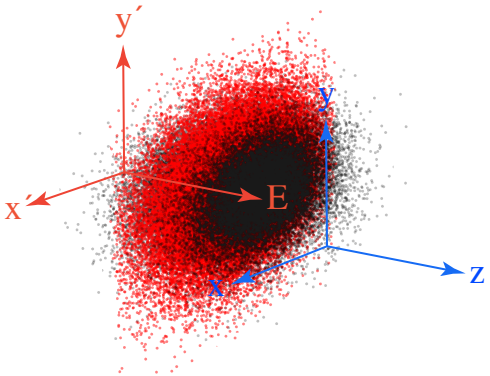
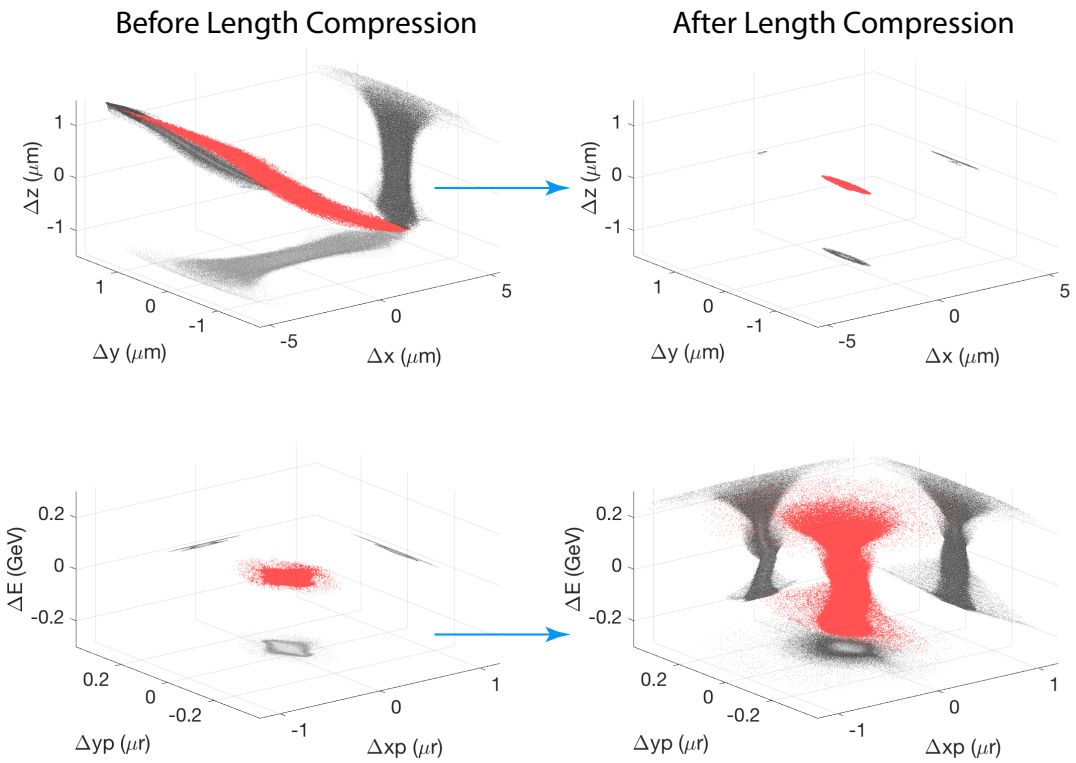
Feedback and ML for Phase Space Tuning and Non-Invasive Diagnostics

Alexander Scheinker

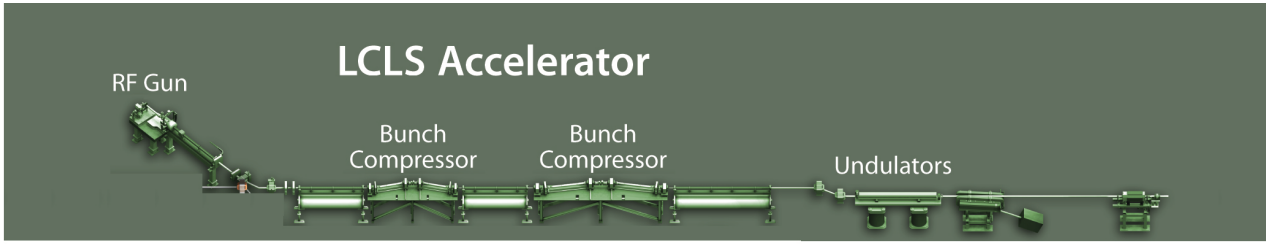
Goal

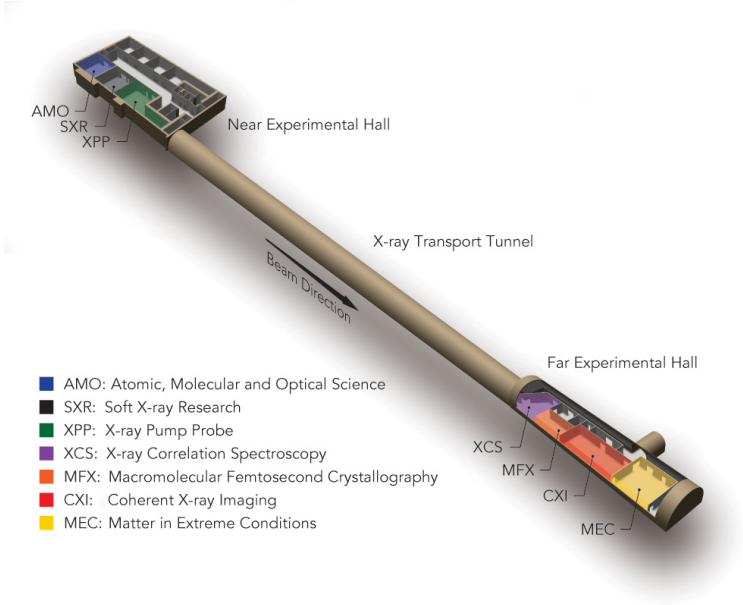
Enable full 6D (x,x',y,y',z,E) phase space control of particle accelerator beams by a combination of novel non-invasive diagnostics and new adaptive machine learning / feedback control algorithms.



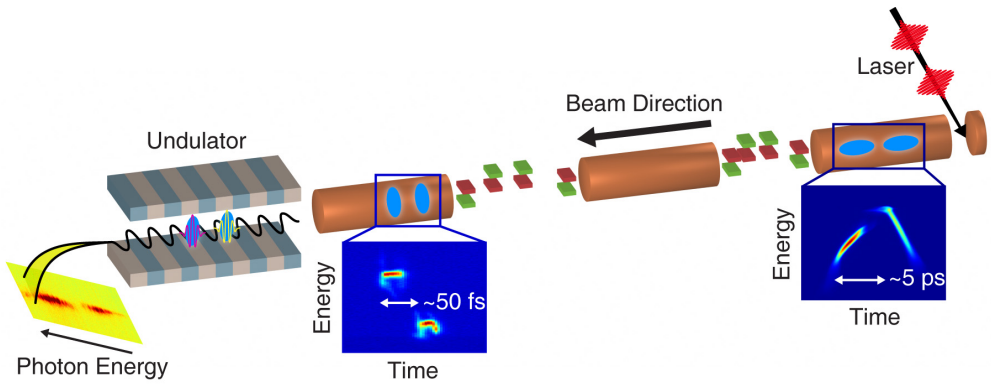


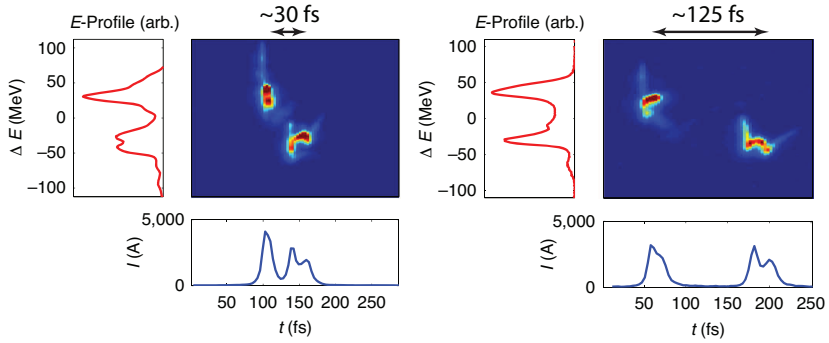
Motivation

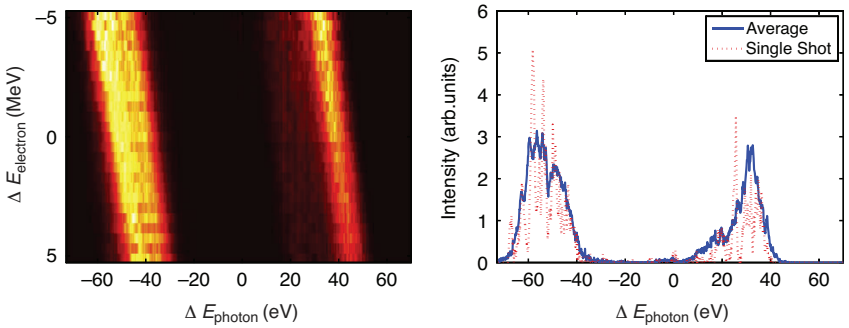

LCLS Accelerator
RF Gun
Bunch Compressor
Bunch Compressor
Undulators


AMO
SXR
XPP
Near Experimental Hall
X-ray Transport Tunnel
Beam Direction
Far Experimental Hall
XCS
MFX
CXI
MEC
AMO: Atomic, Molecular and Optical Science
SXR: Soft X-ray Research
XPP: X-ray Pump Probe
XCS: X-ray Correlation Spectroscopy
MFX: Macromolecular Femtosecond Crystallography
CXI: Coherent X-ray Imaging
MEC: Matter in Extreme Conditions

