LONGITUDINAL FEEDBACK FOR THE LCLS-II SUPERCONDUCTING LINEAR ACCELERATOR AT SLAC*

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Abstract

SLAC recently commissioned a new continuous-wave, MHz repetition-rate Superconducting (SC) Linear Accelerator (Linac). This accelerator can produce a 4 GeV electron beam that drives two dedicated Hard and Soft X-ray Undulator lines as part of the Linac Coherent Light Source (LCLS) Free Electron Laser. A new Python-based longitudinal feedback is used to control the electron beam energy and bunch length along the accelerator. This feedback was written to be simple, easily maintainable and easily portable for use on other accelerators or systems as a general-purpose feedback with minimal dependencies. Design and operational results of the feedback will be discussed, along with the Graphical User Interfaces built using Python Display Manager (PyDM).

SUPERCONDUCTING LINAC LAYOUT

The Superconducting Linear Accelerator is divided into four main accelerating regions defined in terms of the included cryomodules (CMs): L0B (CM01), L1B (CM02-3), L2B (CM04-15) and L3B (CM16-35). Each cryomodule contains eight individual 9-cell radiofrequency (RF) cavities.

Figure 1 illustrates these regions by showing an expanded view of the SC Linac which occupies the first third of the original 3 km SLAC Linac tunnel. At the end of each of these regions is a bend which can used to measure the beam energy. After L1B and L2B, there are dedicated bunch compressor chicanes (BC1B and BC2B respectively) which also have bunch length monitors. This makes for a total of six parameters we want to precisely control – electron beam energy at four locations and electron bunch length at two locations.

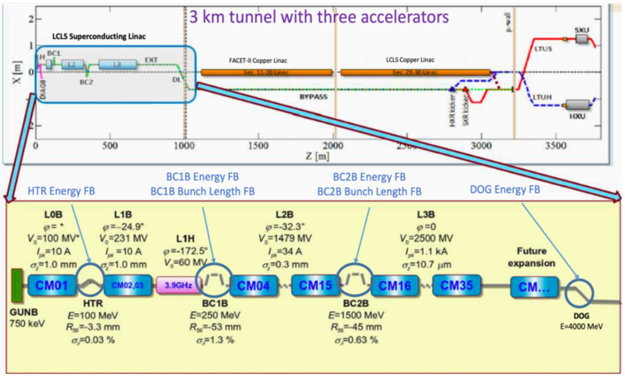

Figure 1: Layout of SC linac.

RF ABSTRACTION LAYER

The SC Linac currently has 296 superconducting RF cavities (thirty-five 1.3 GHz accelerating CMs and two 3.9 GHz harmonic linearizer CMs). Each of these cavities is powered by an individual solid-state amplifier with its own amplitude and phase controls. Trying to control the overall electron beam energy and longitudinal profile by adjusting each of these individual cavities would be next to impossible.

For this reason, the RF Abstraction Layer (RFAL) was developed as a tool to orchestrate the management of all cavities in order to achieve the desired energy and energy spread (chirp) in each region. It provides a way of abstracting away the mathematical details of achieving these parameters using large collections of RF cavities, making it easy and efficient for an end-user (or feedback) to control these parameters. The RFAL is a dedicated EPICS soft IOC that seamlessly integrates Python control code (using pyDevSup [1]) to perform real-time calculation, vector plotting and distribution of settings to individual RF cavities at up to ~20 Hz.

RFAL Working Principles

Continuous-wave SC RF cavities experience Lorentz Force Detuning that changes with RF field amplitude. If the amplitude is kept constant, the corresponding Lorentz Force Detuning effect is static [2] and can more easily be compensated for. This motivates a strong desire to keep the cavity amplitudes fixed. The RFAL therefore only changes cavity phases to control the electron beam energy and chirp.

A prerequisite for calculating and distributing phases is that the RFAL needs to know which cavities should be used for pure acceleration, imparting energy spread, or main-taining average energy. Four cavity roles are specified in Table 1.

