ADAPTIVE MACHINE LEARNING AND FEEDBACK CONTROL FOR AUTOMATIC PARTICLE ACCELERATOR TUNING

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NAPAC 2019, Lansing, Michigan

Los Alamos
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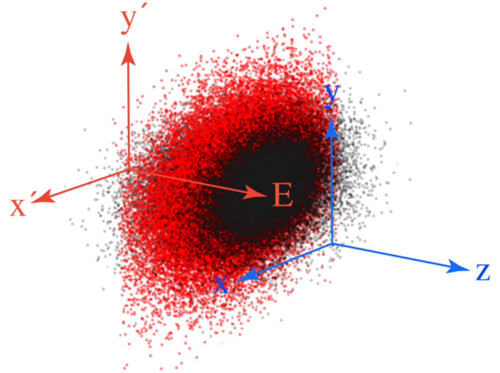
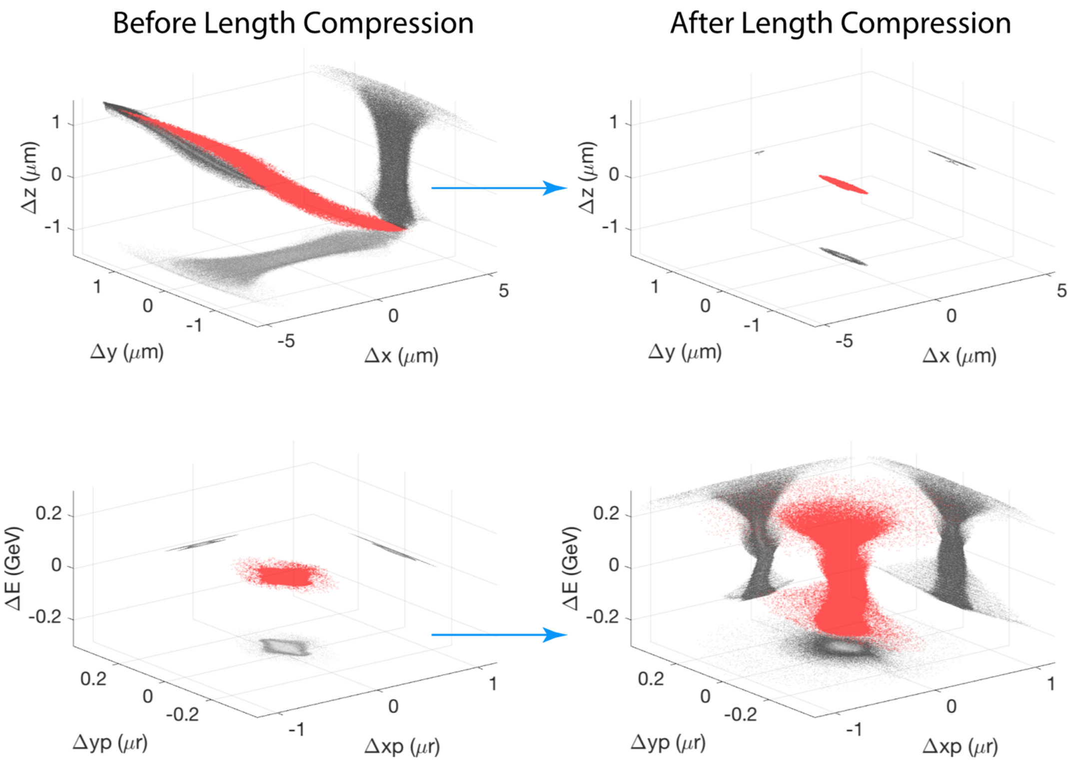
EST. 1943