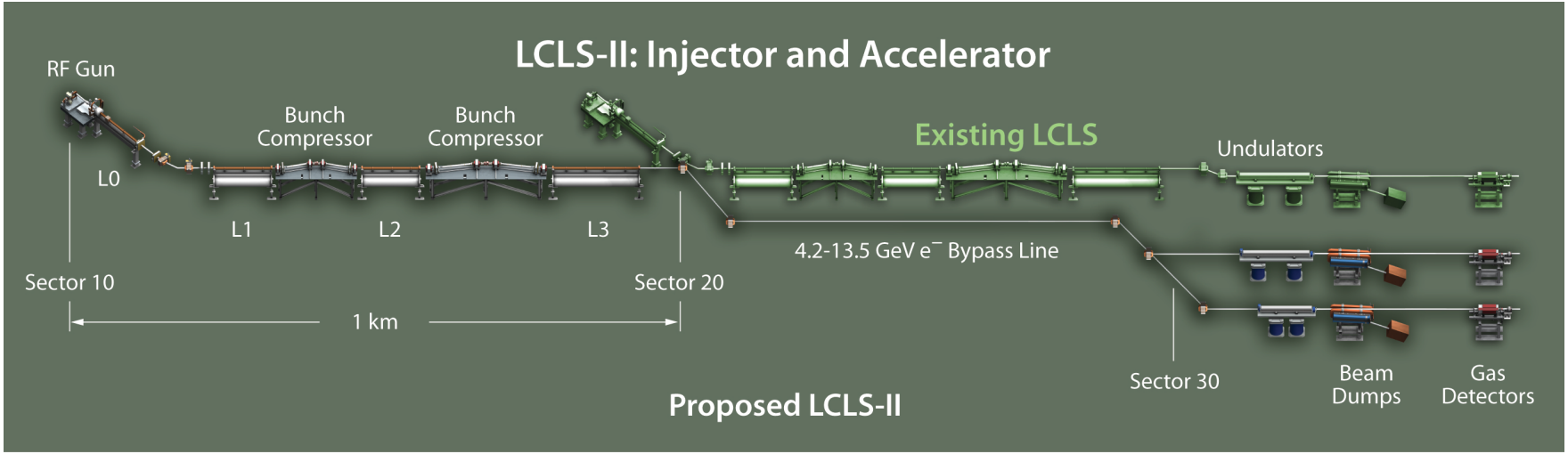
A. Marinelli et al., “High-intensity double-pulse X-ray free-electron laser.” Nature Communications, 2015. DOI: 10.1038/ncomms7369



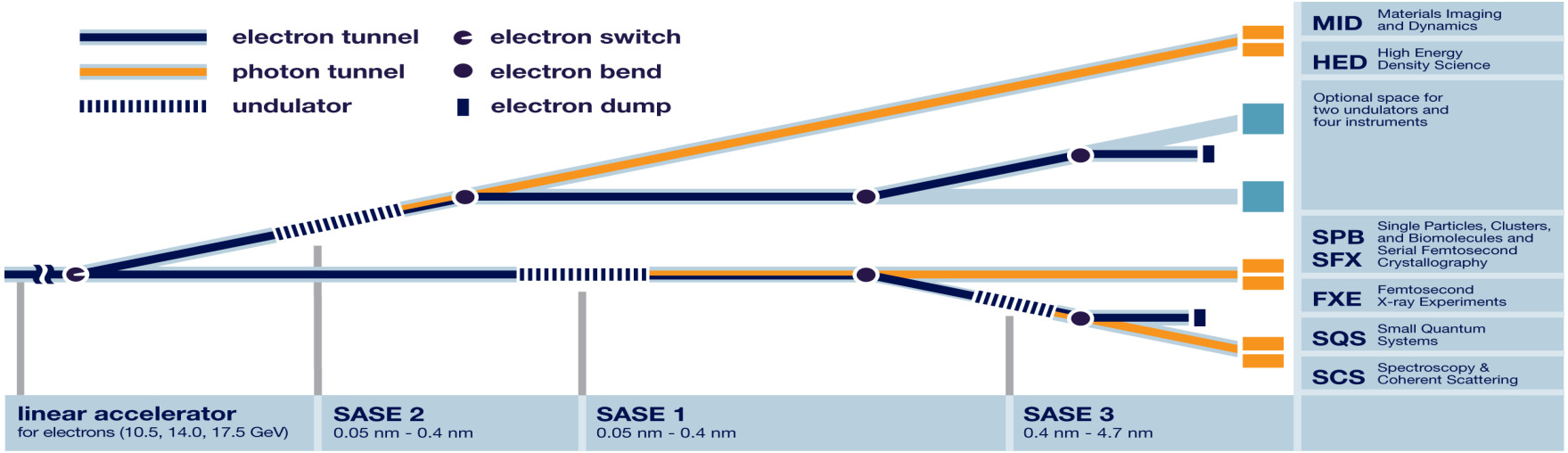




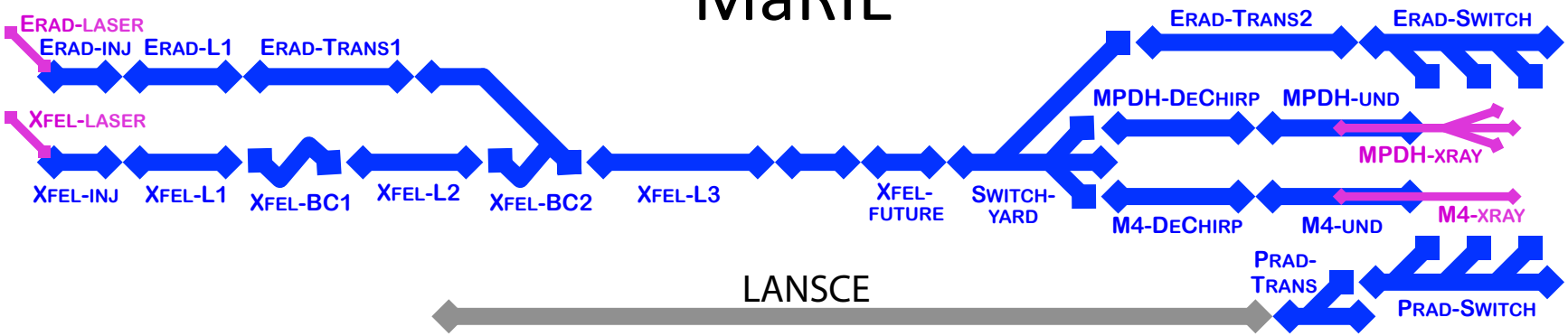
LCLS-II

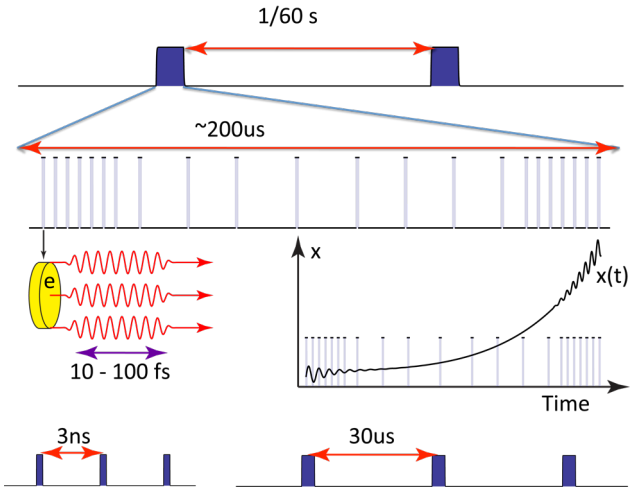

LCLS-II: Injector and Accelerator
RF Gun
L0
Bunch Compressor
Bunch Compressor
L1
L2
L3
Existing LCLS
Undulators
4.2-13.5 GeV e⁻ Bypass Line
Sector 10
Sector 20
1 km
Sector 30
Beam Dumps
Gas Detectors
Proposed LCLS-II

European XFEL



MaRIE





Photon energy: 4– 42 keV

Accelerator Tuning Challenges

- Dynamics of intense charged particle bunches dominated by:
  - **Components drift unpredictably with time, misalignments**
    - **Uncertain and time varying electron bunch distribution off cathode**
  - **Complex collective effects:**
    - **Wakefields**
    - **Space charge**
    - **Coherent synchrotron radiation**
  - **Limited non-invasive diagnostics**

Extremum Seeking

Model-independent feedback

- Noisy and time varying systems
- Many coupled parameters

A. Scheinker, “Model independent beam tuning,” in Proceedings of the 2013 International Particle Accelerator Conference, Shanghai, China, 2013, http://JACoW.org/ IPAC2013/papers/tupwa068.pdf.

A. Scheinker and D. Scheinker, "Bounded extremum seeking with discontinuous dithers." *Automatica* 69 (2016): 250-257.

$$\begin{bmatrix} \dot{x}_1 \\ \vdots \\ \dot{x}_n \end{bmatrix} = \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{p}, t) = \begin{bmatrix} f_1(x_1, \ldots, x_n, p_1, \ldots, p_m, t) \\ \vdots \\ f_n(x_1, \ldots, x_n, p_1, \ldots, p_m, t) \end{bmatrix}$$

$$y = V(\mathbf{x}, t) + n(t)$$

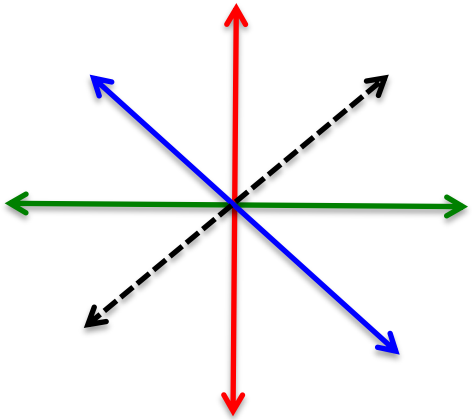
$$\frac{dp_1}{dt} = \sqrt{\alpha\omega_1}\cos(\omega_1 t + ky)$$

$$\frac{dp_2}{dt} = \sqrt{\alpha\omega_2}\cos(\omega_2 t + ky)$$

$$\frac{dp_3}{dt} = \sqrt{\alpha\omega_3}\cos(\omega_3 t + ky)$$

$$\vdots$$

$$\frac{dp_m}{dt} = \sqrt{\alpha\omega_m}\cos(\omega_m t + ky)$$



$$\frac{d\mathbf{p}}{dt} = -\frac{k\alpha}{2}\left(\nabla_{\mathbf{p}} V(\mathbf{x}, t)\right)^T$$

Allows simultaneous tuning of ALL parameters in parallel.