Table 1: RF Abstraction Layer Cavity Roles

Cavity Role	Purpose	RFAL Sets Phase
NOTA	Acceleration only	No
Chirp Only	Add energy spread and increase energy	Yes
FB -	Maintain total energy, preserve chirp	Yes
FB +	Maintain total energy, preserve chirp	Yes

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These cavity roles work together to provide a final energy and chirp. How they work together is illustrated using vectors in chirp/energy space as shown in Fig. 2:

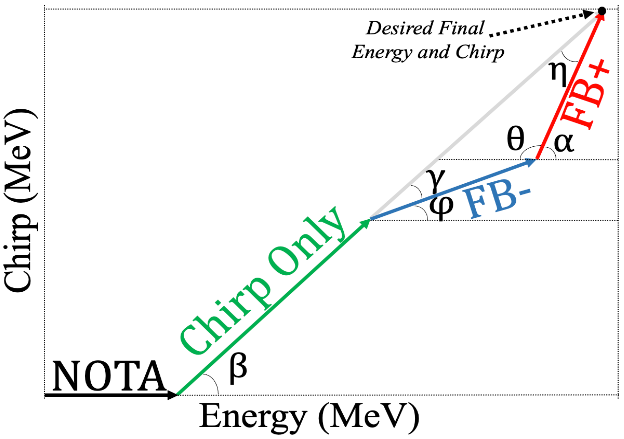


Figure 2: Visualization of different cavity roles. The end of the gray vector is the user requested energy and chirp.

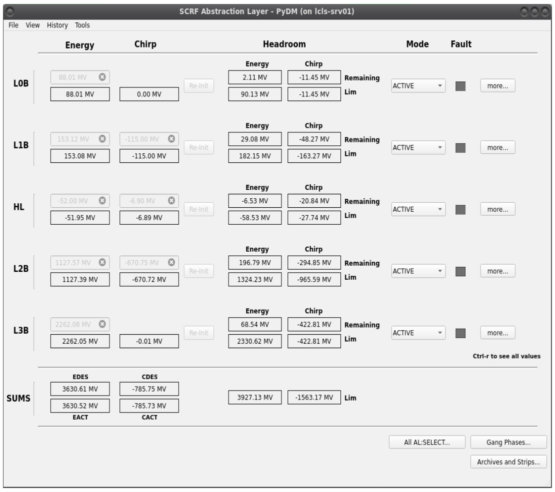
The current role of any cavity can be changed at any time as each cavity has an associated *cavity role* EPICS Process Variable (PV) hosted by the RFAL IOC.

RFAL Control Interfaces

The RFAL provides *desired energy and chirp* PVs for each of the four accelerating regions. There are also similar PVs for control of the harmonic linearizer cavities. There is a *mode* PV for each region, which can be set to *active* to calculate/distribute new phases or set to *inactive* to only calculate (but not distribute) new phases.

When a desired energy or chirp PV is written, the RFAL will consider all current RF cavity amplitude/phase readbacks in the relevant region in order to calculate new phases and will then distribute phases if the relevant region is set to *active* mode.

A variety of readbacks are provided as PVs, including total and remaining *headroom* values for both energy and chirp. The main RFAL PyDM user interface conveniently displays these parameters for the user as shown in Fig. 3:

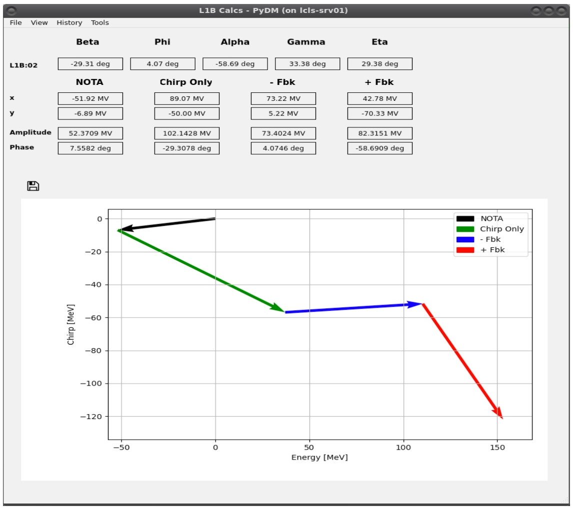


	Energy	Chirp	Headroom Energy	Headroom Chirp		Mode	Fault
L0B	88.01 MV 88.01 MV	 0.00 MV	2.11 MV 90.13 MV	-11.45 MV -11.45 MV	Remaining Lim	ACTIVE	■
L1B	153.12 MV 153.08 MV	-115.00 MV -115.00 MV	29.08 MV 182.15 MV	-48.27 MV -163.27 MV	Remaining Lim	ACTIVE	■
HL	-52.00 MV -51.95 MV	-6.90 MV -6.89 MV	-6.53 MV -58.53 MV	-20.84 MV -27.74 MV	Remaining Lim	ACTIVE	■
L2B	1127.57 MV 1127.39 MV	-670.75 MV -670.72 MV	196.79 MV 1324.23 MV	-294.85 MV -965.59 MV	Remaining Lim	ACTIVE	■
L3B	2262.08 MV 2262.05 MV	 -0.01 MV	68.54 MV 2330.62 MV	-422.81 MV -422.81 MV	Remaining Lim	ACTIVE	■
SUMS	EDES 3630.61 MV 3630.52 MV EACT	CDES -785.75 MV -785.73 MV CACT	3927.13 MV	-1563.17 MV	Lim		

Ctrl-r to see all values

Figure 3: Main RFAL user interface, built using PyDM.