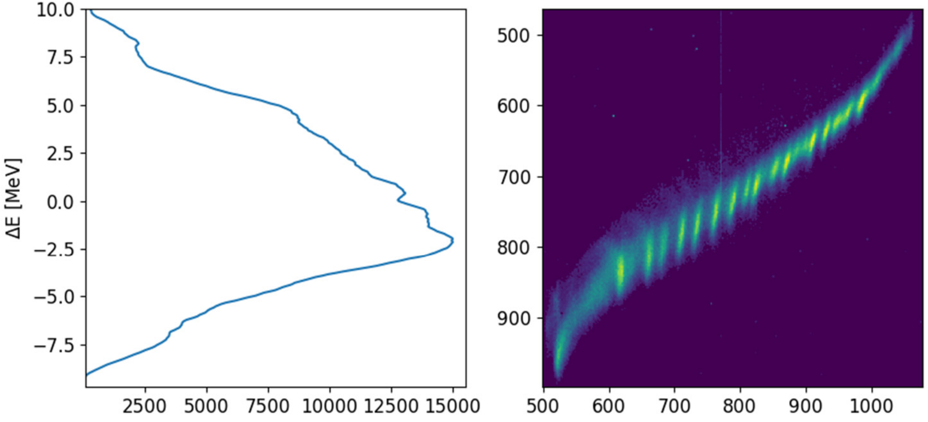
FACET-II, bunch compression

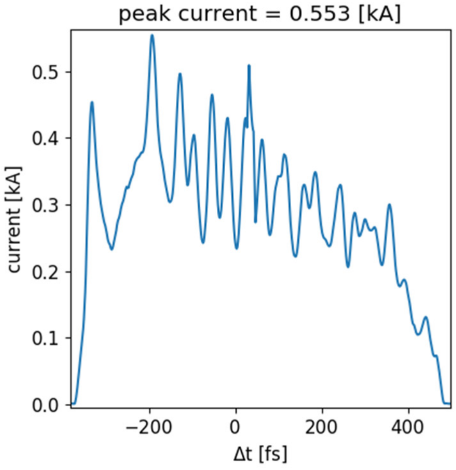




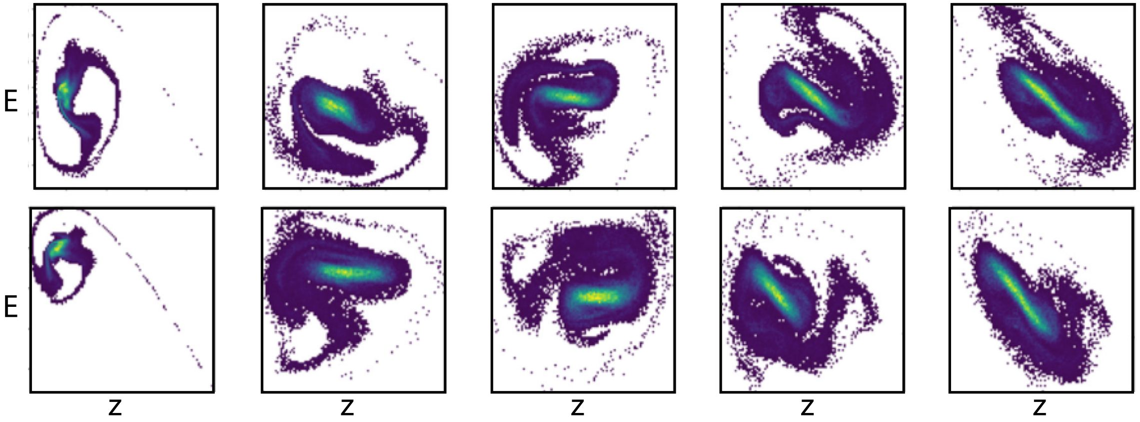
Motivation

EuXFEL: μBunch Instabilities

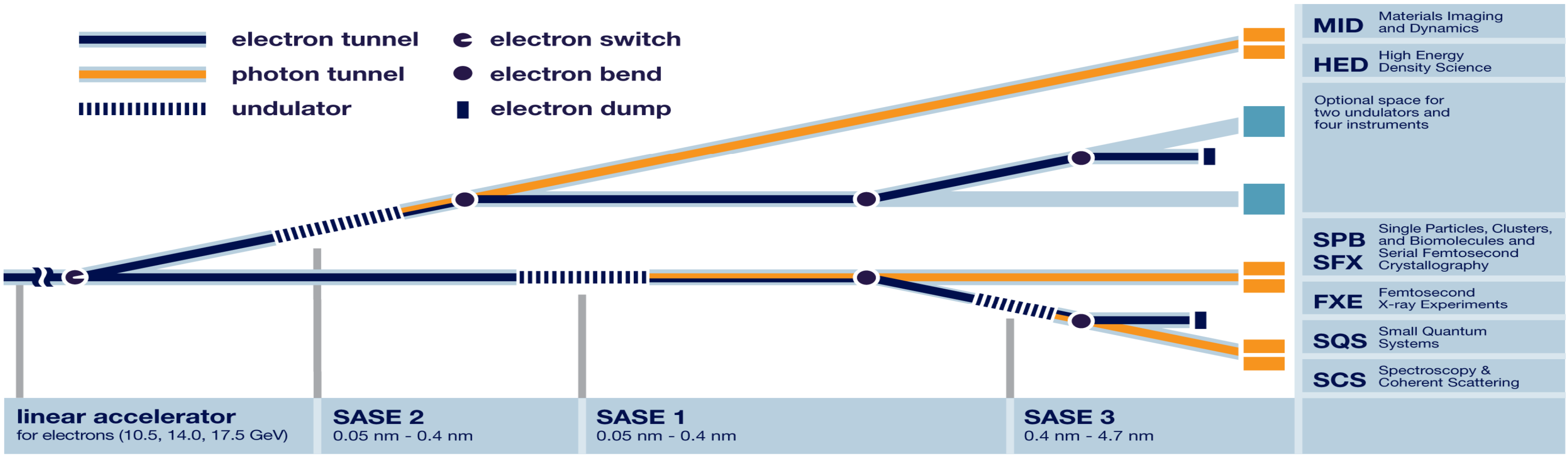




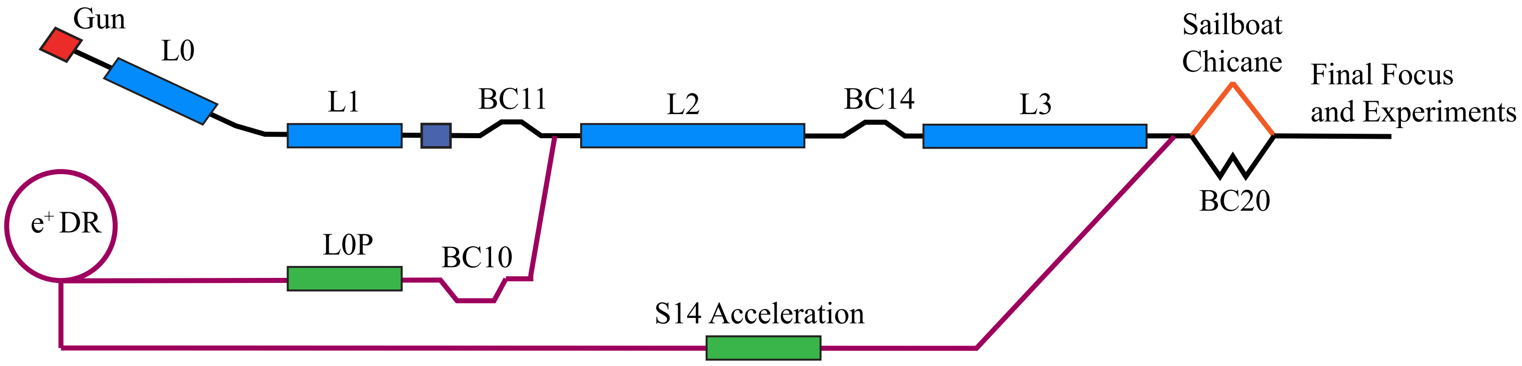
LANSCE: Space charge dominated proton beam



European XFEL



FACET-II


Gun
L0
L1
BC11
L2
BC14
L3
Sailboat
Chicane
Final Focus
and Experiments
BC20
e+ DR
L0P
BC10
S14 Acceleration

Adaptive Feedback

Extremum Seeking

- Model independent
- Noisy and time varying systems
- Many coupled parameters

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

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

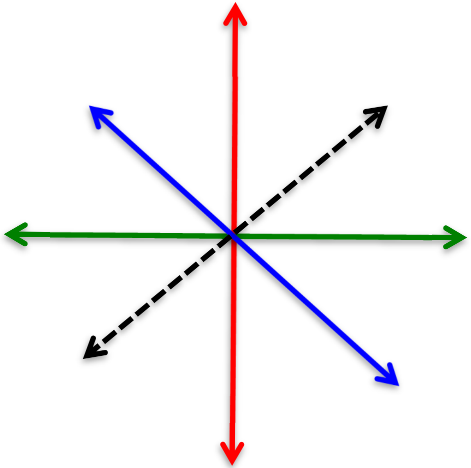
$$\frac{dp_1}{dt} = \sqrt{\alpha\omega_1} \cos(\omega_1 t + ky)$$

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

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

$$\vdots$$

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



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

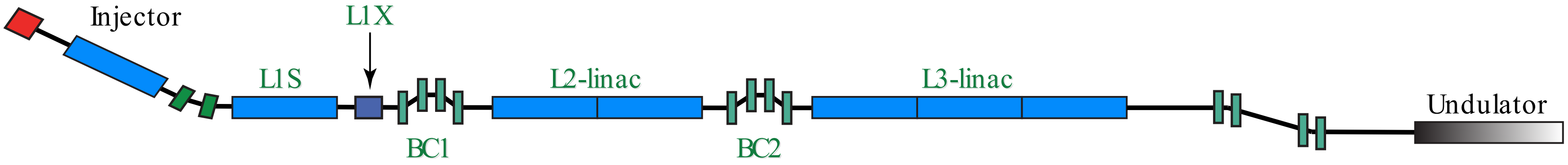
On average, the system performs minimizes the **unknown, time-varying** function V(x,t)

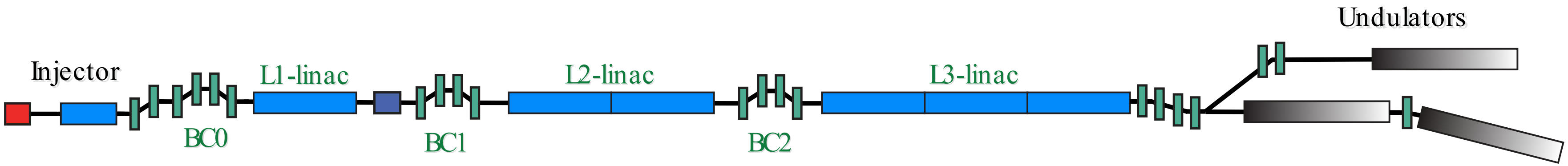
Allows simultaneous tuning of ALL parameters in parallel.

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

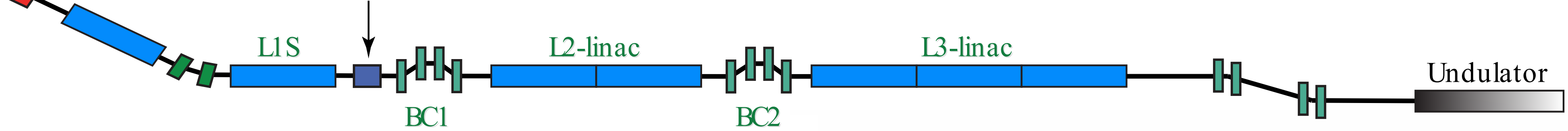
$$\lim_{\omega \to \infty} \langle \cos(\omega_i t), \cos(\omega_j t) \rangle = \lim_{\omega \to \infty} \int_0^t \cos(\omega_i \tau) \cos(\omega_j \tau) d\tau = 0$$