On average, the system performs minimizes the **unknown, time-varying** function V(x,t)

$$\omega_i = \omega r_i, \;\; r_i \neq r_j \implies \text{for any } t > 0$$

$$\lim_{\omega \to \infty} \langle \cos(\omega_i t), \cos(\omega_j t) \rangle = \lim_{\omega \to \infty} \int_0^t \cos(\omega_i \tau)\cos(\omega_j \tau) d\tau = 0$$

Bounded Extremum Seeking: Model-Independent Tuning and Optimization

$$\begin{bmatrix} \dot{x}_1 \\ \vdots \\ \dot{x}_n \end{bmatrix} = \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{p}, t) = \begin{bmatrix} f_1(x_1, \ldots, x_n, p_1, \ldots, p_m, t) \\ \vdots \\ f_n(x_1, \ldots, x_n, p_1, \ldots, p_m, t) \end{bmatrix}$$

$$y = V(\mathbf{x}, t) + n(t)$$

noise

$$y = (I(t) - I_0)^2 + n(t)$$

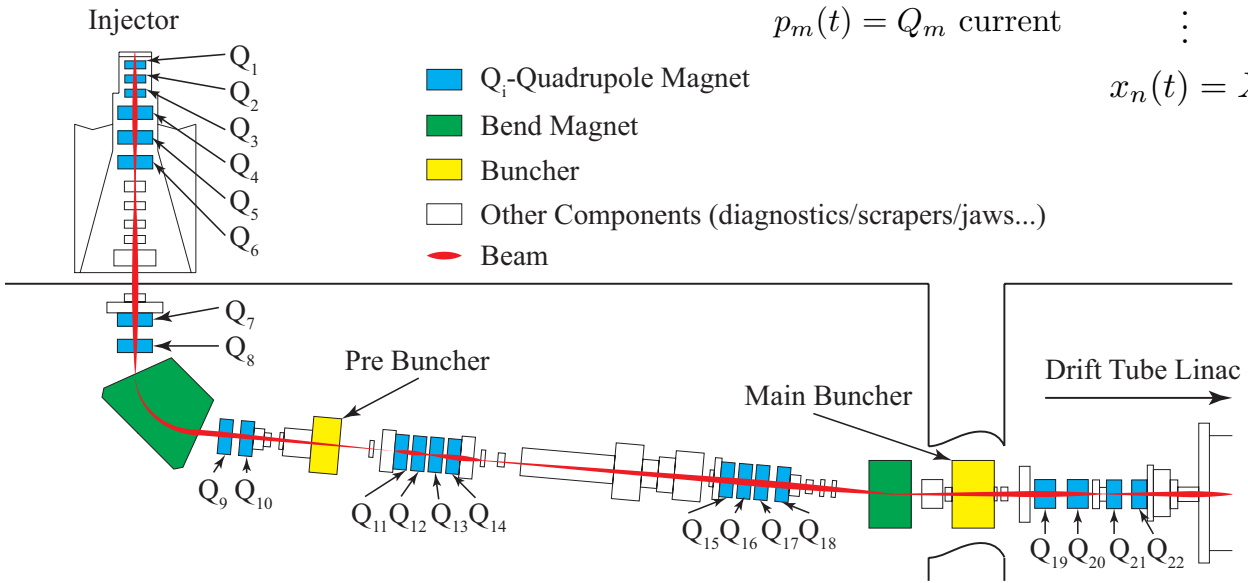
Surviving beam current at end.

$$p_1(t) = Q_1 \text{ current} \qquad x_1(t) = X_{\text{rms}}(\text{position } 1)$$

$$\vdots \qquad x_2(t) = Y_{\text{rms}}(\text{position } 1)$$

$$p_m(t) = Q_m \text{ current} \qquad \vdots$$

$$x_n(t) = X_{\text{rms}}(\text{position n})$$

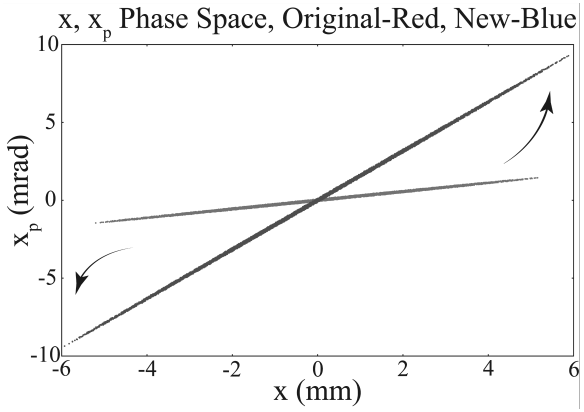


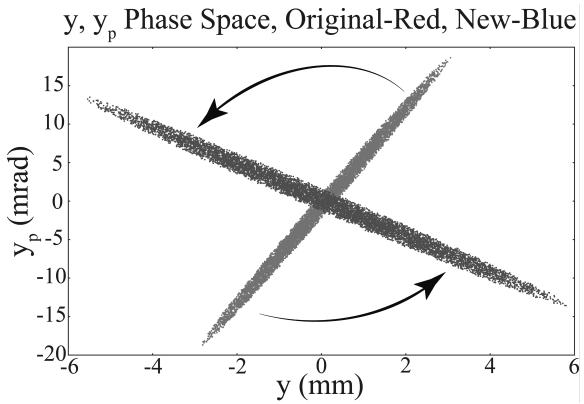
A. Scheinker, et al., "Model-independent particle accelerator tuning." *Physical Review Special Topics-Accelerators and Beams* 16.10 (2013): 102803.

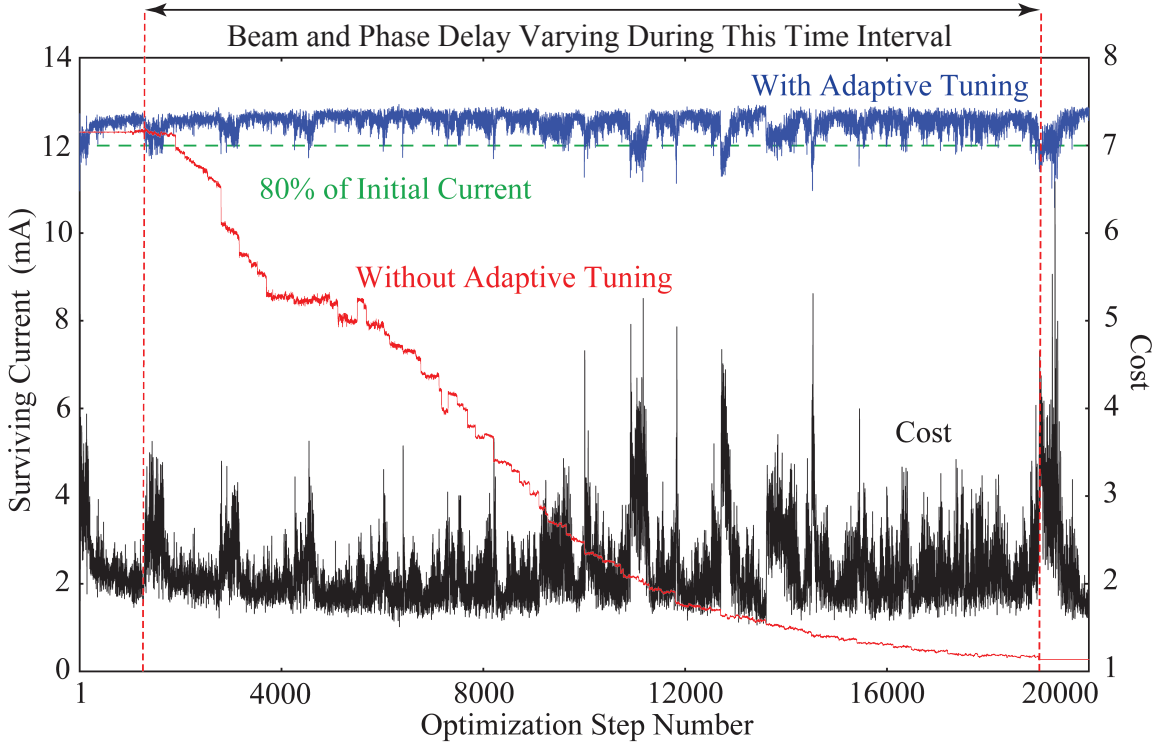
After the magnetic lattice was matched to transport the beam, beam phase space was continuously varied, and arbitrary phase drifts were introduced into the RF buncher cavities.

Without adaptive feedback all beam is quickly lost (red line in figure below).

With adaptive tuning the 22 quad magnetic lattice and 2 RF buncher cavities are continuously re-tuned to maintain maximal beam transmission and acceleration.

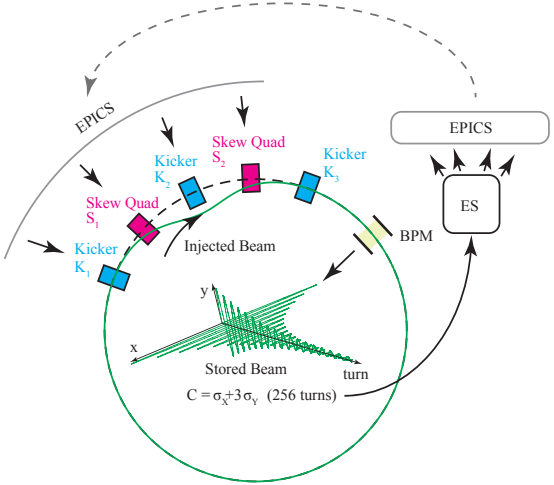


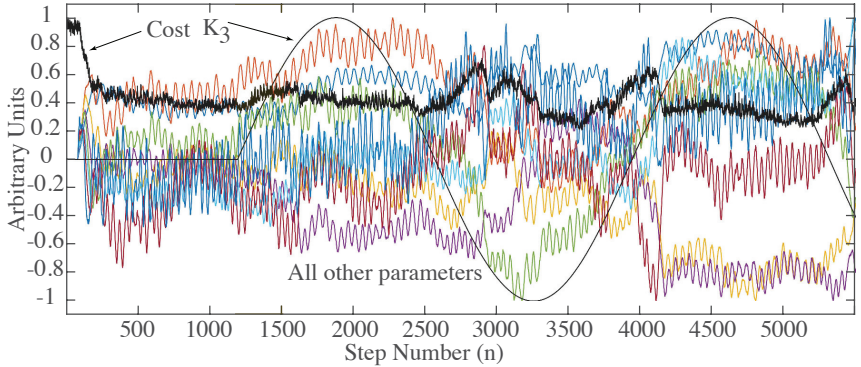


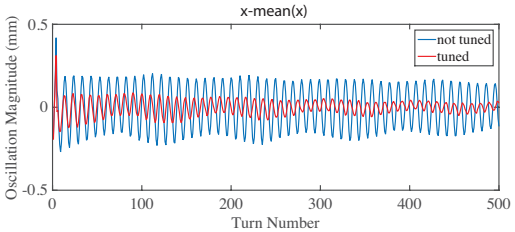


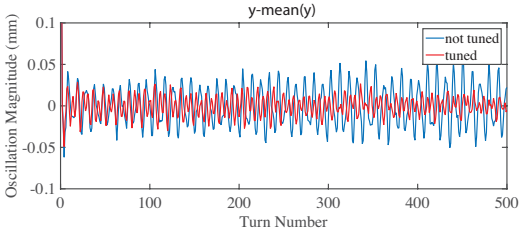
A. Scheinker, et al. "Minimization of betatron oscillations of electron beam injected into a time-varying lattice via extremum seeking." *IEEE Transactions on Control Systems Technology* 26.1, 2018.

