FEL Optimization: from Model-Free to Mode-Dependent Approaches and ML prospects

S. Tomin, G. Geloni, M. Scholz

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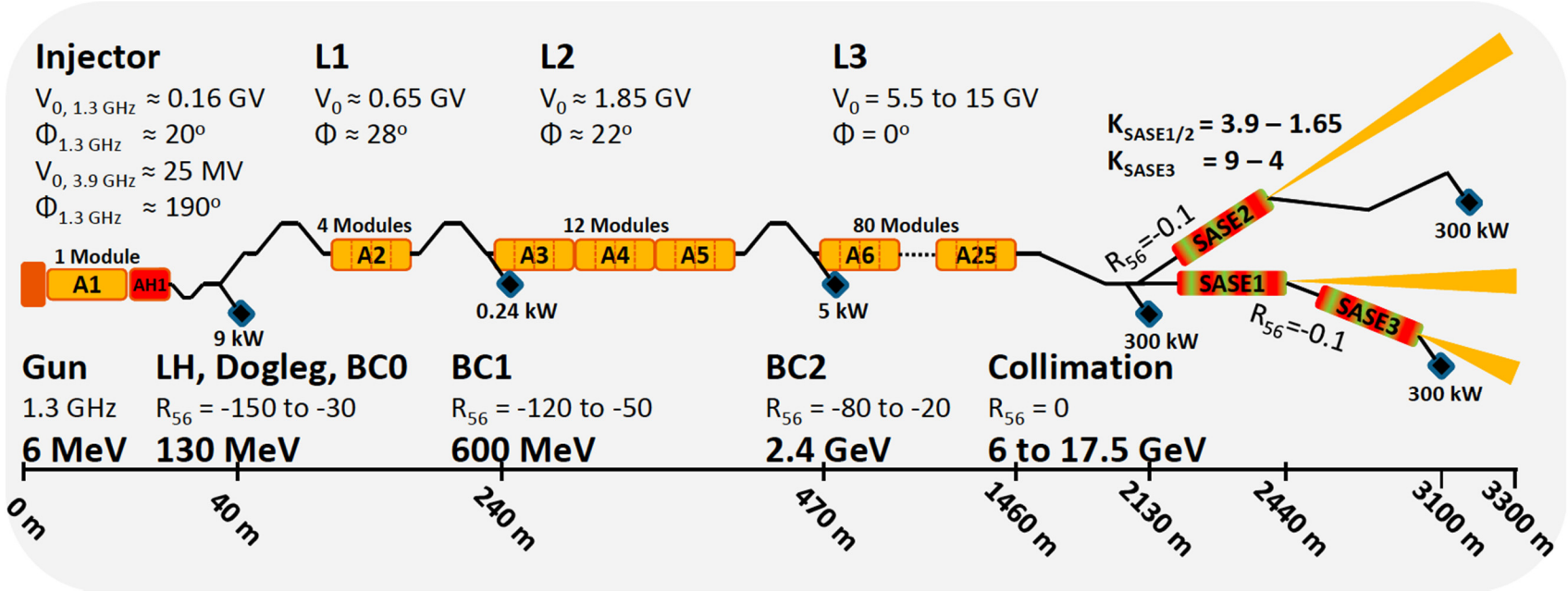
29 AUGUST 2019

Outline

- Motivation
- Model-free optimization and ML prospects
- Model-dependent optimizations and ML prospects
- Conclusion & Outlook

Accelerator Overview



Nominal parameters

- Electron beam energy up to 17.5 GeV
- Pulse rep. rate 10 Hz
- Bunches per pulse 2700
- Intratrain rep. rate 4.5 MHz
- Bunch charge 0.02 – 1 nC

- Electron bunches in a single pulse are distributed by a fast kicker system to three SASE undulators

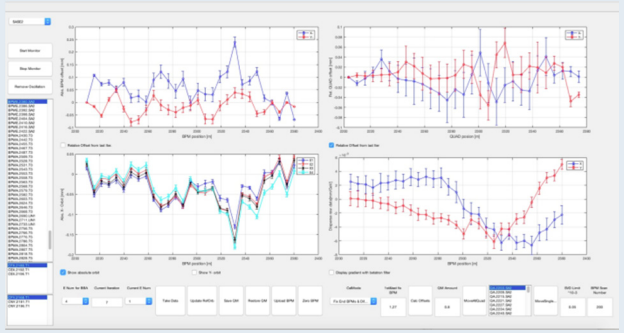
W. Decking et al, "Commissioning of the European XFEL", https://doi.org/10.18429/JACoW-IPAC2017-MOXAA1