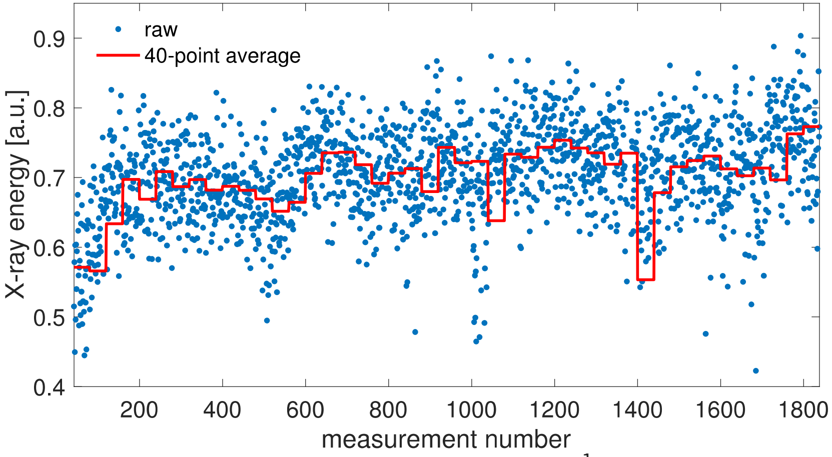
ES for Maximizing FEL Output Power

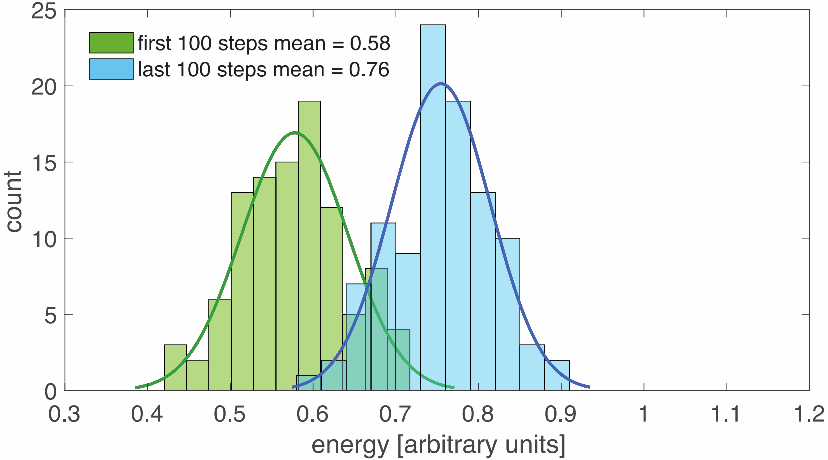


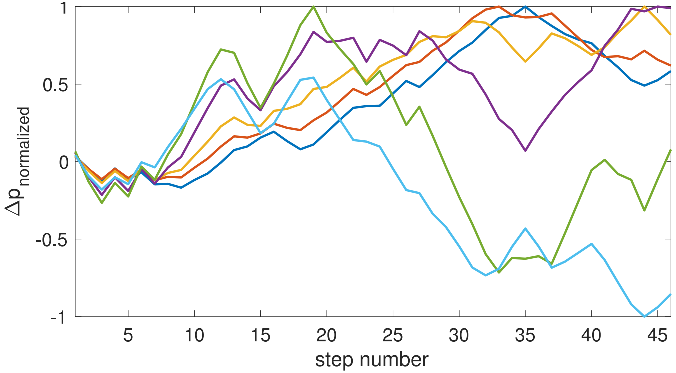


LCLS

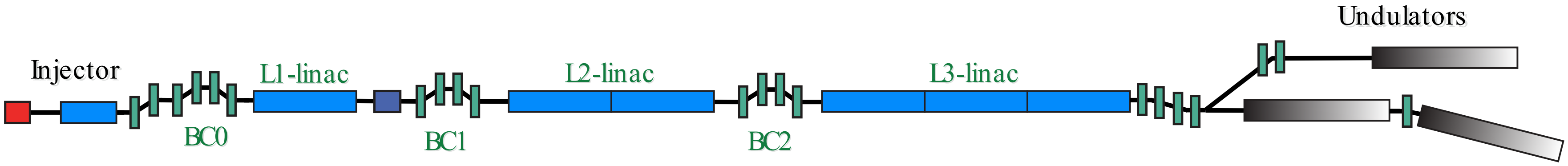


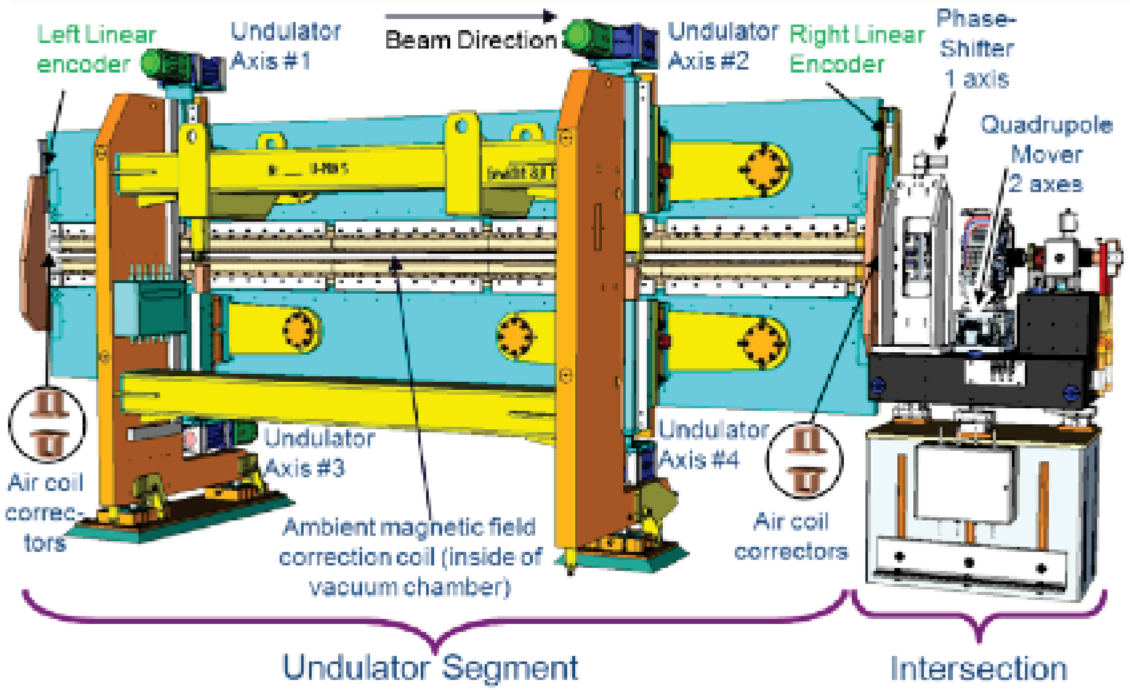






A. Scheinker et al., *PRAB*, 2019.

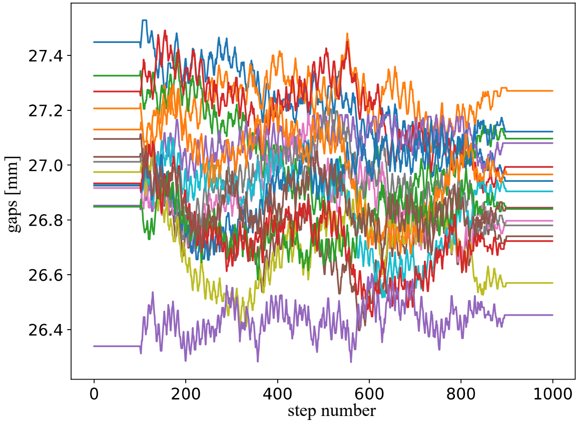


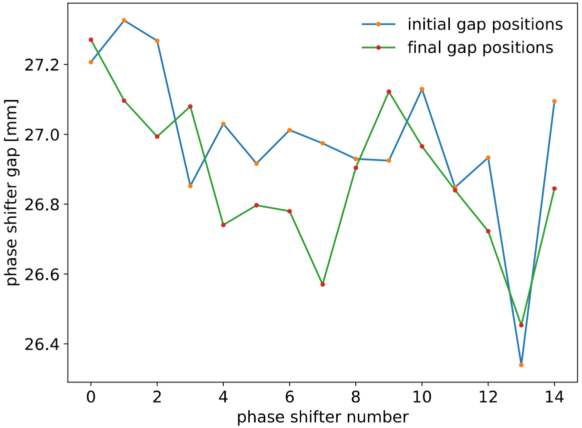


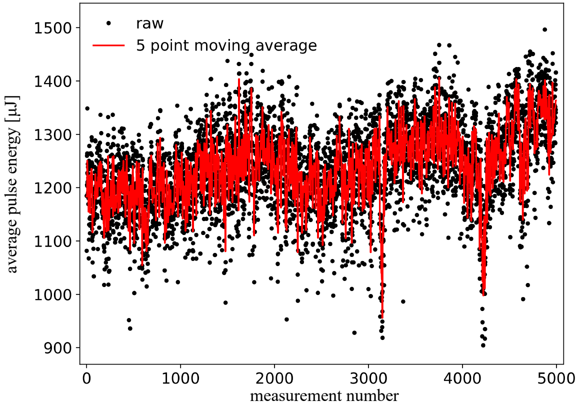
Phase shifters: phase advance between beam and light

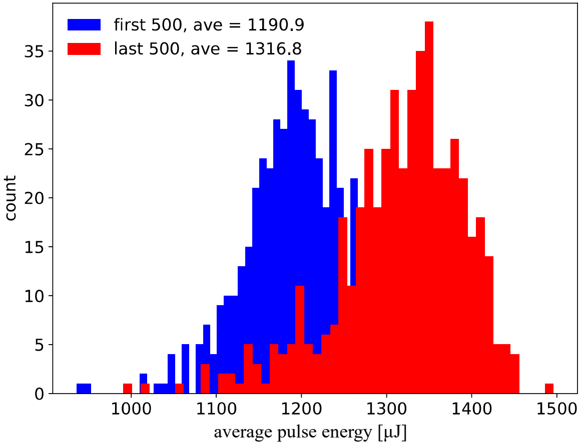
Air coils (x,y): before and after each section control beam orbit