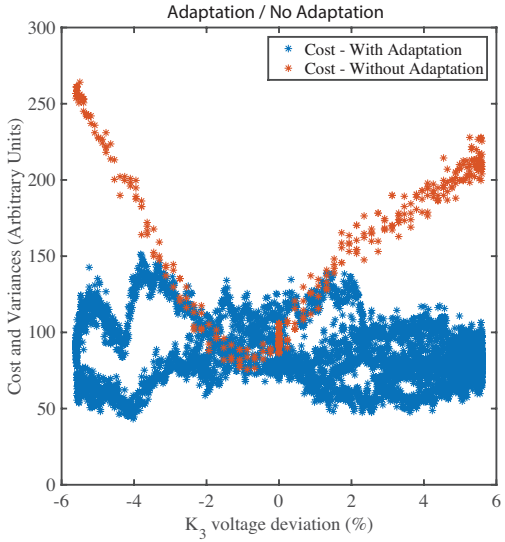
SPEAR3 time-varying magnetic lattice



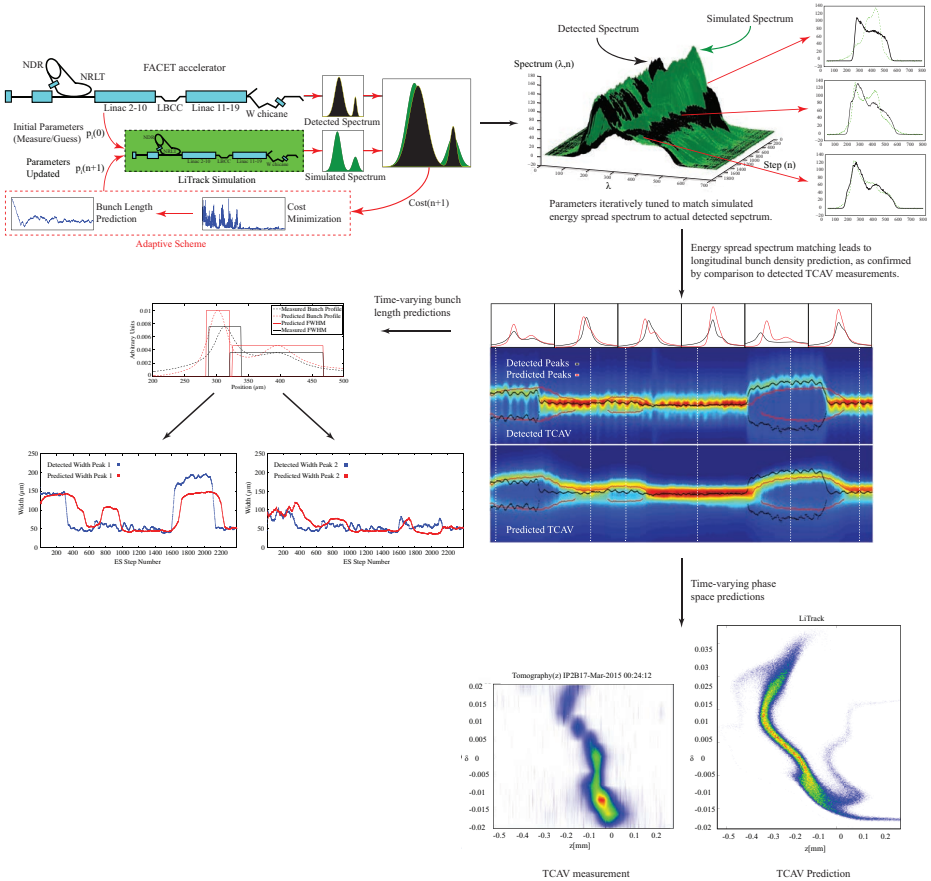


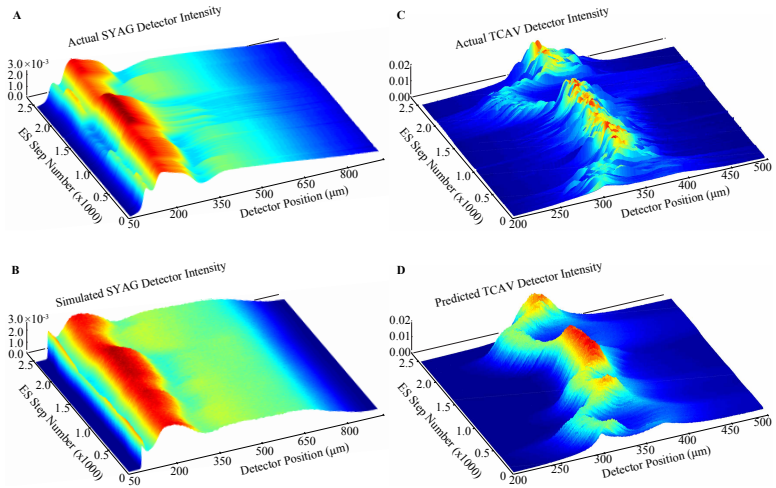




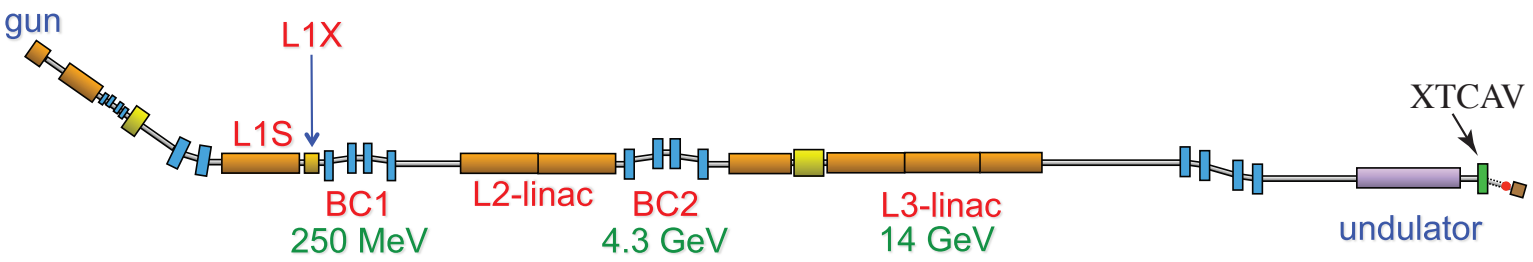


FACET: E-bunch profile prediction based on non-destructive measurements of energy spread spectrum. **A. Scheinker** and S. Gessner, "Adaptive method for electron bunch profile prediction," *Physical Review Accelerators and Beams*, 18, 102801, 2015.



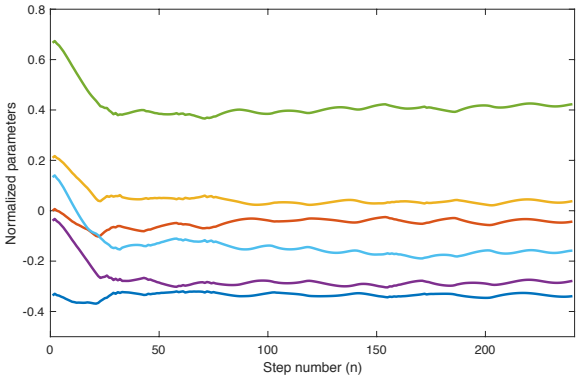


LCLS automatic longitudinal phase space tuning

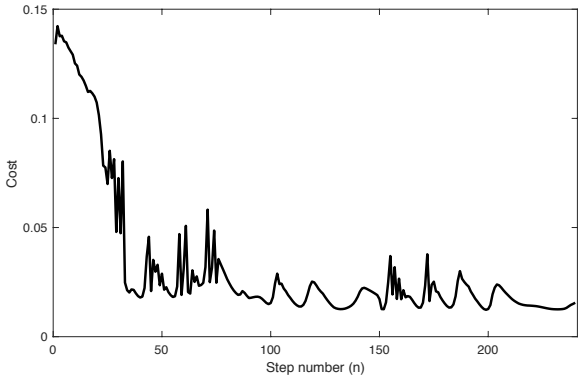


Normalized within [-1, 1]