Motivation

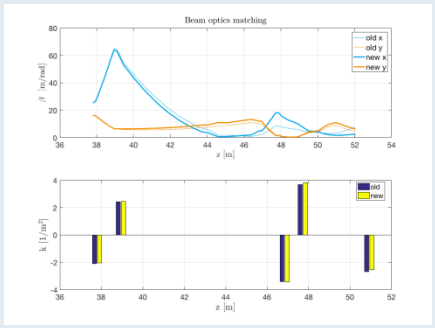
- Modern Free Electron Lasers are complex facilities with hundreds of free tuning parameters
  - Bunch compression, orbit, beam optics, gun optimization, undulator gaps, phase-shifters, etc
- Even when the main accelerator systems work well, manual fine-tuning is necessary to get the best performance and this is time expensive

Zoo of High Level Control tools

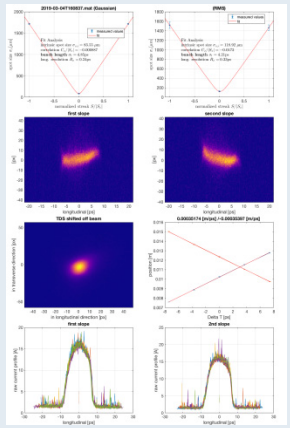
Beam Based Alignment



Beam matching

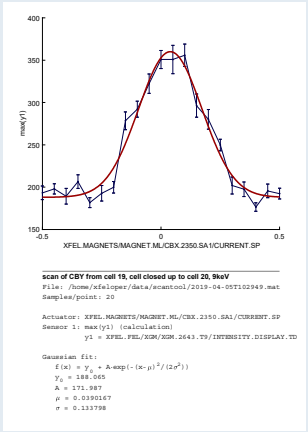


Longitudinal profile measurement