Tuning 15 Undulator Gaps

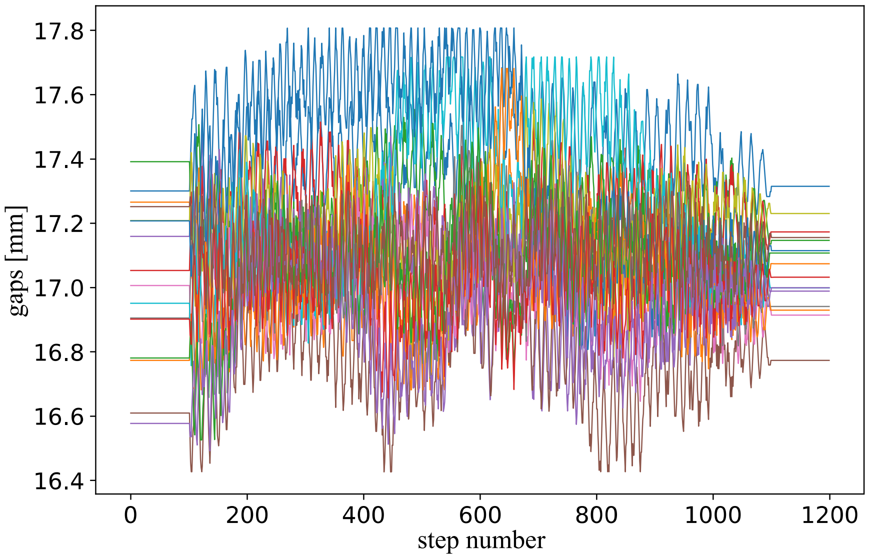


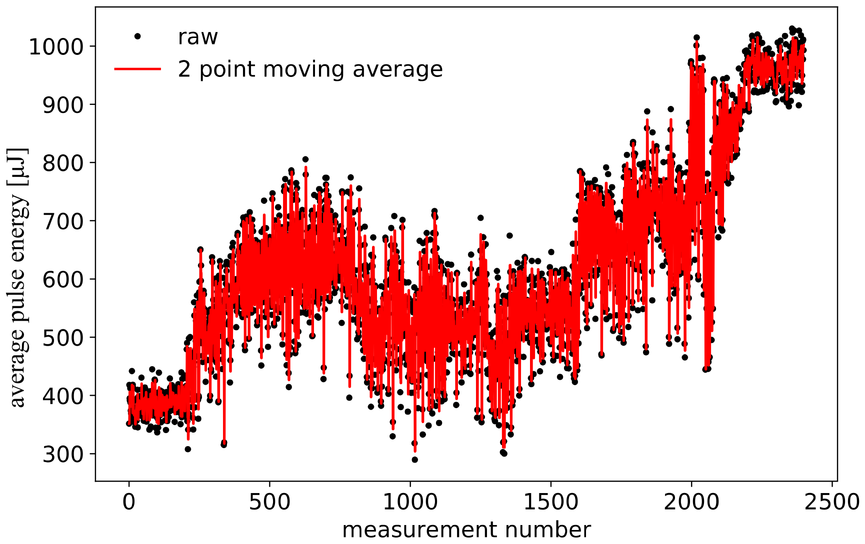




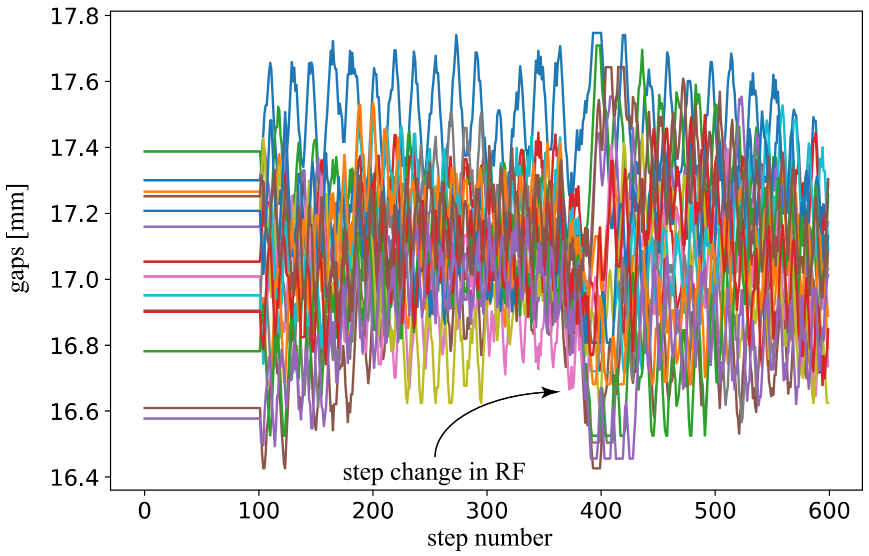


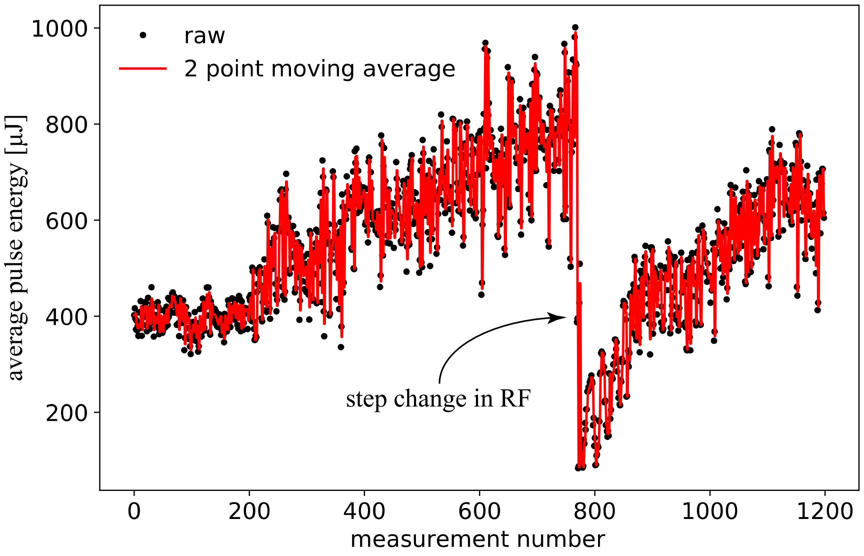
Tuning 15 Undulator Gaps



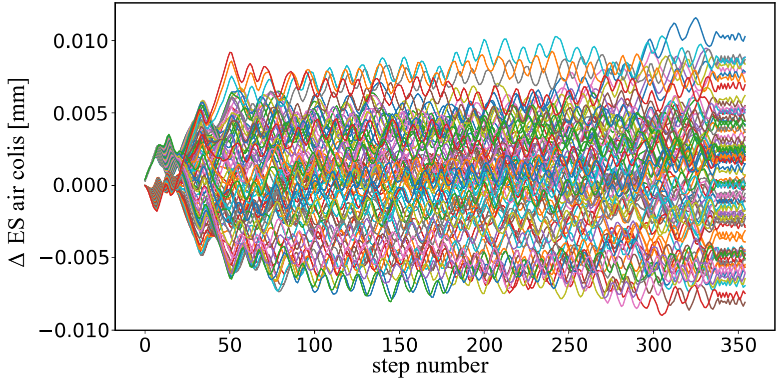


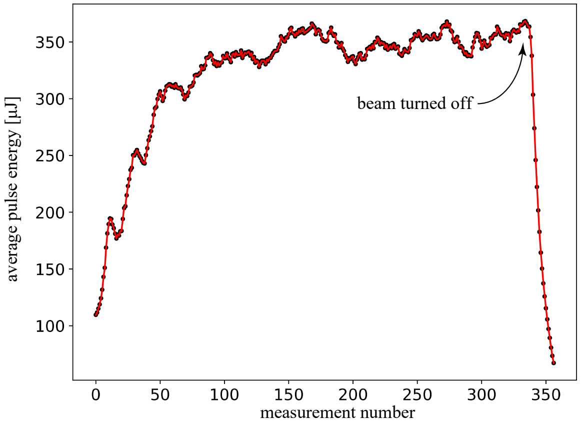
Tuning 15 Undulator Gaps

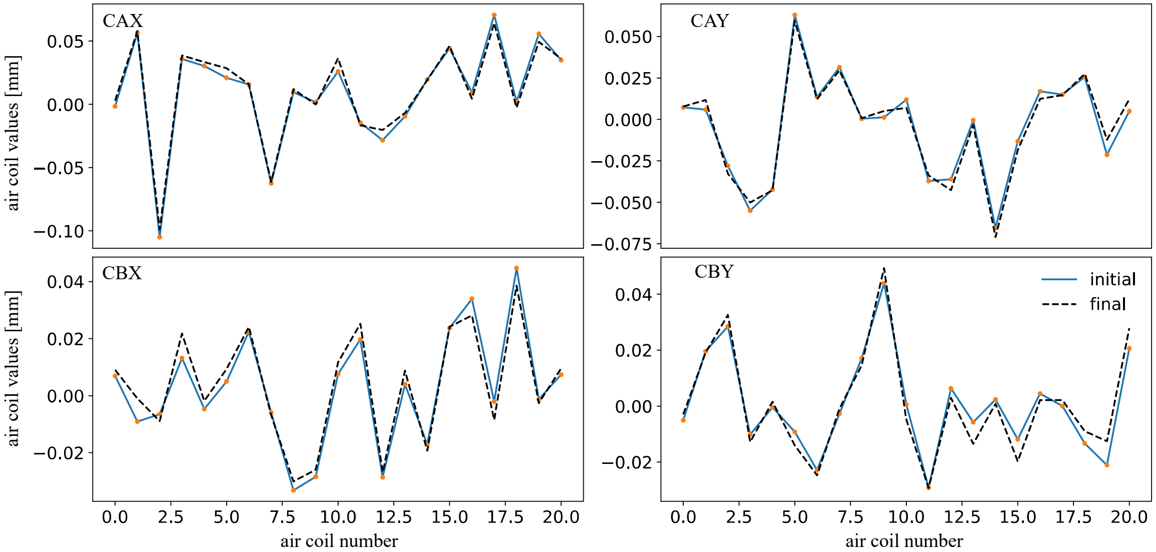




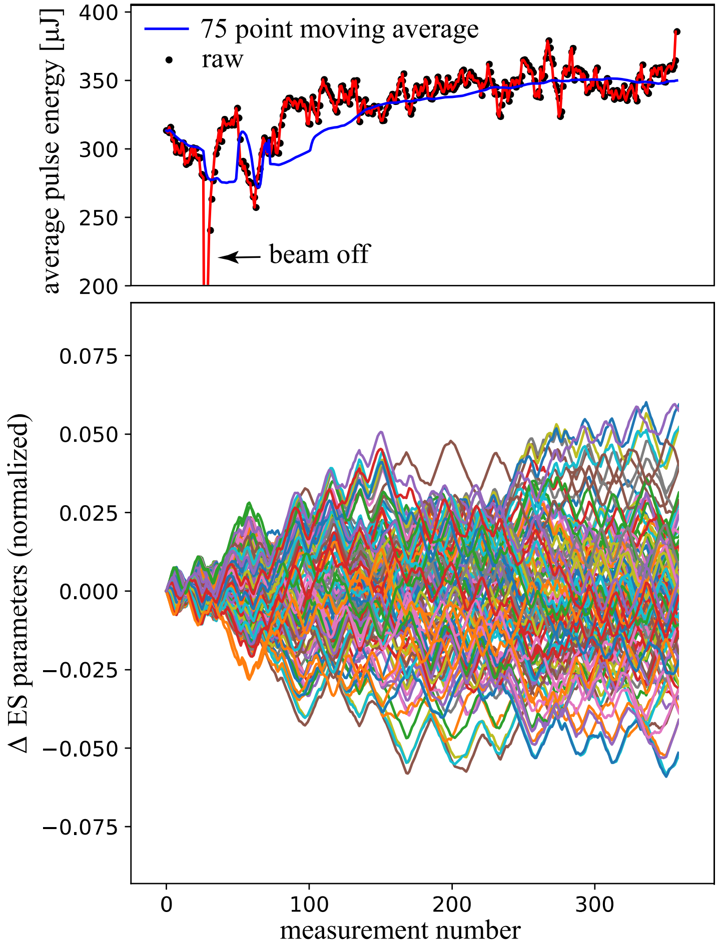
Tuning 84 air coils