There are real-time displays showing the chirp and energy contributions from different cavity role vectors. The L1B region during actual operation of the SC Linac is shown in Fig. 4:

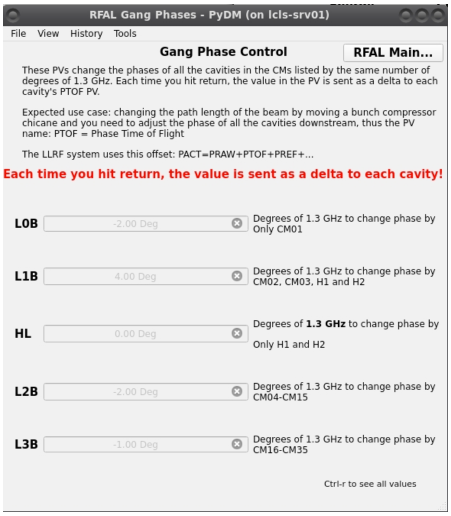


	Beta	Phi	Alpha	Gamma	Eta
L1B:02	-29.31 deg	4.07 deg	-58.69 deg	33.38 deg	29.38 deg

	NOTA	Chirp Only	- Fbk	+ Fbk
x	-51.92 MV	89.07 MV	73.22 MV	42.78 MV
y	-6.89 MV	-50.00 MV	5.22 MV	-70.33 MV
Amplitude	52.3709 MV	102.1428 MV	73.4024 MV	82.3151 MV
Phase	7.5582 deg	-29.3078 deg	4.0746 deg	-58.6909 deg

Figure 4: Live PyDM display of L1B vectors.

Lastly, the RFAL provides the ability to offset the global phase of each region. This was originally provided as a method to compensate for time-of-flight differences through the bunch compressor chicanes. In practice, it has become useful for recovering the SC Linac phases and electron beam after a downtime or maintenance period. The *gang phase* PyDM control panel allows the user to easily implement global phase changes and is shown in Fig. 5:



Gang Phase Control

These PVs change the phases of all the cavities in the CMs listed by the same number of degrees of 1.3 GHz. Each time you hit return, the value in the PV is sent as a delta to each cavity's PTOF PV.

Expected use case: changing the path length of the beam by moving a bunch compressor chicane and you need to adjust the phase of all the cavities downstream, thus the PV name: PTOF = Phase Time of Flight

The LLRF system uses this offset: PACT=PRAW+PTOF+PREF+...

Each time you hit return, the value is sent as a delta to each cavity!

L0B	-2.00 Deg	Degrees of 1.3 GHz to change phase by Only CM01
L1B	4.00 Deg	Degrees of 1.3 GHz to change phase by CM02, CM03, H1 and H2
HL	0.00 Deg	Degrees of **1.3 GHz** to change phase by Only H1 and H2
L2B	-2.00 Deg	Degrees of 1.3 GHz to change phase by CM04-CM15
L3B	-1.00 Deg	Degrees of 1.3 GHz to change phase by CM16-CM35

Ctrl-r to see all values

Figure 5: Gang phase (global phase) PyDM display.

The RFAL is necessary for a user to manually set up the electron beam longitudinal profile and ultimately achieve lasing of the electron beam in the undulator lines. With particle accelerators, there always seems to be an inevitable desire for feedback systems to control natural drift that may originate from any number of places. Even with an expectation that the SC RF cavities are relatively stable in phase and amplitude over time, the design of LCLS-II naturally included plans for longitudinal feedback system. With the

RFAL in place, a convenient set of actuators is readily available for feedback control.

LONGITUDINAL FEEDBACK

The longitudinal feedback was designed to be a relatively slow (< 10 Hz) feedback system, as fast feedback was not within the scope of the LCLS-II project (and arguably not necessary given the nature of the SC Linac). A Python-based feedback was implemented, and accompanying PyDM user interfaces were built.