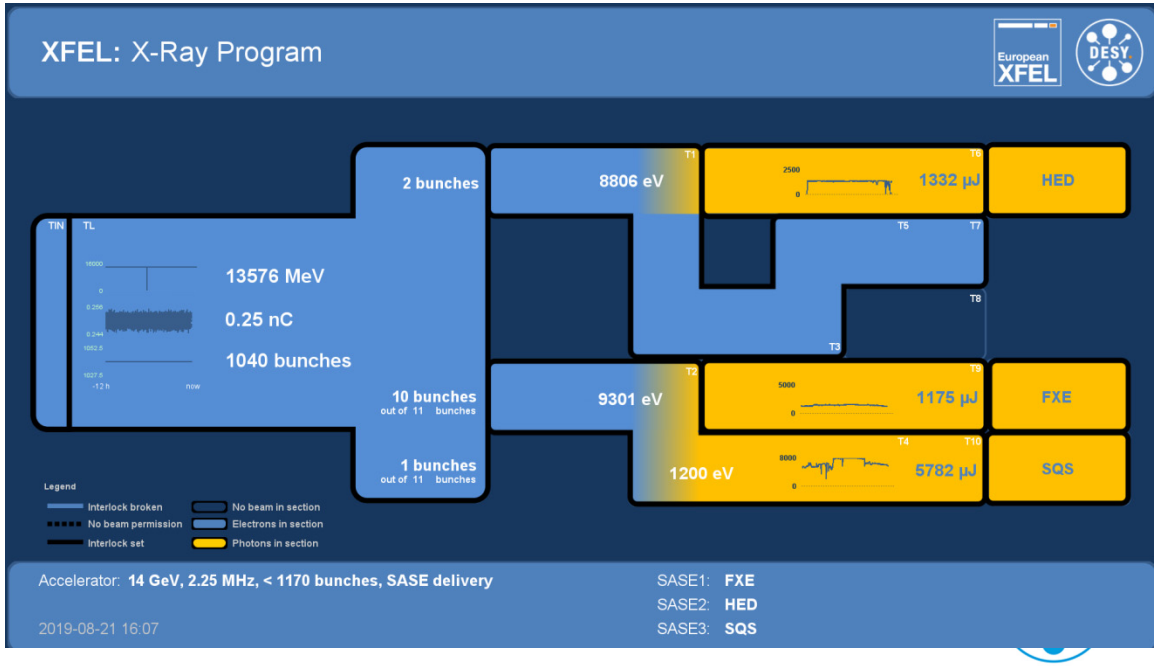
Orbit correction

Scan tool



Motivation

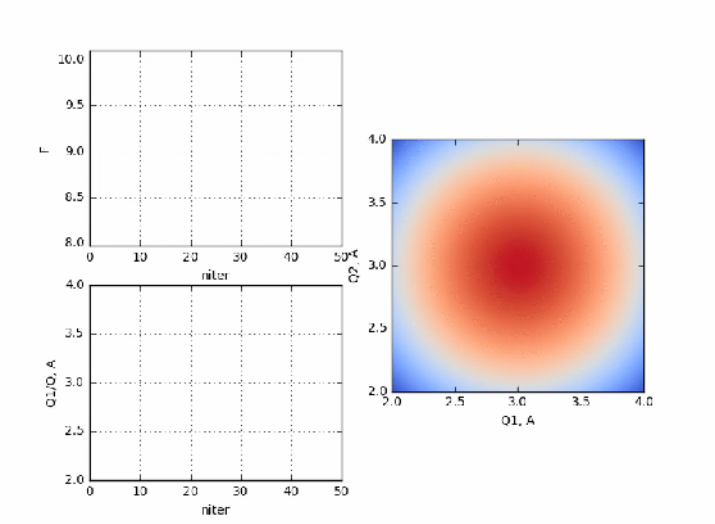
- Multi-user operation puts additional requirements on the photon beam quality and additional pressure to deliver more user beam-time
- More automation of the tuning procedures is needed
- Model-free and model-dependent optimizations
- OCELOT project:
  - OCELOT Optimizer
  - OCELOT multiphysics simulation toolkit
    ► Includes: beam dynamics, photon field simulation, online beam control modules
  - everything in python
  - open source
  - https://github.com/ocelot-collab/



