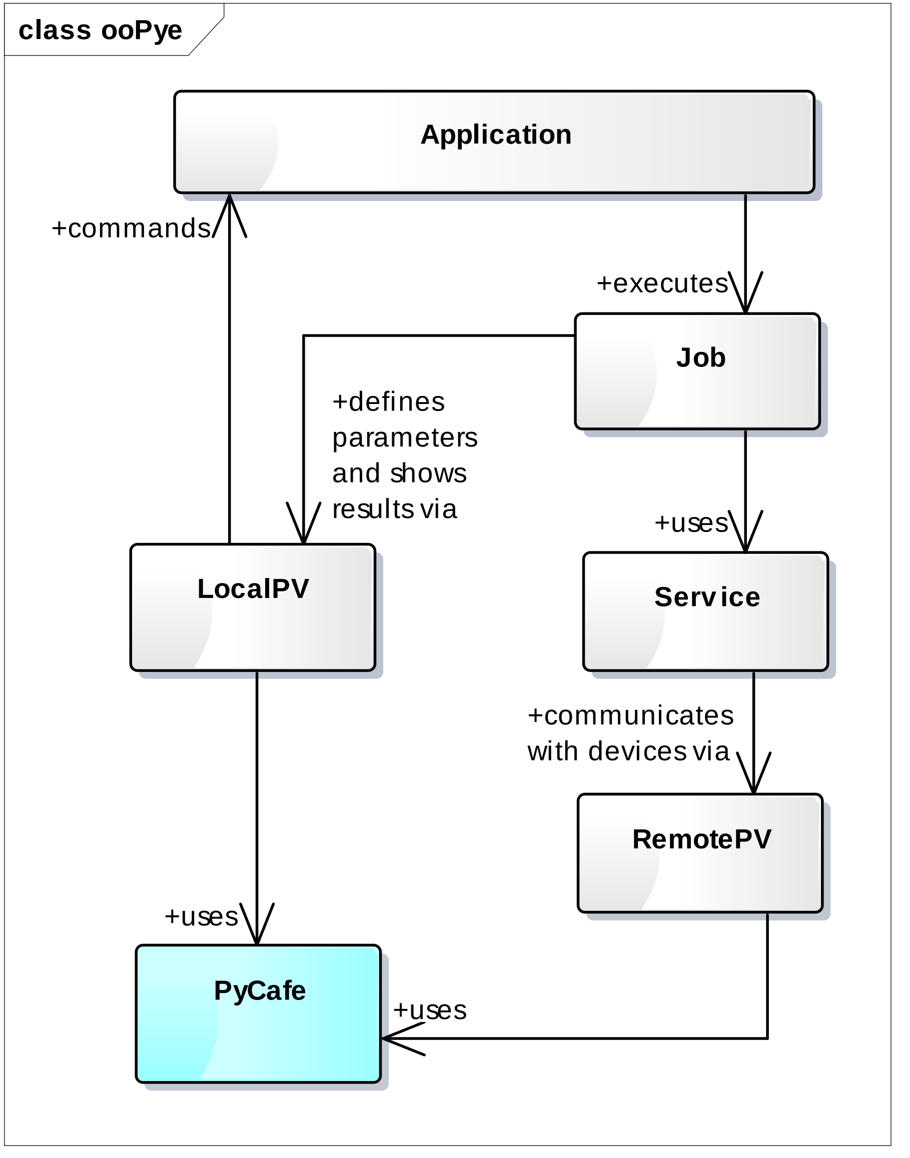


Dispersion
η=-0.85 m,
$\Delta x = \eta \Delta E / E$

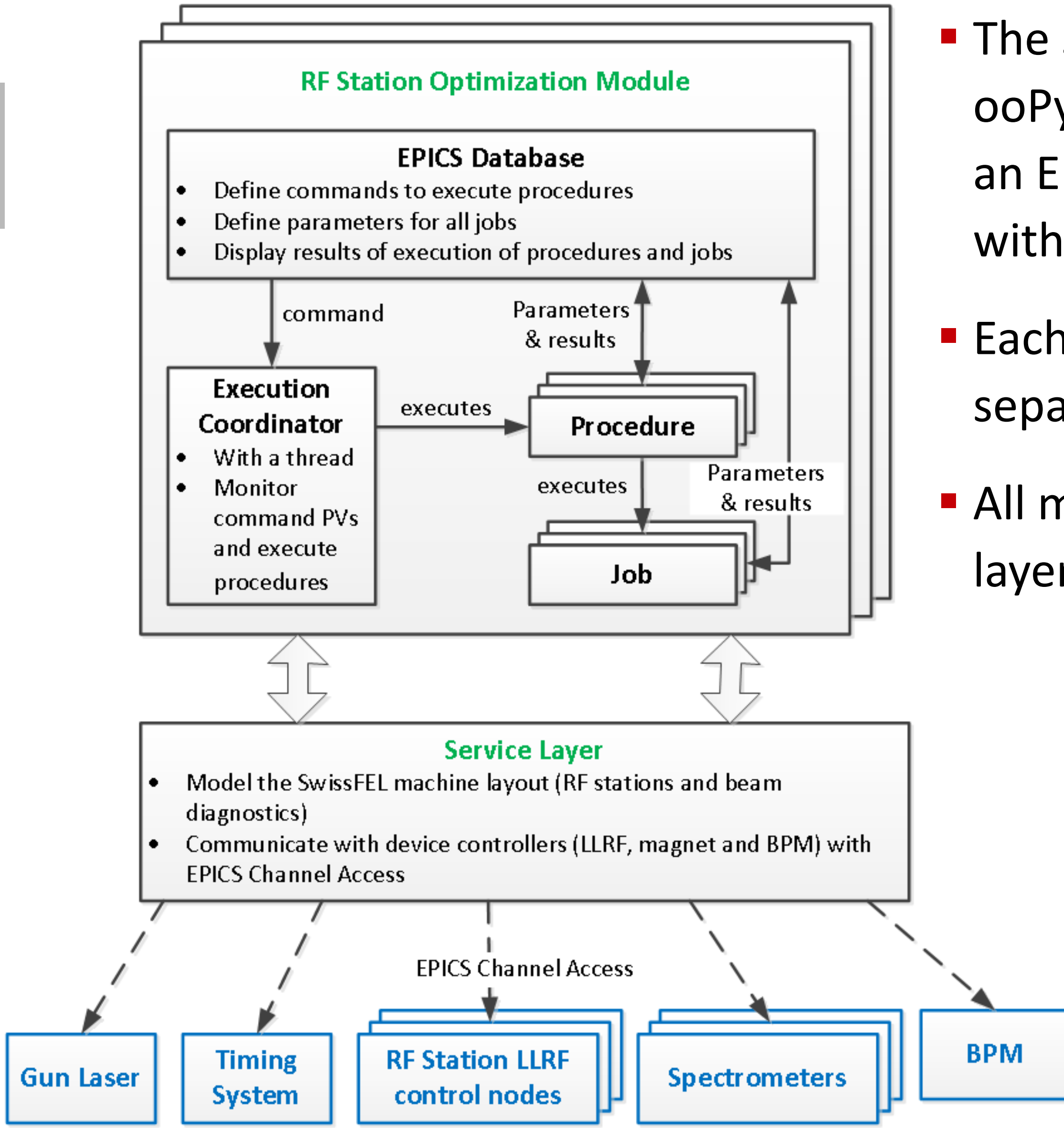
Software Architecture

Python Framework "ooPye"

- 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



Software Architecture



- The software is derived from the ooPye 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