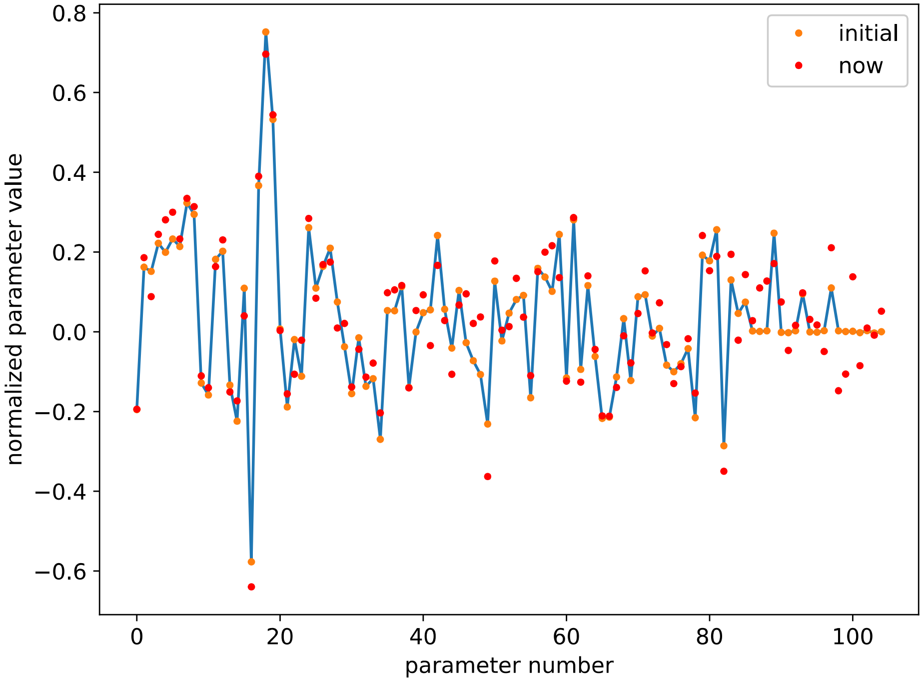




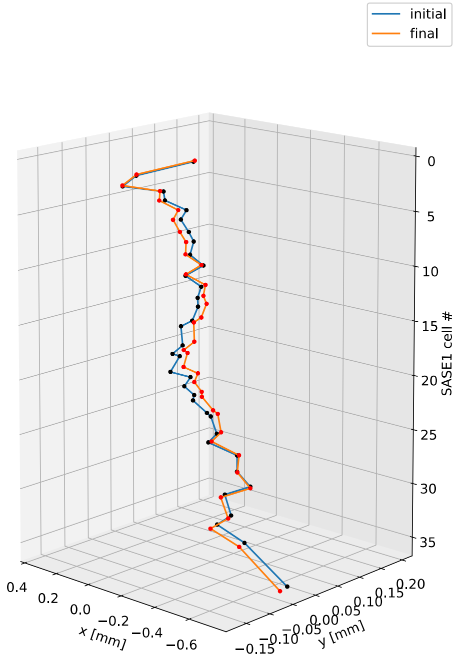


Tuning 105 parameters (84 air coils + 21 phase gaps)





initial
now
normalized parameter value
parameter number
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0
20
40
60
80
100

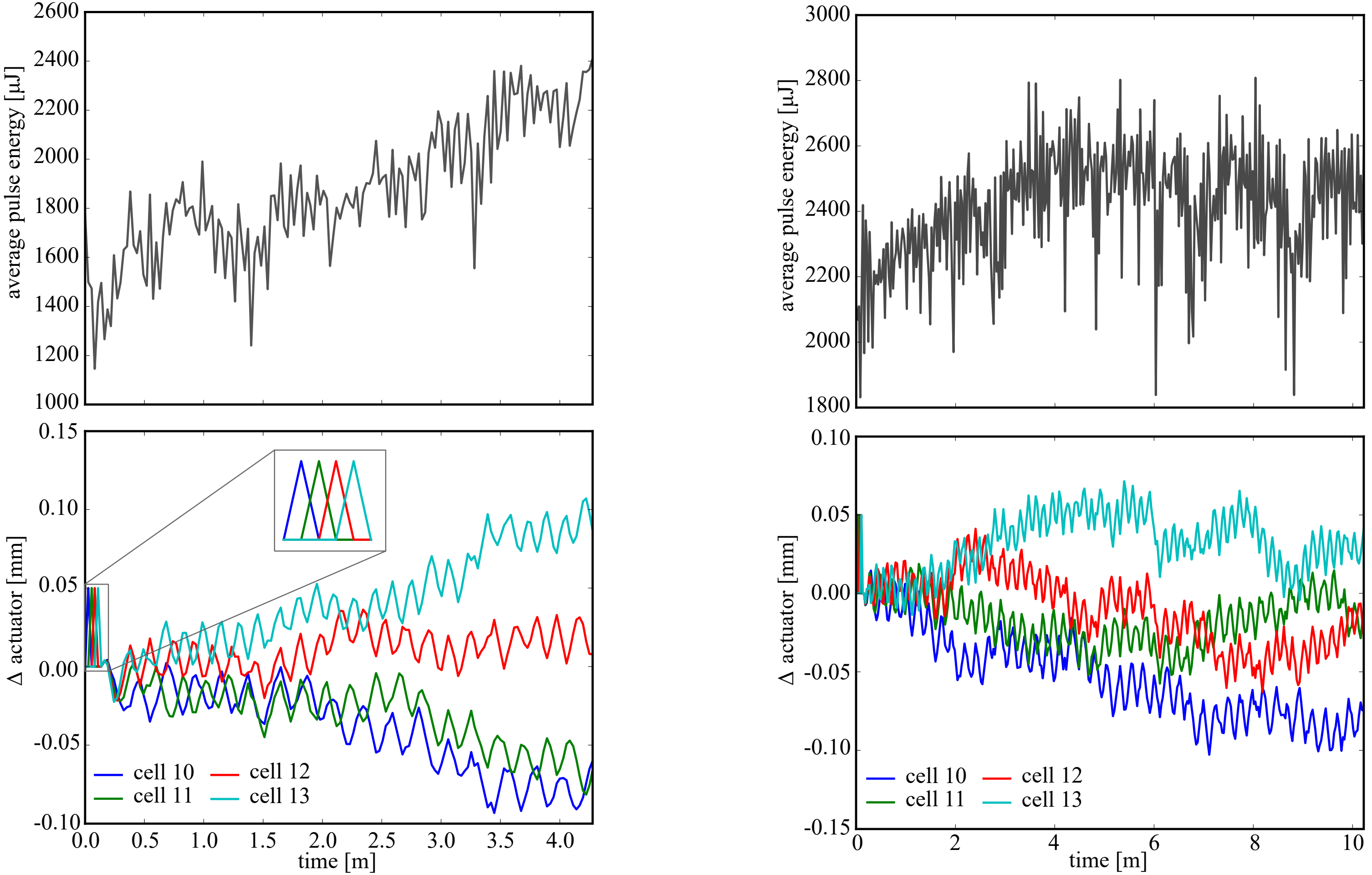


initial
final
SASE1 cell #
x [mm]
y [mm]
0
5
10
15
20
25
30
35
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.15
−0.10
−0.05
0.00
0.05
0.10
0.15
0.20