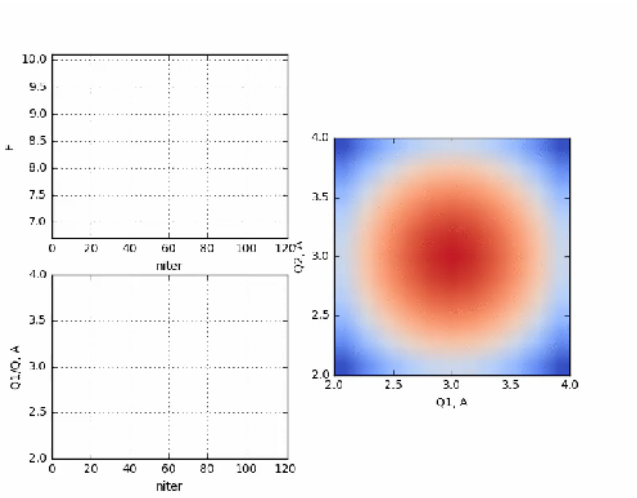
Model-free optimization

- Optimization algorithms are faster than scanning

2D scanning

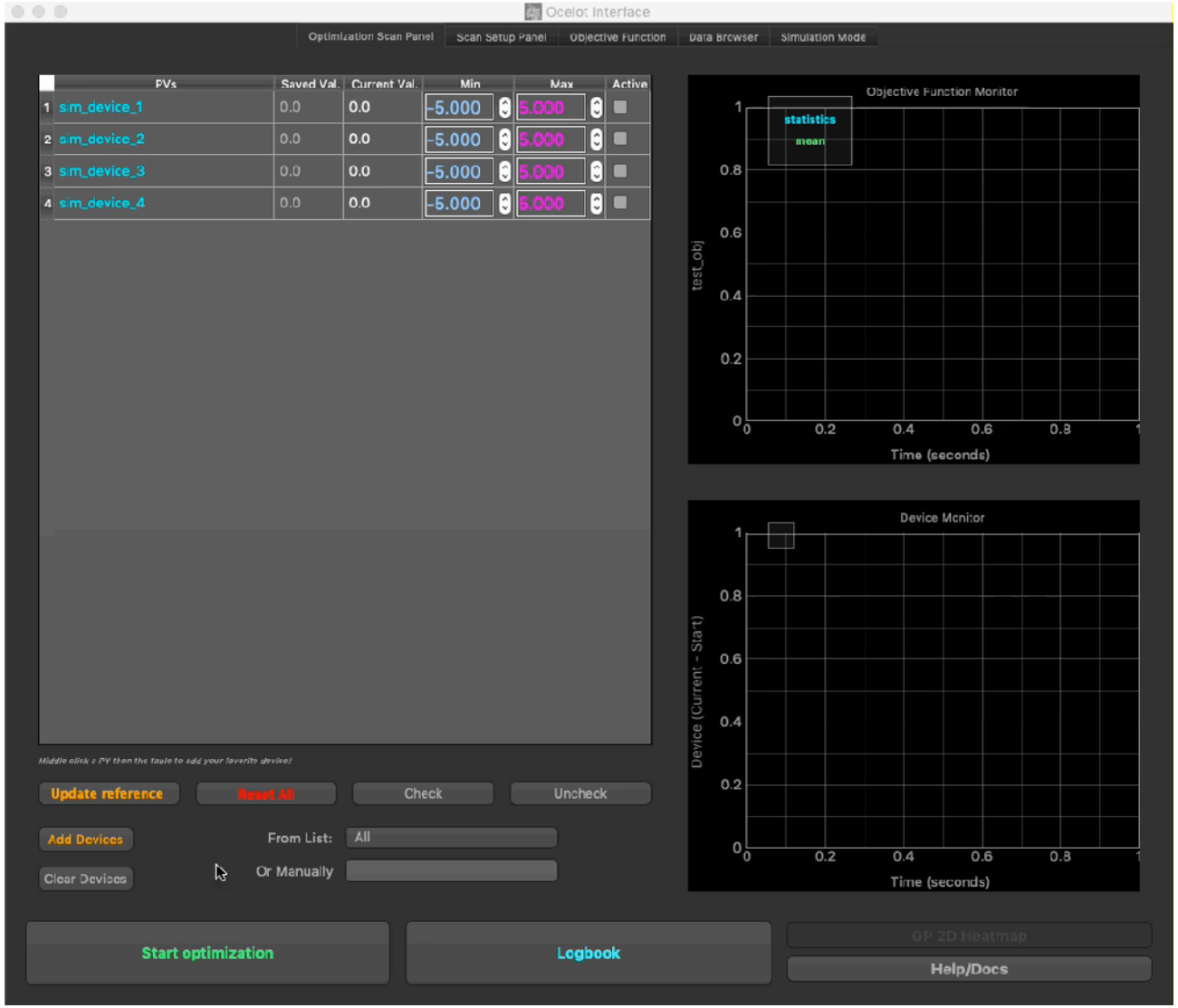


Optim. algorithm: Nelder-Mead



OCELOT Optimizer

- Optimization algorithms are faster than scanning
- OCELOT optimizer is a flexible platform for optimization:
  - Interchangeable optimization methods
  - GUI
    - ► Add/select device or group of devices
    - ► Craft/modify target function
  - Infrastructure for testing new methods
  - Save/load configs
  - Logging
- Collaboration DESY, EuXFEL, SLAC