This feedback is simple, with minimal and widely-available dependencies. It uses a PID feedback algorithm [3]. The feedback code is ~700 lines altogether (including the PID algorithm), making it easily maintainable and upgradeable.

A separate simple configuration file provides all the actuator, measurement and control device names needed for the feedback to fully function. It also provides PV names for machine faults, beam stoppers, profile monitor screens, RFAL faults and other mechanisms that should trigger the feedback to stop actuating. The feedback also has built-in measurement checking to make sure it only actuates on new measurements.

The feedback runs as a single process on a central production server and is fully functional independent of any user interface. All the control parameters are EPICS PVs, so they are inherently global and readable/writeable through a variety of methods.

The feedback was intentionally designed to be general and transferable to other machines or situations where simple feedback may be useful. It has already been repurposed as charge feedback for LCLS-II and serves as charge feedback for the FACET-II copper linear accelerator at SLAC. It was tested in late 2021 as a longitudinal feedback for the original LCLS Copper Linac by only changing the measurement and actuator devices in the configuration file, demonstrating the ease of porting the feedback to other machines.

Longitudinal Feedback Measurements

Energy Measurements The feedback calculates energy in four dispersive regions. It uses the Bmad [4] design model for LCLS-II to obtain Twiss parameters, most importantly the dispersion at the location of beam position monitors (BPMs) located in dispersive (bending) regions. The corresponding position measurement from those beam position monitors is used to find the difference in energy from the target energy:

$$\Delta \mathrm{E} = \mathrm{E}\frac{\sum D_i X_i}{\sum D_i^2},$$

where, D_i represents the dispersion of an individual bpm, X_i represents the position of the beam centroid as reported by an individual BPM, and E represents the target energy (defined by the bend magnet setting).

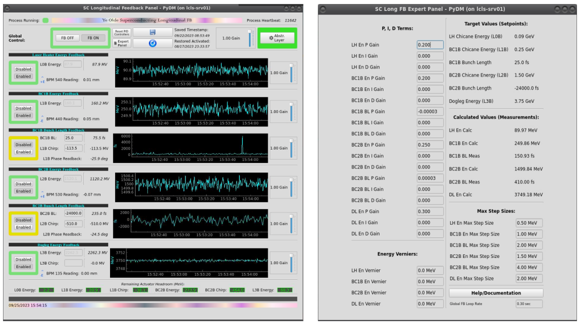
The feedback uses dispersion and beam position in the horizontal plane for all energy loops except the DOG energy feedback (which maintains the final SC Linac energy). In this dispersive region, the bends are rolled, and it was decided to use the vertical dispersion and vertical position to calculate the energy. The DOG energy feedback also uses five BPMs to help separate out the effect of incoming betatron oscillations, whereas the other energy feedbacks use a single BPM for the energy measurement.

Bunch Length Measurements Single shot, non-invasive bunch length monitors are present in both bunch compressor chicanes BC1B and BC2B. These monitors provide a relative measurement of the peak current by detecting coherent edge radiation emitted from the last (fourth) bending dipole of each chicane [5]. Given that the measurement is relative, it needs to be calibrated against an absolute measurement (for instance, using a transverse deflecting RF cavity) for meaningful real-time absolute bunch length measurements. The feedback does not need absolute measurements though, it simply needs to be able to maintain the measurements near a user-specified target number.

The bunch length monitors are still in the process of being fully commissioned, so the bunch length feedback loops have not been running consistently. The BC2B bunch length feedback has been tested briefly as a beam signal was recently found on the BC2B bunch length monitor, and the feedback seemed to work as designed. The new feedback loops (including bunch length) were tested on the original LCLS Copper Linac, so it is expected that the bunch length feedbacks will work well once there are reliable signals from the bunch length monitors.