PAUL SCHERRER INSTITUT

Summary and Outlook

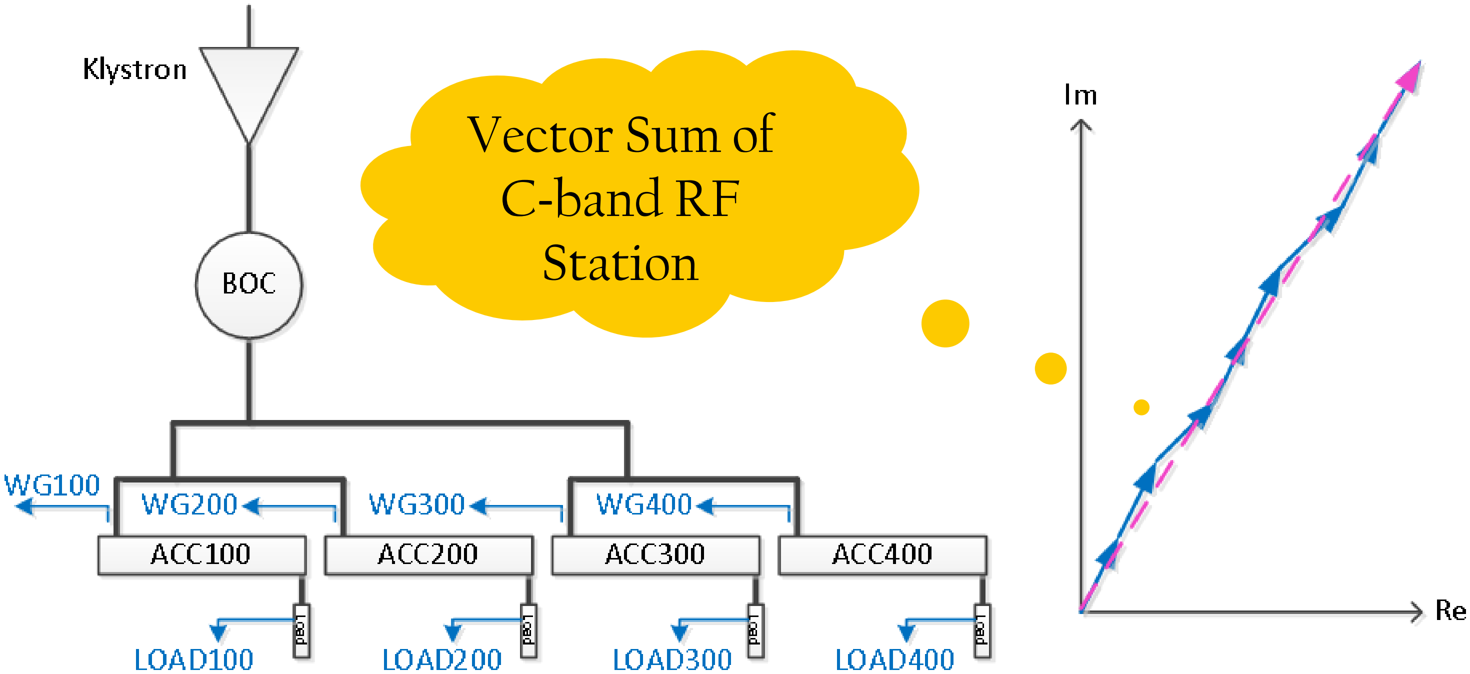
- The automated or semi-automated LLRF optimization procedures have been used in the commissioning of SwissFEL.
  - It significantly reduces the time to setup a fresh RF station for beam operation.
  - It provides very helpful guidelines and tools to optimize the LLRF system after shutdown or maintenance.
- 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!