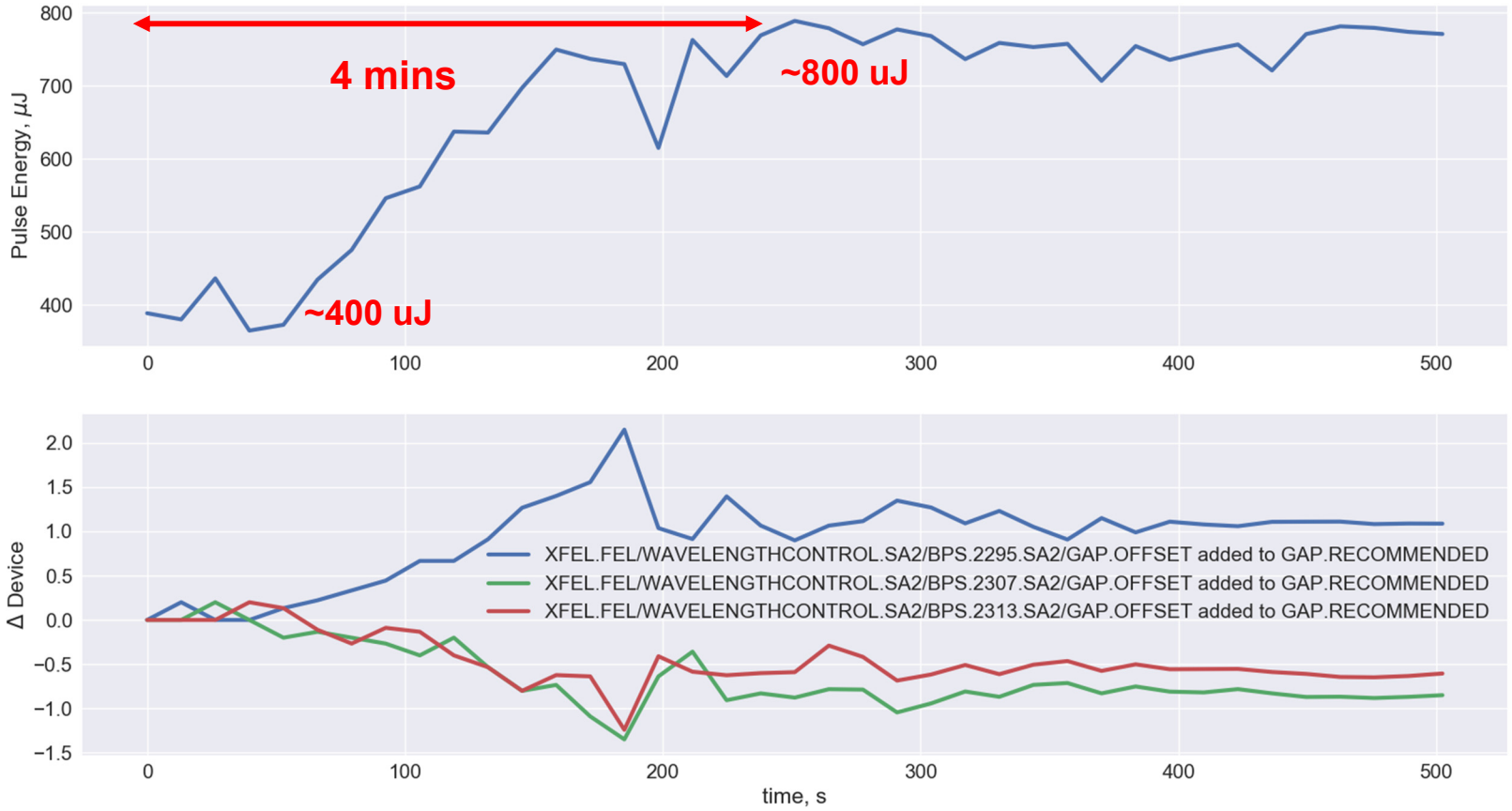


- *I. Agapov et al, arXiv:1704.02335*
- *S. Tomin et al, https://doi.org/10.18429/JACoW-IPAC2017-WEPAB031*
- *M.W. McIntire et al, DOI:10.18429/JACoW-IPAC2016-WEPOW055*