Longitudinal Feedback Control Interfaces

Main and Expert PyDM user interfaces are provided as shown in Fig. 6:


SC Longitudinal Feedback Panel - PyDM (on lcls-srv01)
Process Running: ● Ye Olde Superconducting Longitudinal FB Process Heartbeat: 11642
Global Control:
Saved Timestamp: 09/22/2023 08:53:49
Restored Activated: 08/17/2023 23:33:57
1.00 Gain

Laser Heater Energy Feedback
L0B Energy: 87.9 MV
BPM 540 Reading: 0.01 mm
1.00 Gain

BC1B Energy Feedback
L1B Energy: 160.2 MV
BPM 440 Reading: 0.05 mm
1.00 Gain

BC1B Bunch Length Feedback
BC1B BL: 25.0 75.5 fs
L1B Chirp: -113.5 -113.5 MV
L1B Phase Readback: -25.9 deg
1.00 Gain

BC2B Energy Feedback
L2B Energy: 1120.2 MV
BPM 530 Reading: -0.07 mm
1.00 Gain

BC2B Bunch Length Feedback
BC2B BL: -24000.0 235.0 fs
L2B Chirp: -510.0 -510.0 MV
L2B Phase Readback: -24.5 deg
1.00 Gain

Dogleg Energy Feedback
L3B Energy: 2262.3 MV
L3B Chirp: -0.0 MV
BPM 135 Reading: 0.00 mm
1.00 Gain

Remaining Actuator Headroom (MeV):
L0B Energy: 2.2
L1B Energy: 20.9
L1B Chirp: -38.1
BC2B Energy: 273.9
BC2B Chirp: -464.0
L3B Energy: 68.3
09/25/2023 15:54:15

SC Long FB Expert Panel - PyDM (on lcls-srv01)

P, I, D Terms:
LH En P Gain 0.200
LH En I Gain 0.000
LH En D Gain 0.000
BC1B En P Gain 0.200
BC1B En I Gain 0.000
BC1B En D Gain 0.000
BC1B BL P Gain -0.00003
BC1B BL I Gain 0.000
BC1B BL D Gain 0.000
BC2B En P Gain 0.250
BC2B En I Gain 0.000
BC2B En D Gain 0.000
BC2B BL P Gain 0.00003
BC2B BL I Gain 0.000
BC2B BL D Gain 0.000
DL En P Gain 0.300
DL En I Gain 0.000
DL En D Gain 0.000

Energy Verniers:
LH En Vernier 0.0 MeV
BC1B En Vernier 0.0 MeV
BC2B En Vernier 0.0 MeV
DL En Vernier 0.0 MeV

Target Values (Setpoints):
LH Chicane Energy (L0B) 0.09 GeV
BC1B Chicane Energy (L1B) 0.25 GeV
BC1B Bunch Length 25.0 fs
BC2B Chicane Energy (L2B) 1.50 GeV
BC2B Bunch Length -24000.0 fs
Dogleg Energy (L3B) 3.75 GeV

Calculated Values (Measurements):
LH En Calc 89.97 MeV
BC1B En Calc 249.86 MeV
BC1B BL Meas 150.93 fs
BC2B En Calc 1499.84 MeV
BC2B BL Meas 410.00 fs
DL En Calc 3749.18 MeV

Max Step Sizes:
LH En Max Step Size 0.50 MeV
BC1B En Max Step Size 1.00 MeV
BC1B BL Max Step Size 2.00 MeV
BC2B En Max Step Size 1.50 MeV
BC2B BL Max Step Size 4.00 MeV
DL En Max Step Size 2.00 MeV
Global FB Loop Rate 0.30 sec

Figure 6: PyDM Main (Left) and Expert (Right) user interfaces for the SC Linac Longitudinal Feedback.

From the main panel, the user can interact with the feedback in a straightforward manner. There are enables for each feedback loop and a global enable for all feedbacks. There are individual gains for each feedback along with an overall feedback gain that applies to all feedback loops. Users see a time plot of either measured energy or measured bunch length for each loop. Actuators can be adjusted manually only if the relevant loop is disabled, and a user may save and restore actuator settings at will.

The Expert panel includes several options that are configurable on the fly. A user may change the loop iteration time, individual PID gains, overall system gains, maximum step sizes per iteration and lastly may apply energy offsets (verniers) to make changes to the beam energy targets for the feedback. These changes will all take immediate effect if the feedback is running.

Longitudinal Feedback Performance

The feedback has been running on the SC Linac since late 2022. It has proven to be reliable and robust. So far, we have only run the energy feedback loops with a proportional gain (zero integral or derivate gain), which works well. The original LCLS Copper Linac longitudinal feedback has also only used proportional gain for many years. The feedback has been running with an actuation rate of ~3 Hz although this may be increased in the future.

Initial characterization of stability has taken place, both over short time periods with fast sampling and over longer time periods with slower sampling. This characterization has so far shown that there is no perceptible negative impact on the stability or jitter of the beam with feedback on, demonstrated with pulse-by-pulse 1000 Hz beam repetition-rate data shown in Fig. 7. The feedback also effectively controls longer-term energy variation, as demonstrated by archived 1Hz data shown in Fig. 8 and pulse by pulse 10Hz beam repetition-rate data shown in Fig. 9.