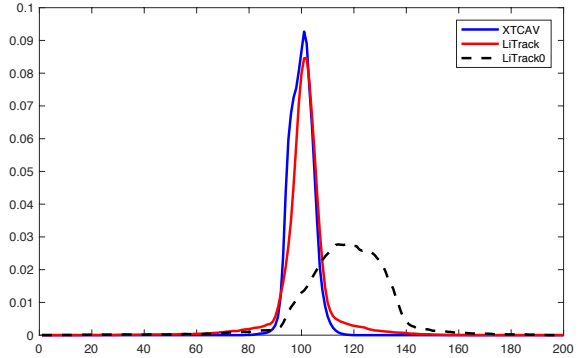
6 parameters being tuned



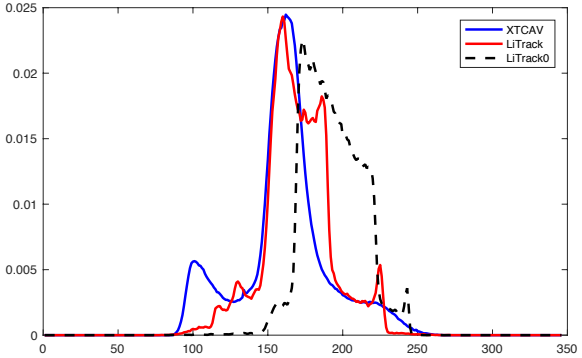
Cost function being minimized



Longitudinal charge density distribution



Energy Spread

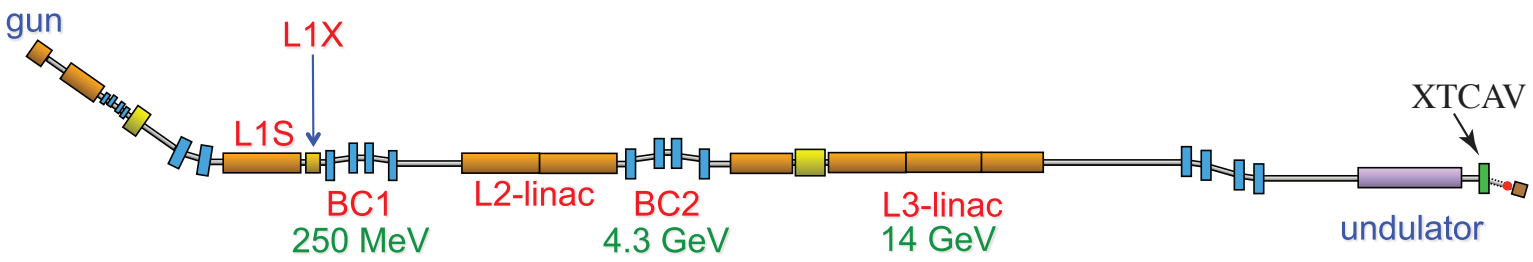


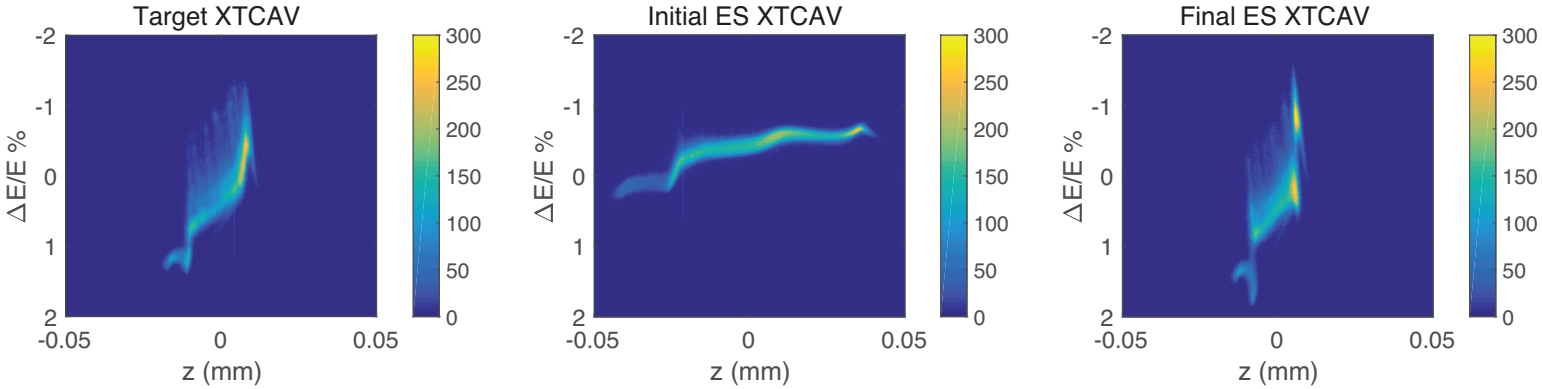
LiTrackES intial

LiTrackES final

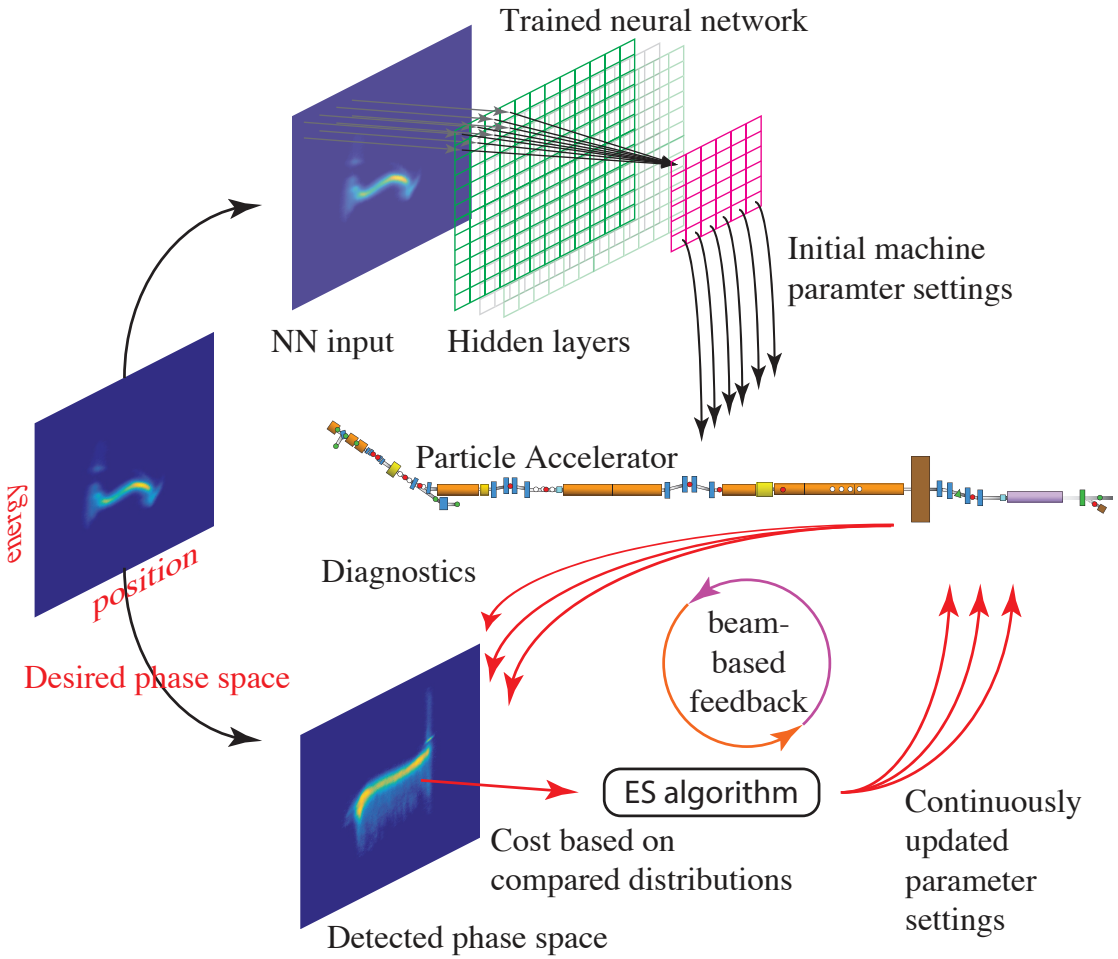
Goal

LCLS automatic longitudinal phase space tuning

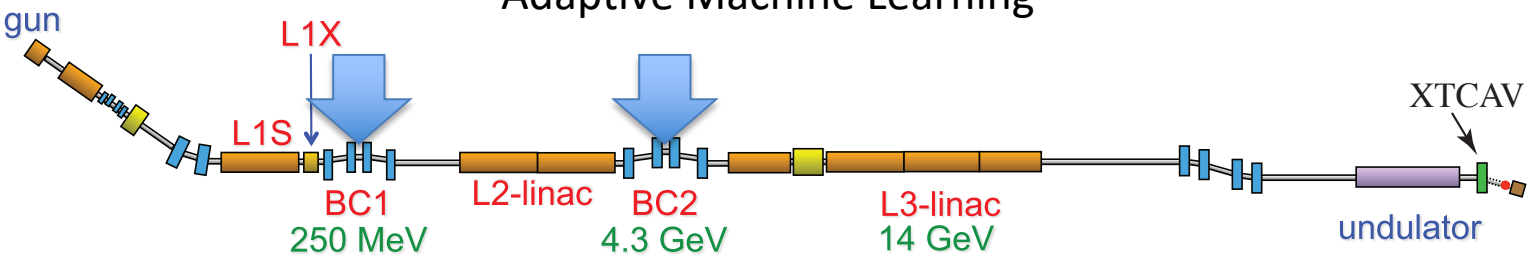