OCELOT Optimizer: Use cases

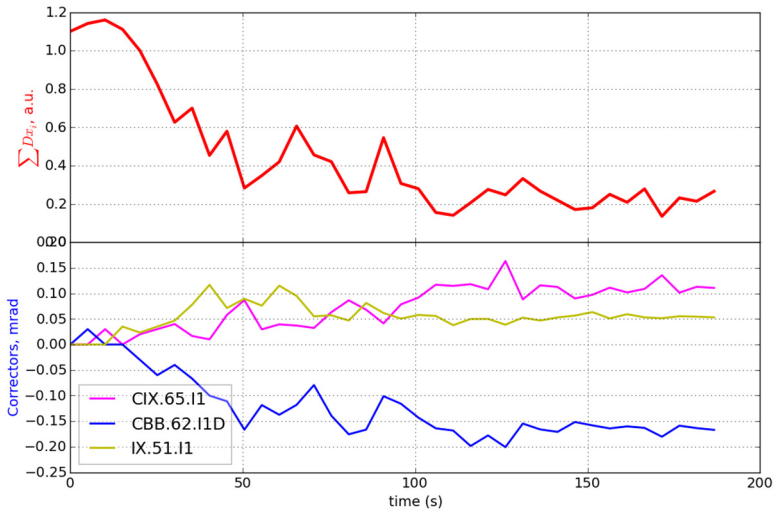
- European XFEL
  - FEL pulse energy maximization:
    - ► Orbit inside an undulator
    - ► Phase-shifters
    - ► Orbit in injector
    - ► Matching quads
    - ► RF settings

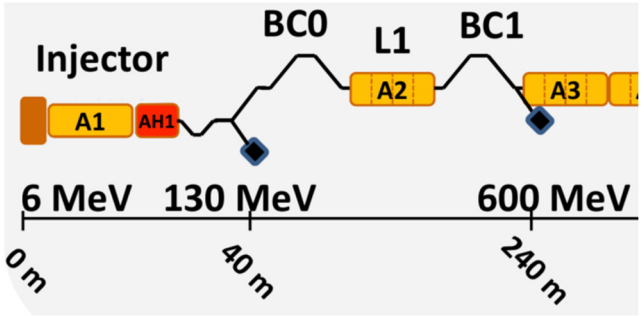
Phase-shifters



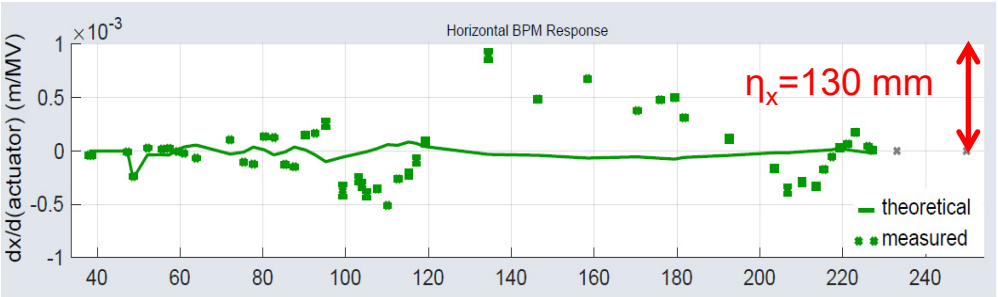
OCELOT Optimizer: Use cases

- European XFEL
  - FEL pulse energy maximization:
    - ► Orbit inside an undulator
    - ► Phase-shifters
    - ► Orbit in injector
    - ► Matching quads
    - ► RF settings
  - Local dispersion correction in injector