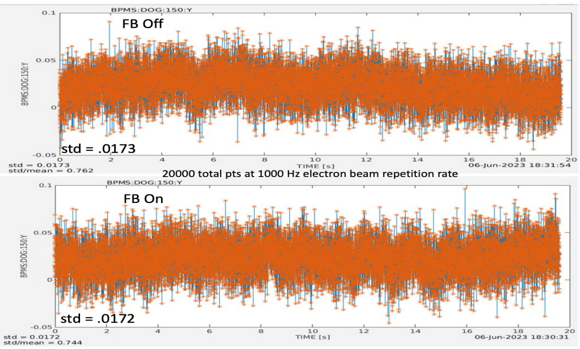


Figure 7: Pulse-by-pulse (1000 Hz beam rate) data of electron beam position (mm) vs. time in a dispersive region at the end of the SC Linac. Data taken with all energy feedbacks off (top plot) and on (bottom plot).

More characterization will be performed in the coming months to ensure stability and proper tuning of the feedback loops, but initial results are excellent.

CONCLUSION

SLAC National Accelerator Laboratory achieved first lasing with the SC Linac in both the Hard and Soft Undulator lines in August and September of 2023, an impressive achievement years in the making. This would have been difficult without the RF Abstraction Layer and Longitudinal Feedback managing the large number of individually controlled RF cavities. These systems have been deployed and tested in operation for many months and have proven to be effective and reliable while not introducing any observable instabilities.

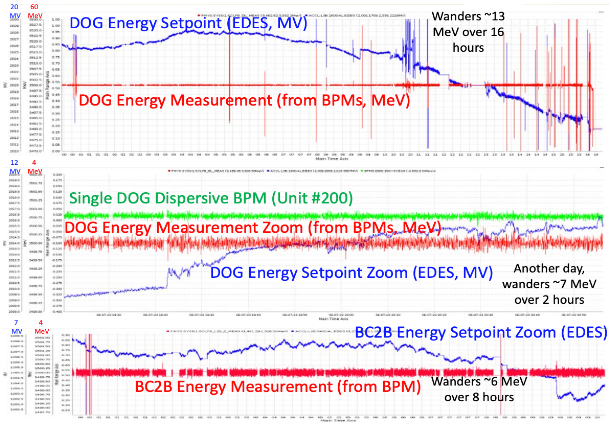


Figure 8: Long-term energy drift being compensated by feedback. These images show energy measurements and RFAL Desired Energy (EDES) setpoints under feedback control. Top two plots are linac end energy (DOG) feedback, bottom plot is second bunch compressor chicane (BC2B) energy feedback. Full range y axis values are shown above each relevant y axis.

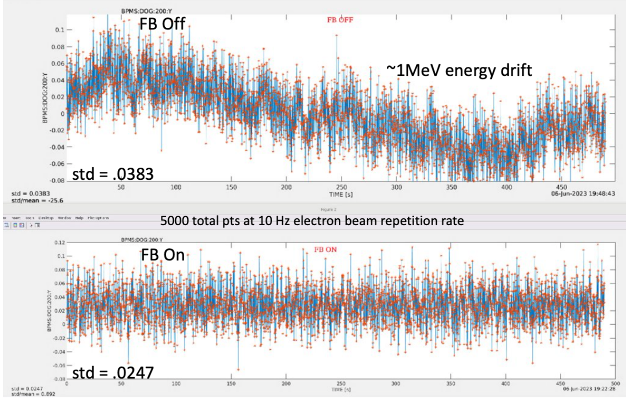


Figure 9: Pulse-by-pulse (10 Hz beam rate) data of electron beam position (mm) vs. time in a dispersive region at the end of the SC Linac with all energy feedbacks off (top plot) and on (bottom plot). Total time range is 500 seconds.

ACKNOWLEDGEMENTS

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[3] Simple-pid, `https://github.com/m-lundberg/simple-pid`

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[5] E. Aneke, T. Maxwell, A. Fisher, L. Sapozhnikov, and B. Jacobson, “Design of the bunch-length monitors for the new superconducing LCLS linac,” in *Proc. IBIC’21*, Pohang, Republic of Korea, Sep. 2021, pp. 422-424. `doi:10.18429/JACoW-IBIC2021-WEPP20`