Adaptive Machine Learning

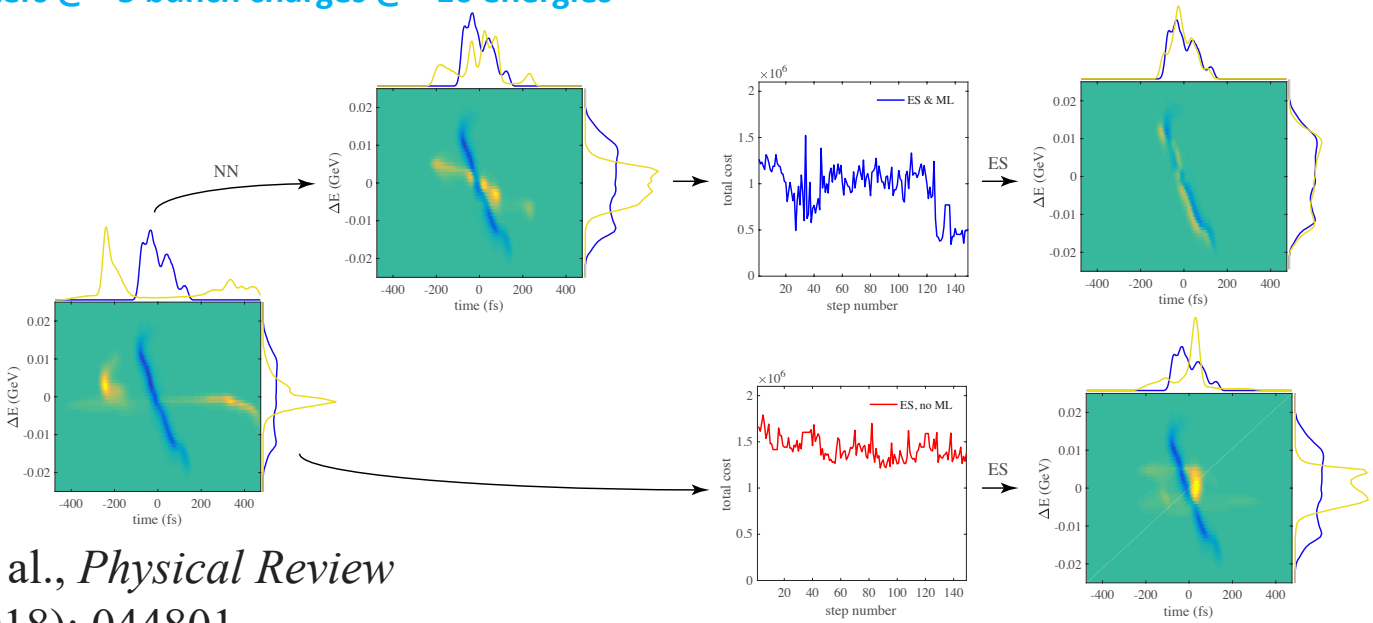


Adaptive Machine Learning

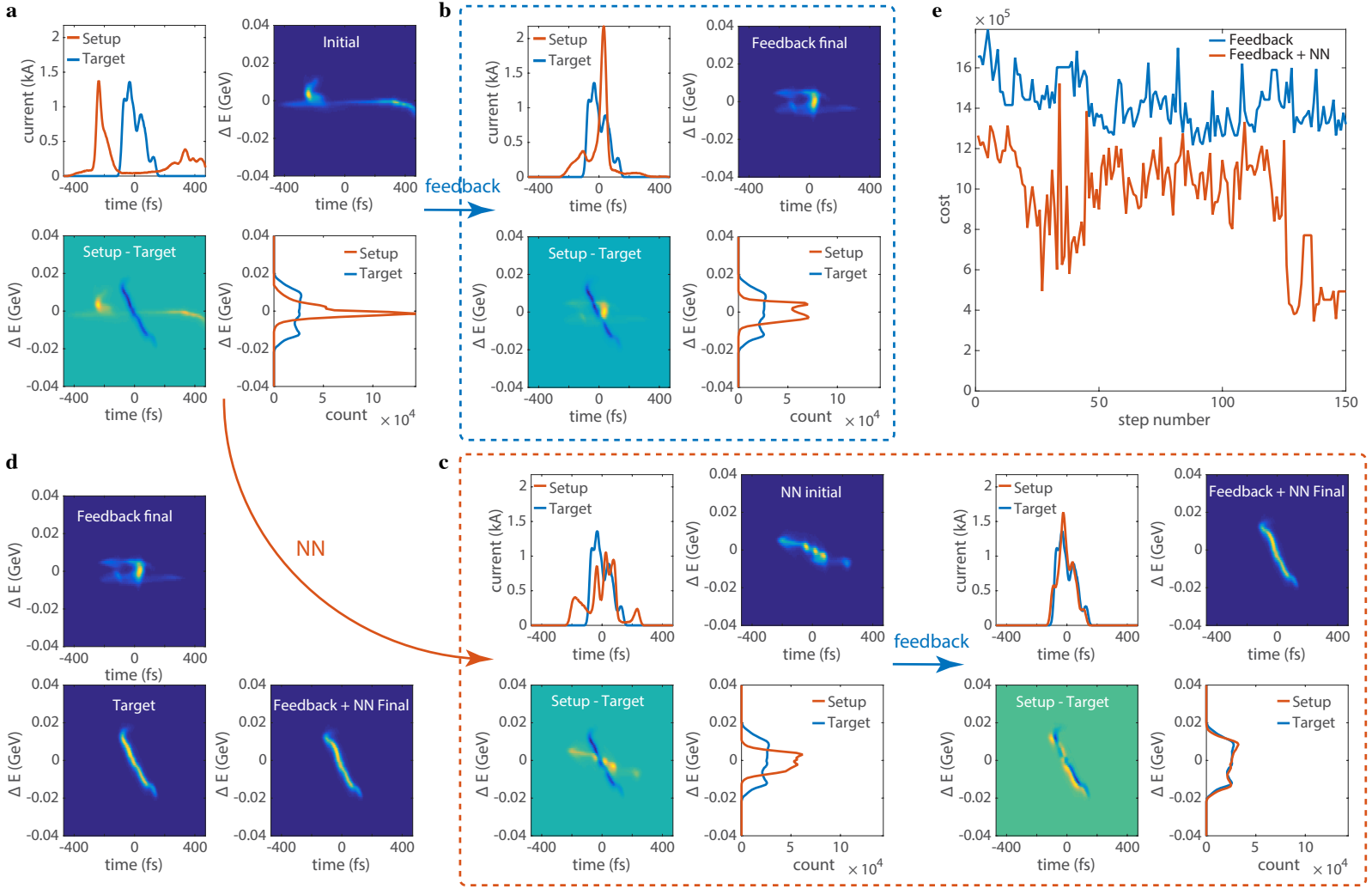


Proof of principle experiment: 1 hour, limited range 2 parameter scan: ~ 10 GB of data.

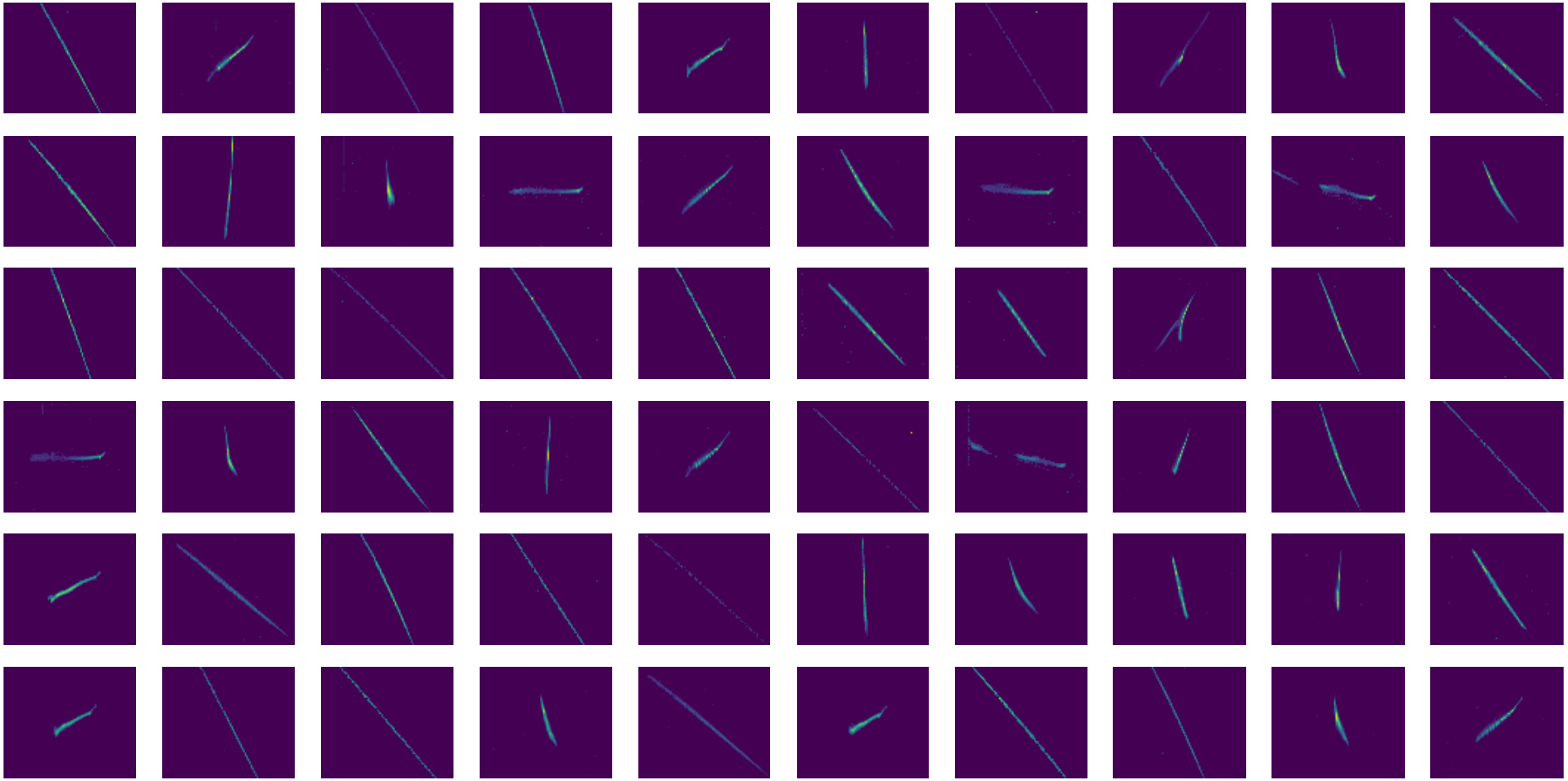
Goal: ~ 10 parameters @ ~5 bunch charges @ ~10 energies



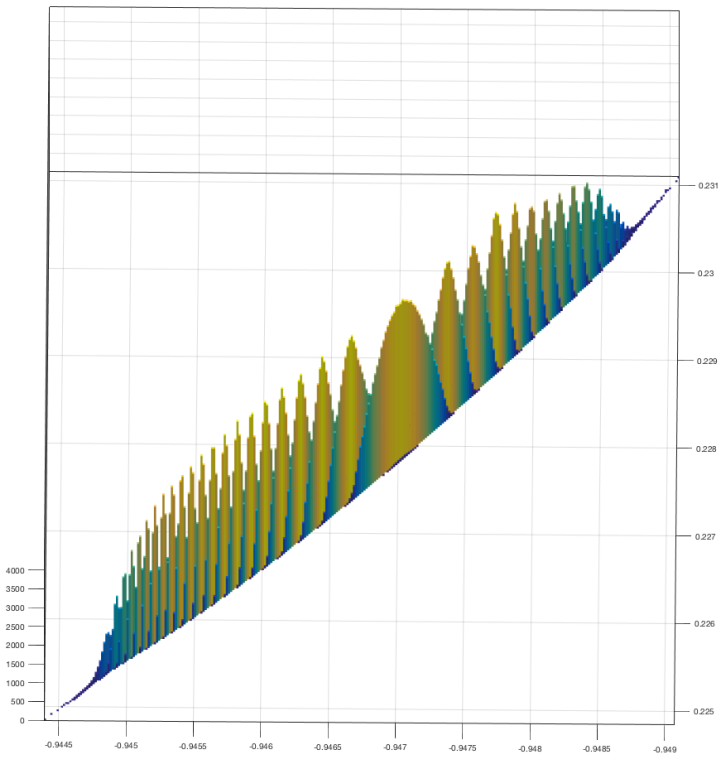
A. Scheinker, et al., *Physical Review Letters* 121.4 (2018): 044801.