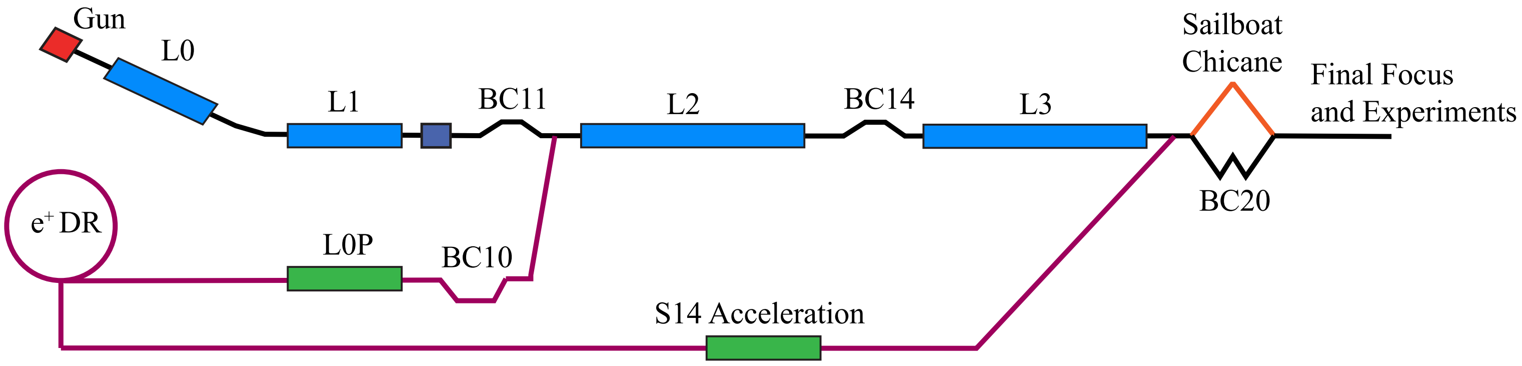
Automated ES Parameter Tuning

$$
\begin{aligned}
\frac{dp_j}{dt} &= \sqrt{\alpha\omega_j}\cos\left(\omega_j t + k_j C(\mathbf{p},t)\right) \\
&= \sqrt{\alpha\omega_j}\cos\left(\theta_j(\mathbf{p},t)\right), \\
\frac{d\theta_j}{dt} &= \frac{\partial\theta_j}{\partial t} + \sum_{i=1}^{n}\frac{\partial\theta_j}{\partial p_i}\frac{\partial p_i}{\partial t} \\
&= \omega_j + k_j\left(\frac{\partial C}{\partial t} + \sum_{i=1}^{n}\frac{\partial C}{\partial p_i}\frac{\partial p_i}{\partial t}\right), \\
\frac{d\bar{p}_j}{dt} &= -\frac{k_j\alpha}{2}\frac{\partial C}{\partial \bar{p}_j}, \\
\frac{d\theta_j}{dt} &\approx \omega_j - \frac{k_j\alpha}{2}\sum_{i=1}^{n}k_i\left(\frac{\partial C}{\partial p_i}\right)^2, \\
0 &= \omega_j - \frac{k_j\alpha}{2}\sum_{i=1}^{n}k_i\left(\frac{\partial C}{\partial p_i}\right)^2
\end{aligned}
$$

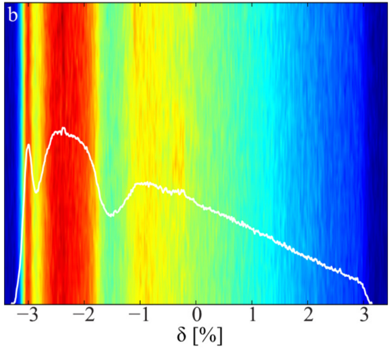
ES Implemented as optimizer in OCELOT

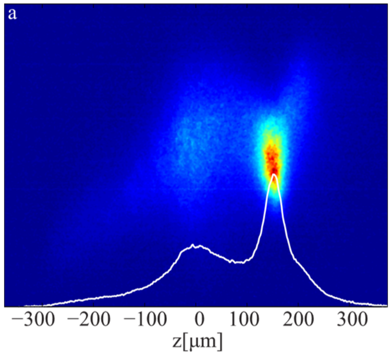


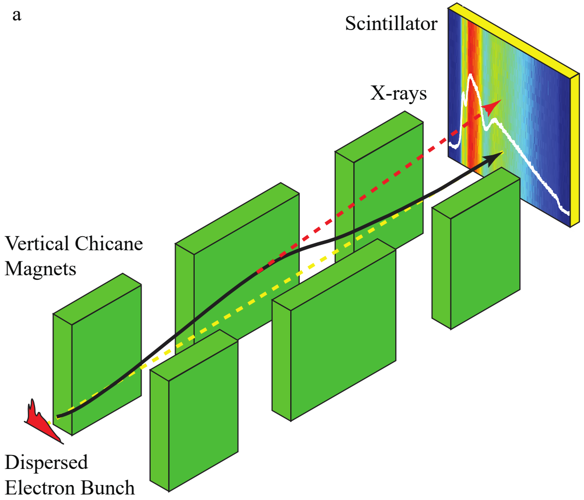
ES for Non-Invasive Longitudinal Phase Space Diagnostics