PAUL SCHERRER INSTITUT

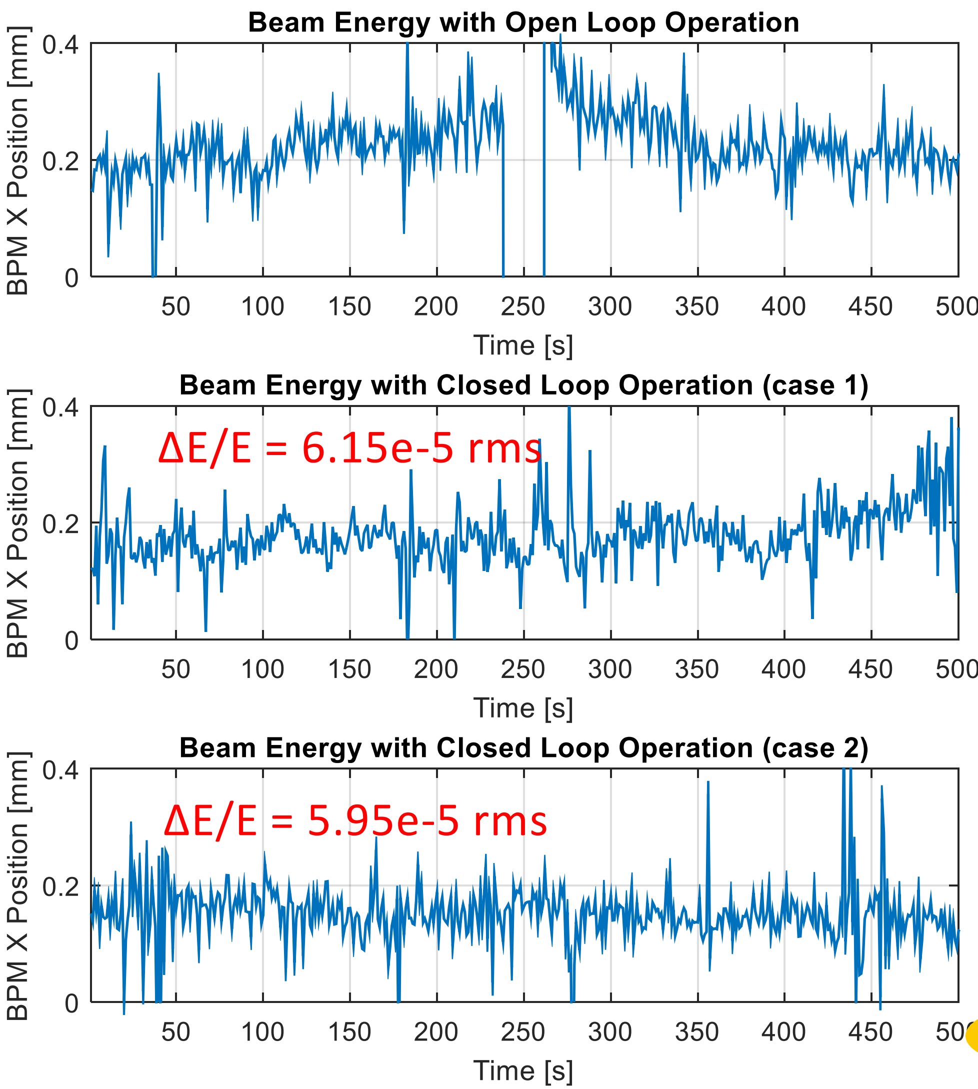
Backup

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 seem 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.

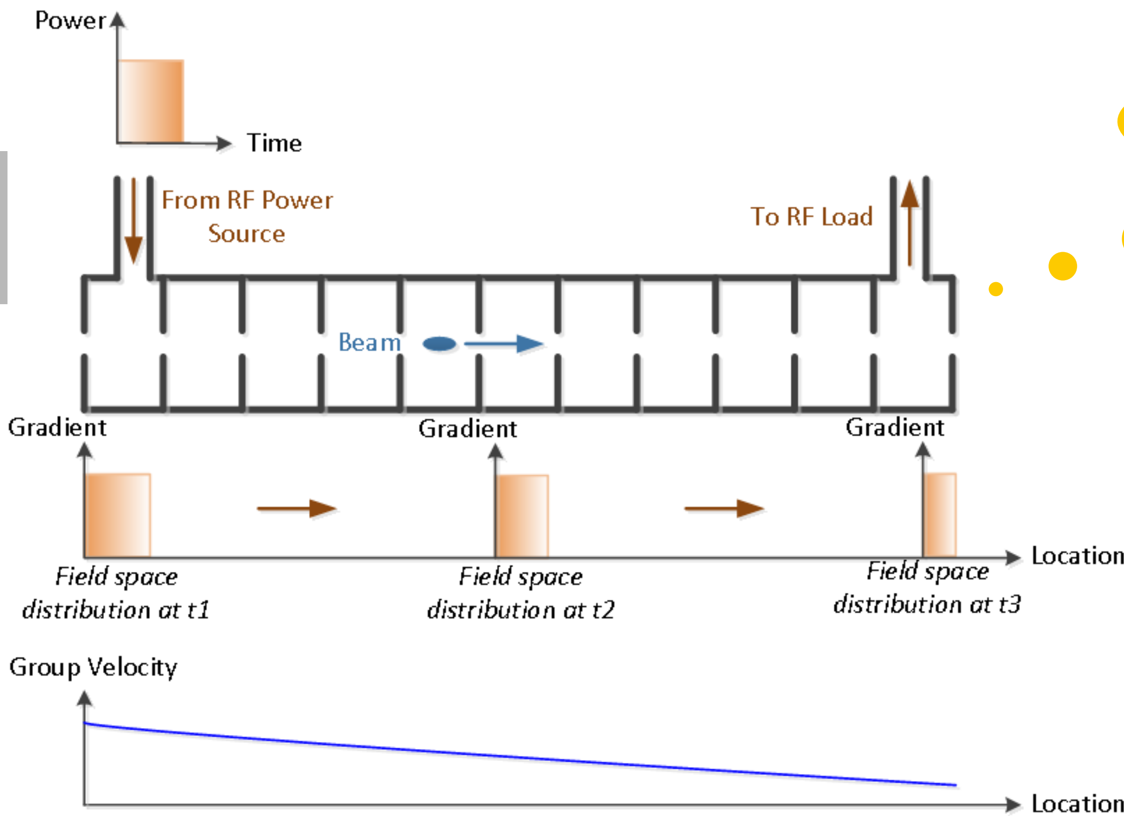
Three tests:

- *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 η=-0.85 m,

$$\Delta x = \eta \Delta E / E$$

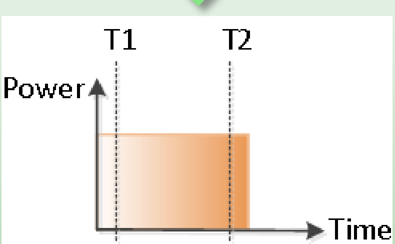
Apply RF on Beam: RF-beam Interaction – cont.



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