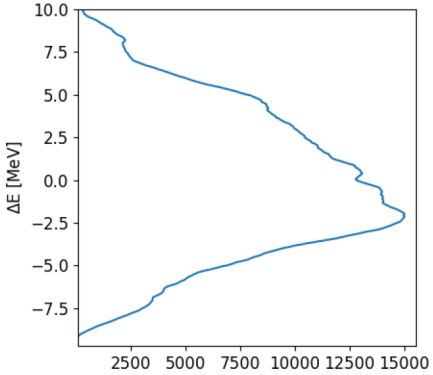

a
Setup
Target
current (kA)
time (fs)
Initial
Δ E (GeV)
Setup - Target
count
× 10^4
b
feedback
Feedback final
c
NN initial
Feedback + NN Final
d
NN
Target
e
× 10^5
Feedback
Feedback + NN
cost
step number

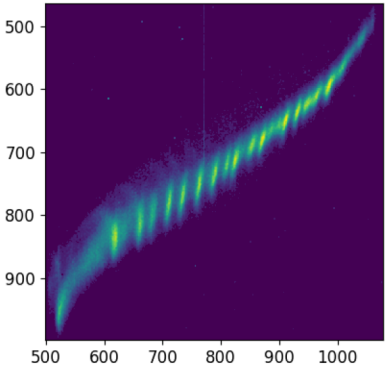
TCAV at EuXFEL B2D



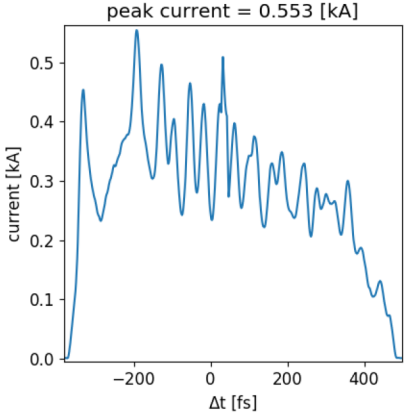
Microbunching in RFTweak?



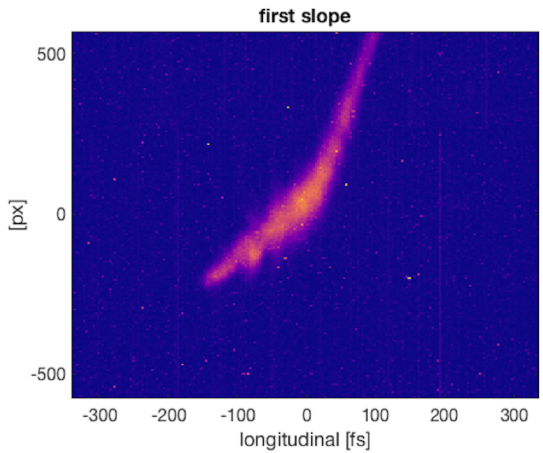


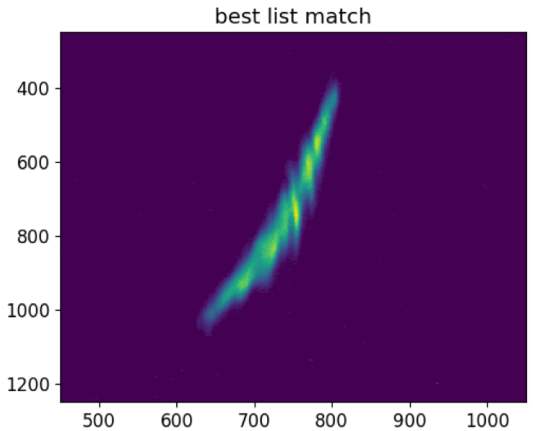


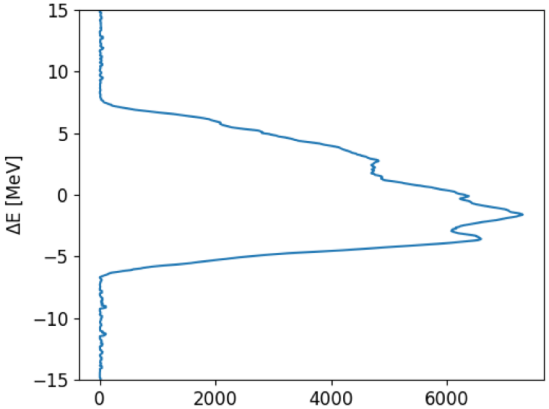

```
injector chirp =  -10.4
injector curvature =  -3.9
injector 3rd derivative =  0.004
L1 chirp =  -13
L2 chirp =  -13
```

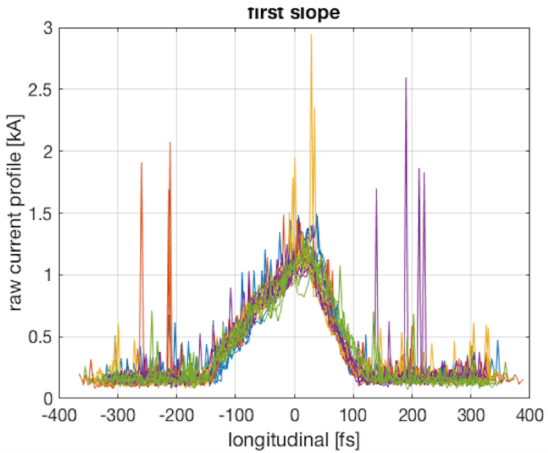


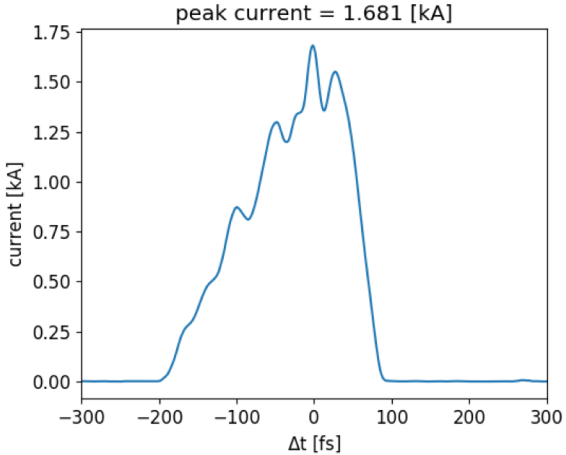
TCAV data at EuXFEL





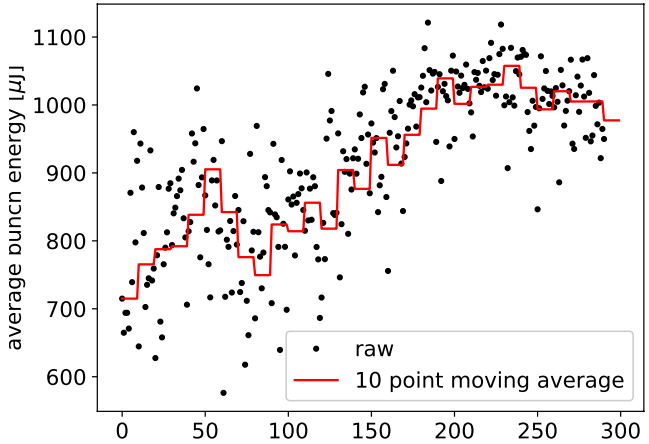


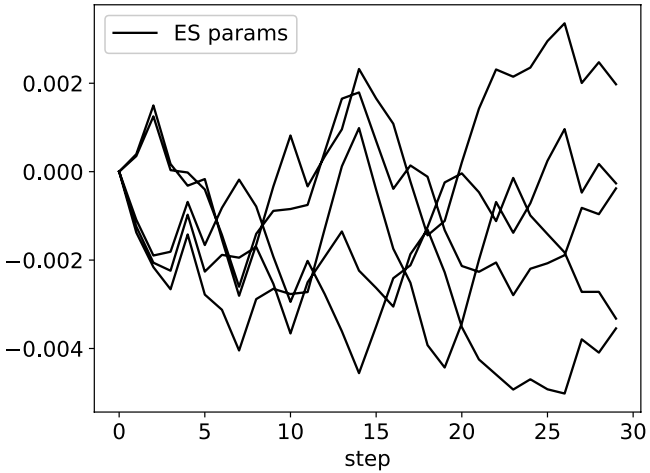




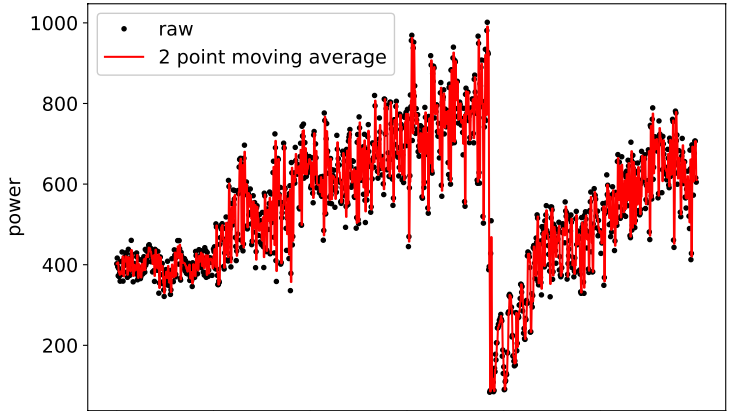
Injector Chirp:	-9.0
Injector Curvature:	150.0
Injector 3rd Derivative:	24000
L1 Chirp:	-10.0
L2 Chirp:	-6.0