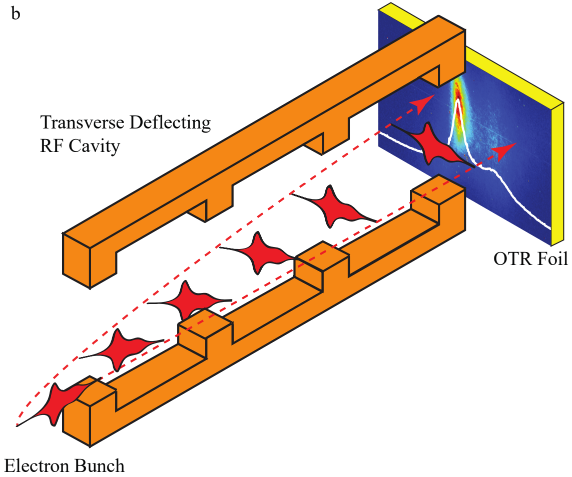


A. Scheinker and S. Gessner, PRAB, 2015.









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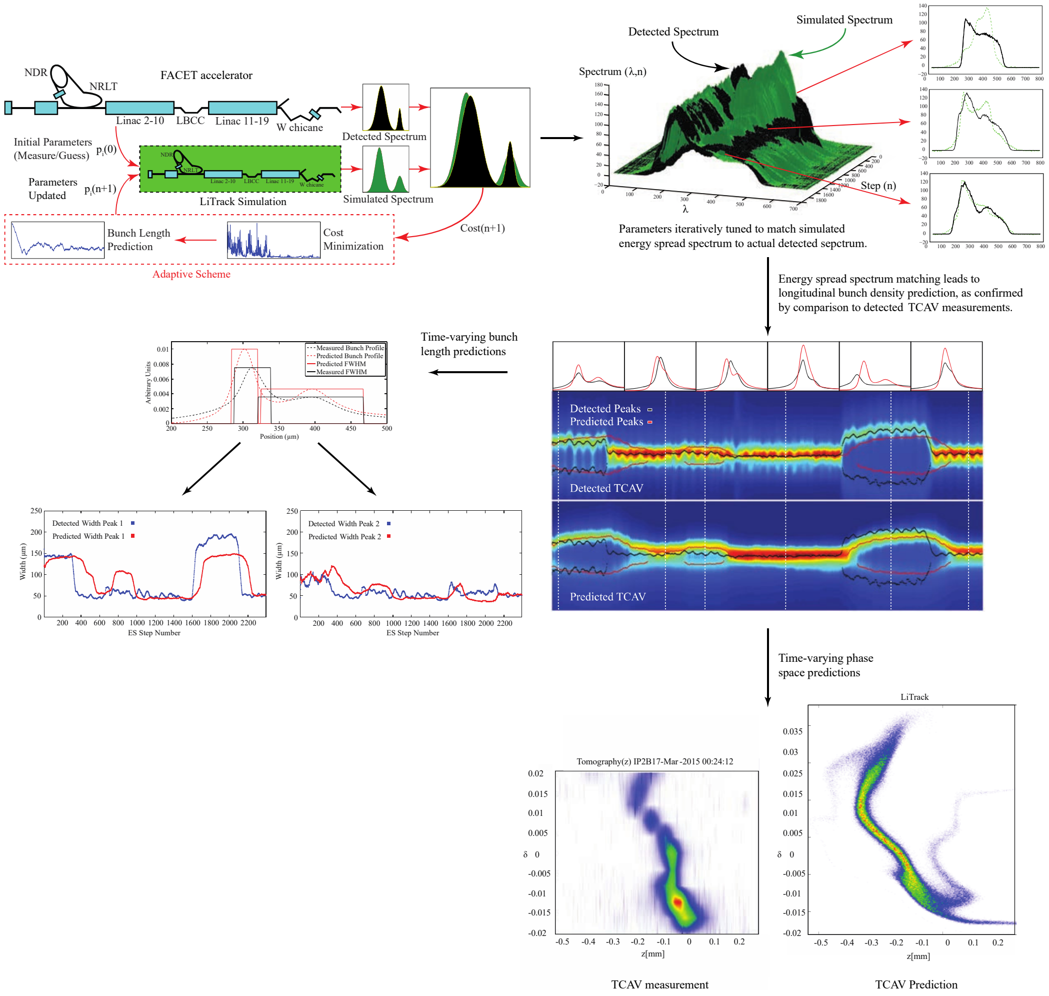
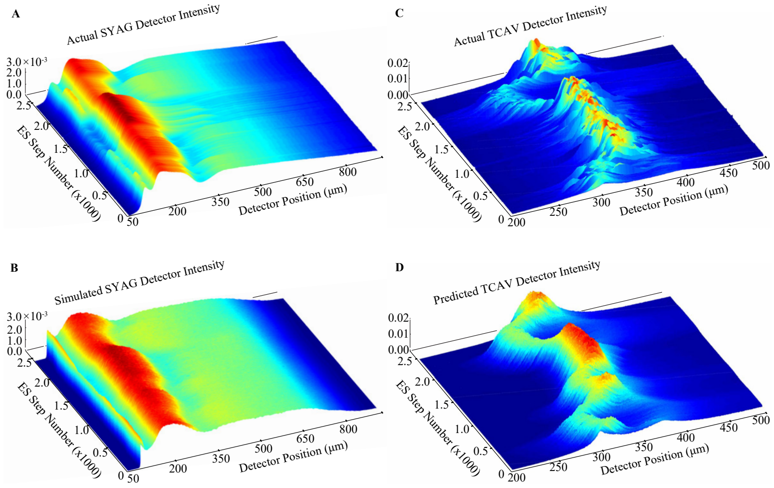
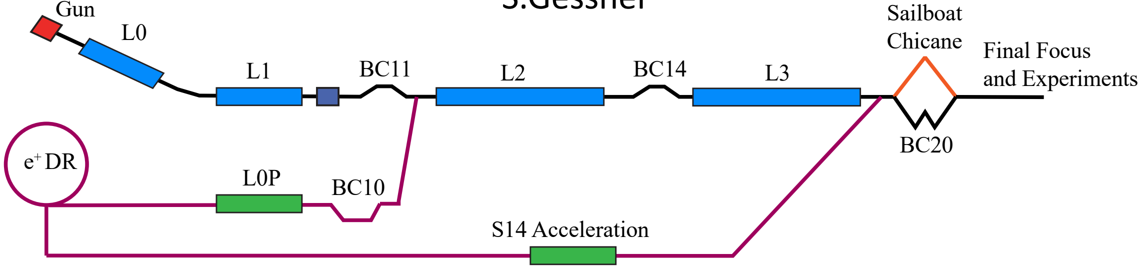
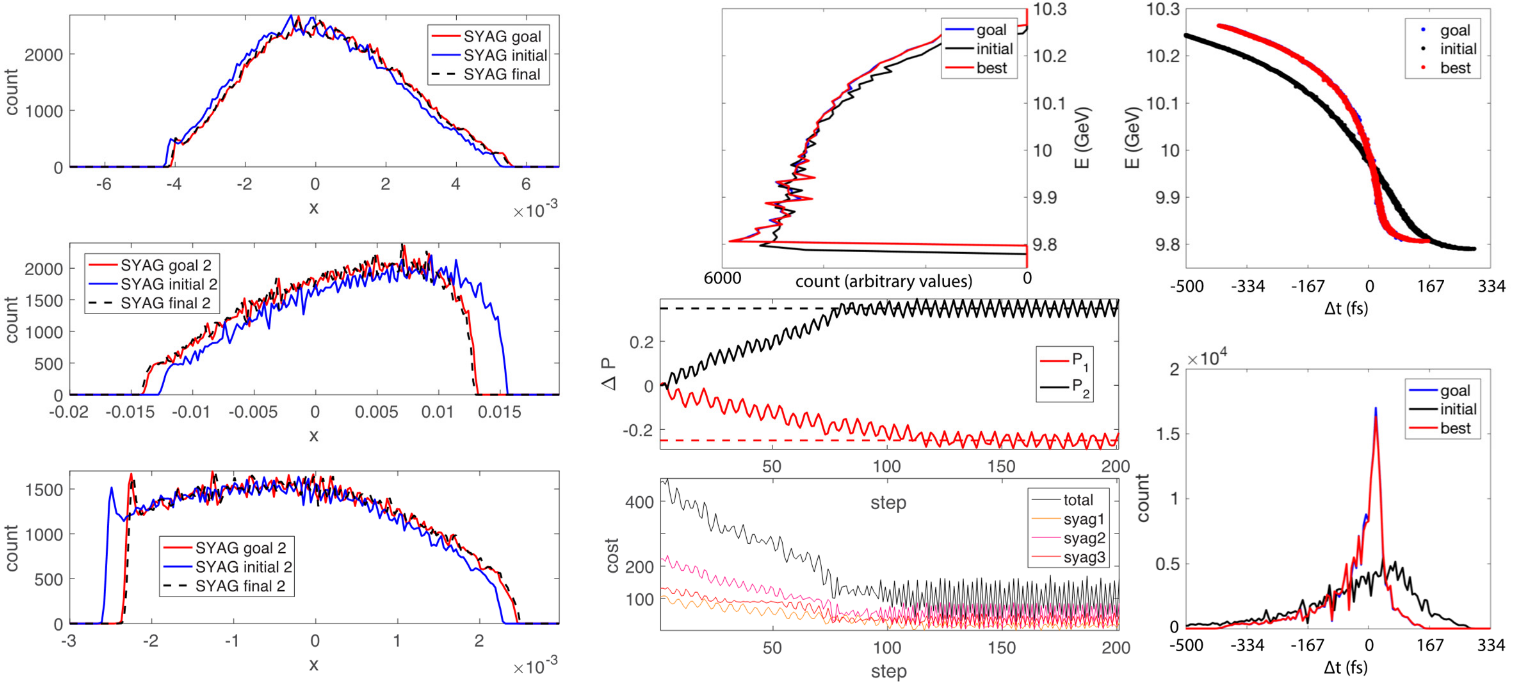
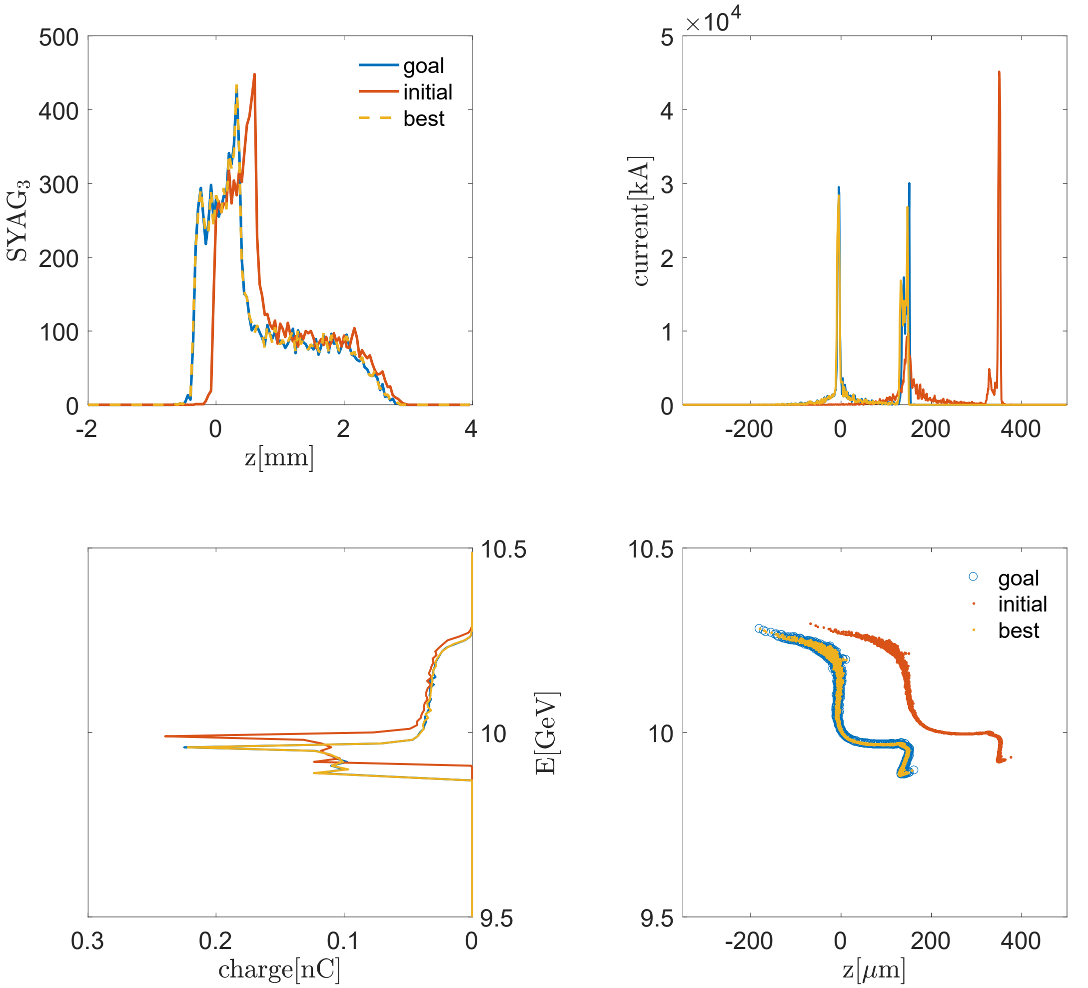