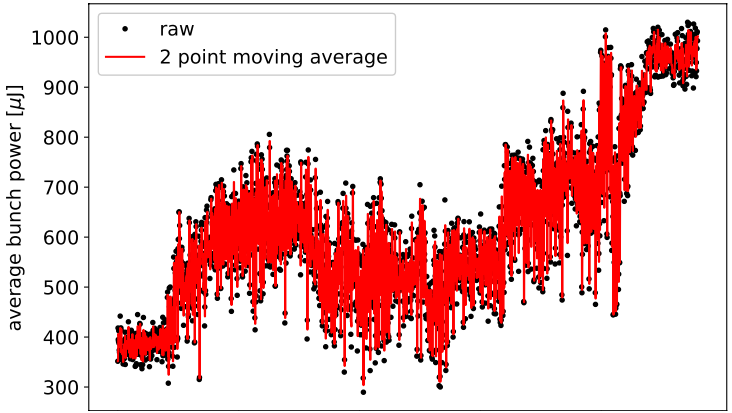
ES at EuXFEL (5 RF parameters: I1 chirp, curvature, 3rd derivative, L1 chirp, L2 chirp)

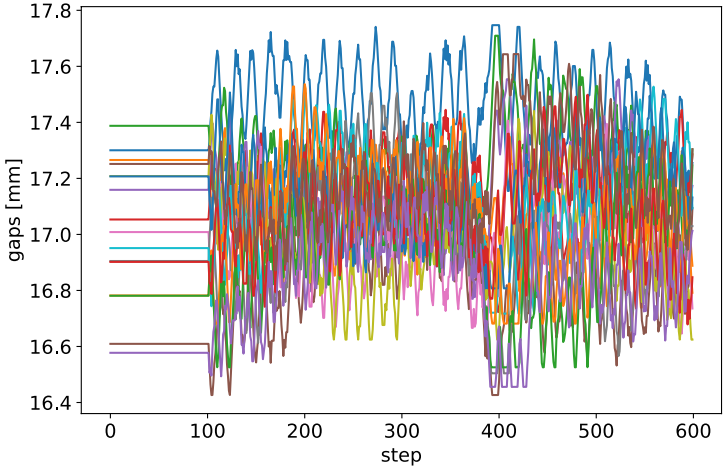


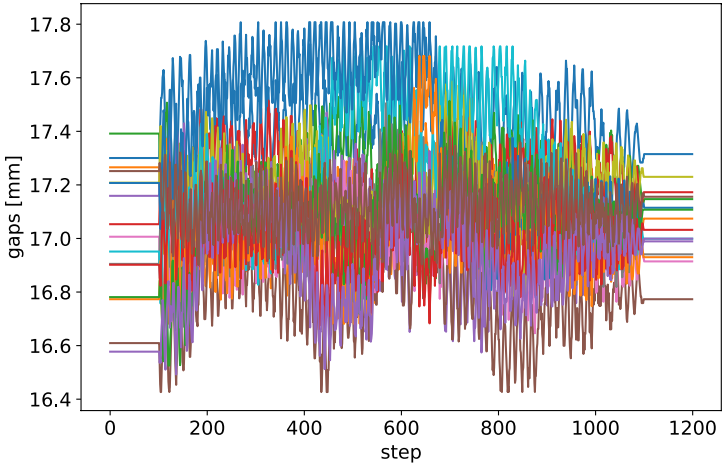


ES at EuXFEL (13 undulator phase shift gaps)

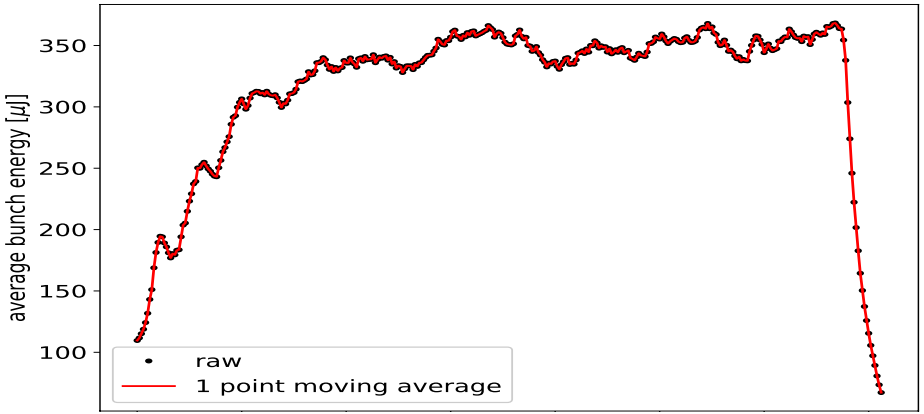


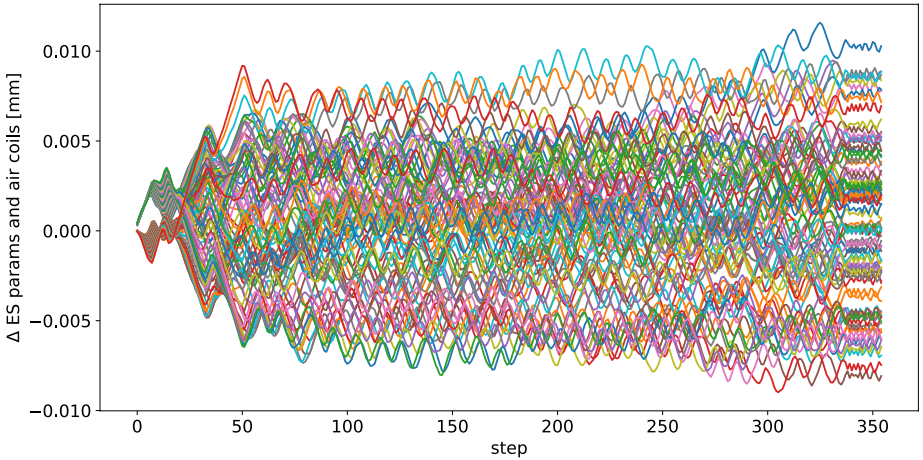




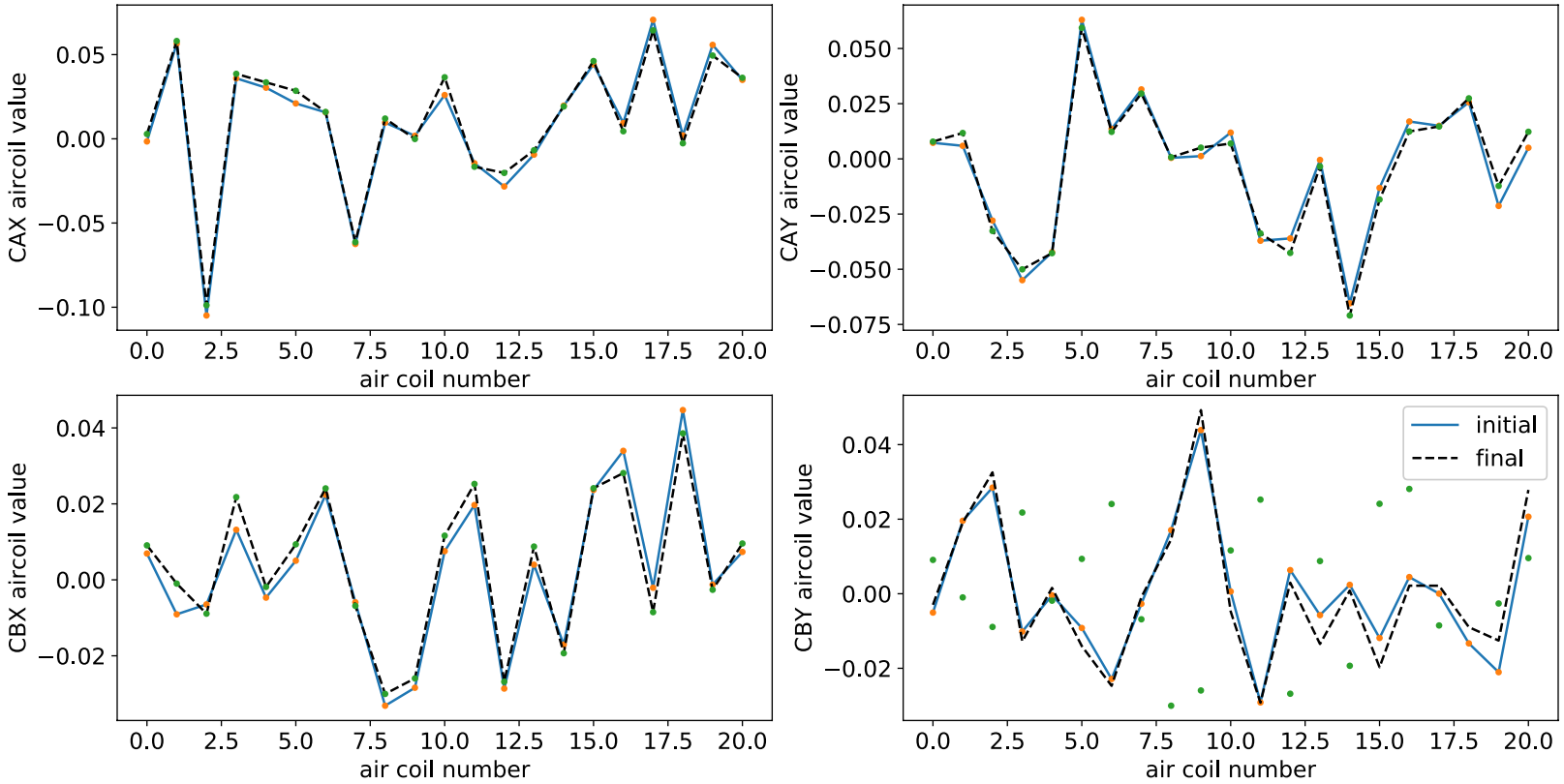


ES at EuXFEL (84 air coils)





ES at EuXFEL (84 air coils)



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