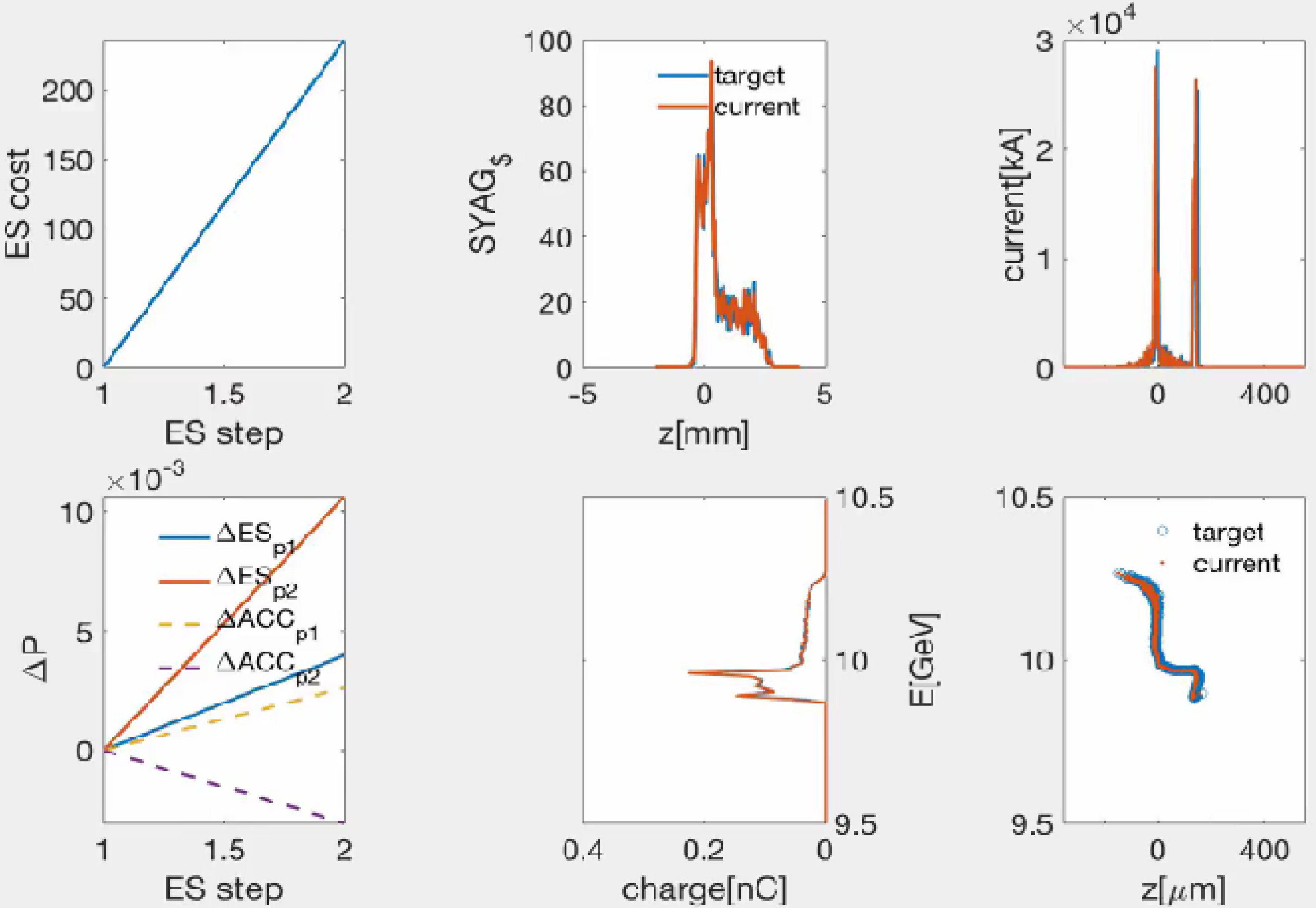
FACET-II Virtual Diagnostic: A. Scheinker, C. Emma, S.Gessner



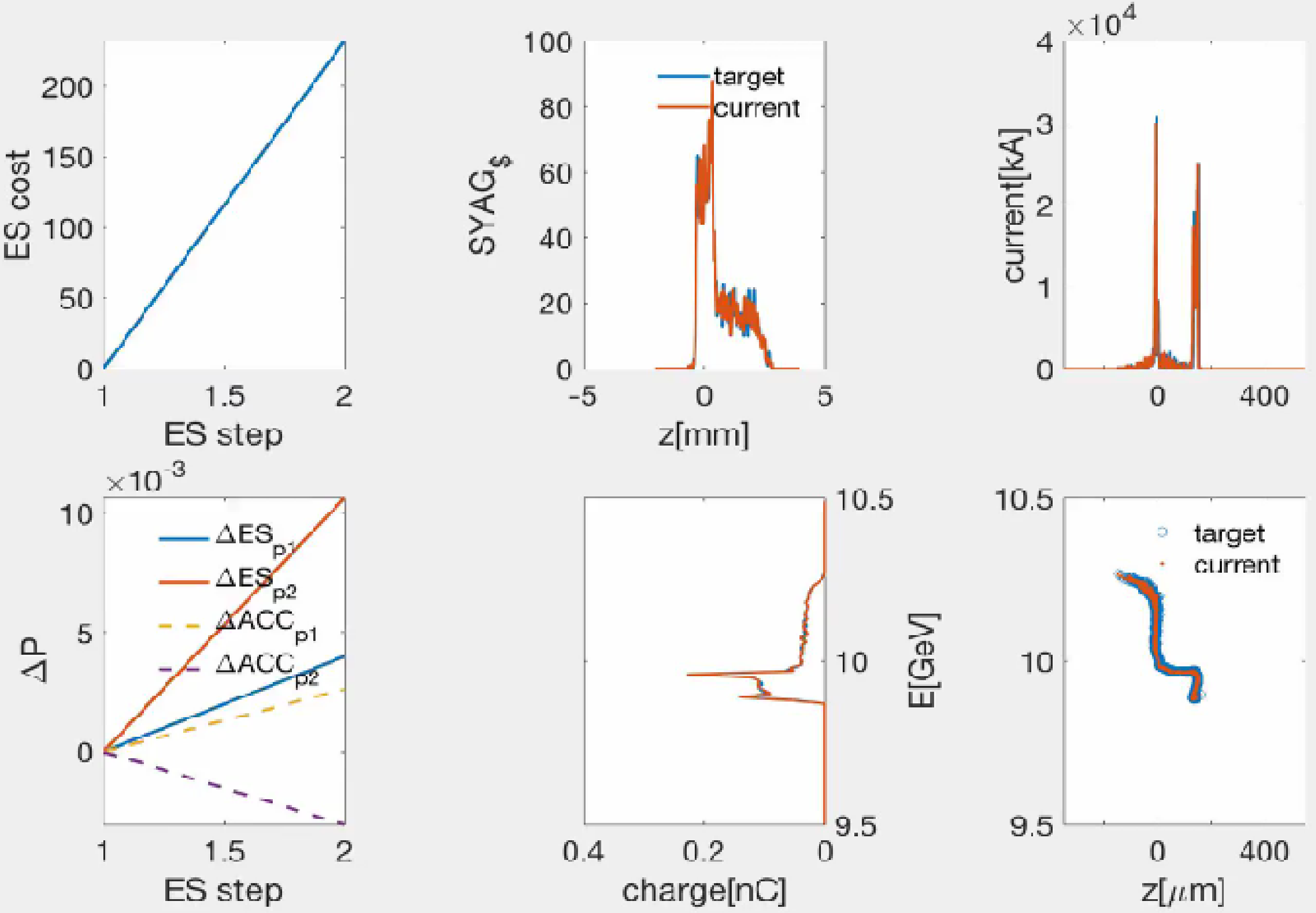




500
400
300
200
100
0
-2
0
2
4
z[mm]
SYAG3
goal
initial
best
×10^4
5
4
3
2
1
0
-200
0
200
400
current[kA]
10.5
10
9.5
0.3
0.2
0.1
0
charge[nC]
E[GeV]
10.5
10
9.5
-200
0
200
400
z[μm]
goal
initial
best



ES cost
ES step
SYAG$_s$
target
current
z[mm]
current[kA]
$\times 10^4$
$\times 10^{-3}$
ΔP
ΔES_{p1}
ΔES_{p2}
ΔACC_{p1}
ΔACC_{p2}
ES step
charge[nC]
E[GeV]
target
current
z[μm]



ES cost
ES step
SYAG$_s$
target
current
z[mm]
current[kA]
$\times 10^4$
$\times 10^{-3}$
ΔP
ΔES_{p1}
ΔES_{p2}
ΔACC_{p1}
ΔACC_{p2}
ES step
charge[nC]
E[GeV]
target
current
z[μm]