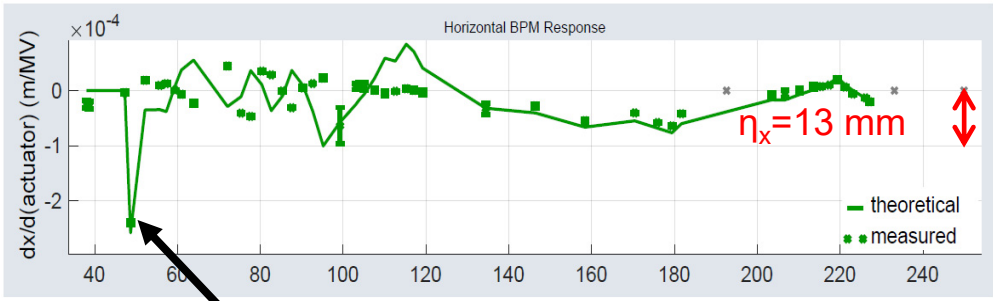




Before correction

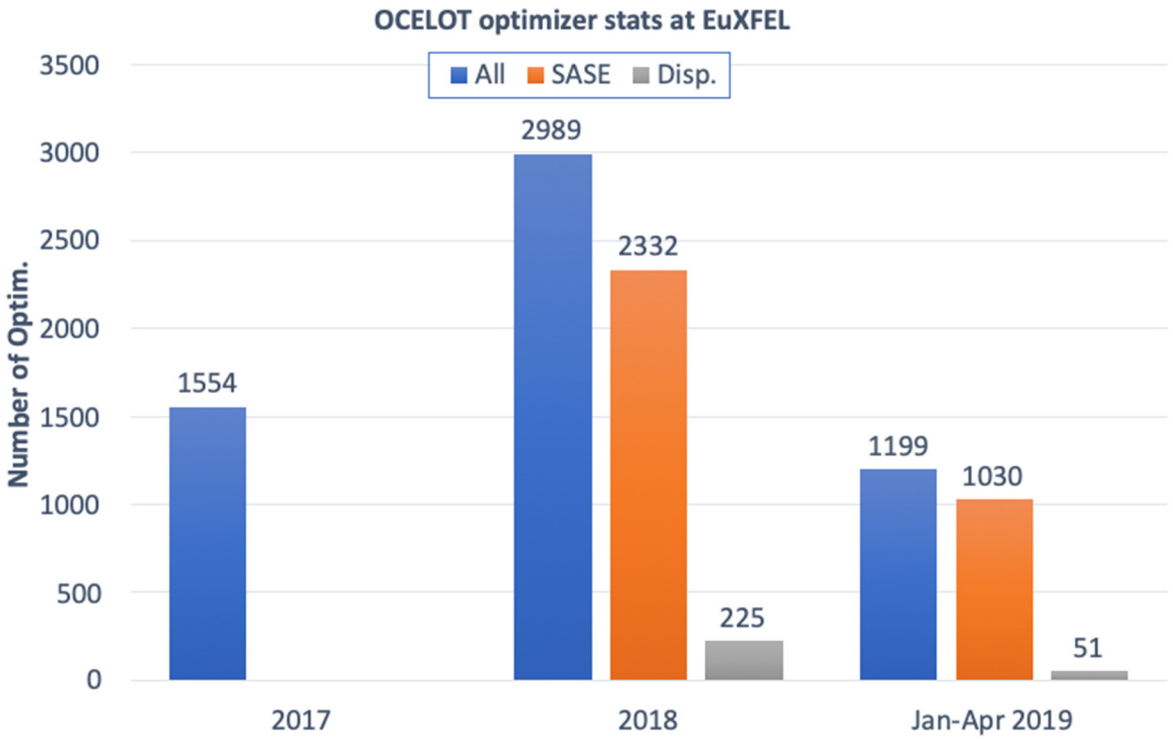


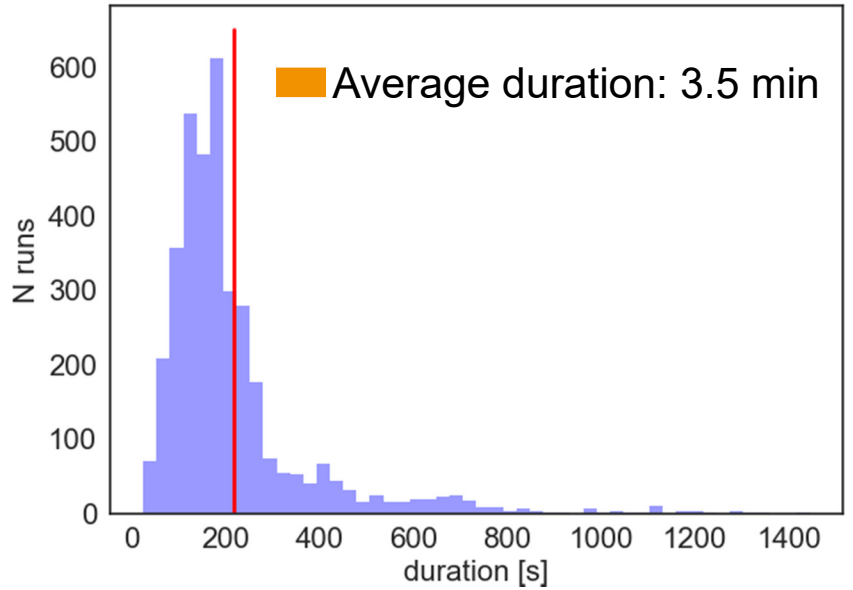
After correction

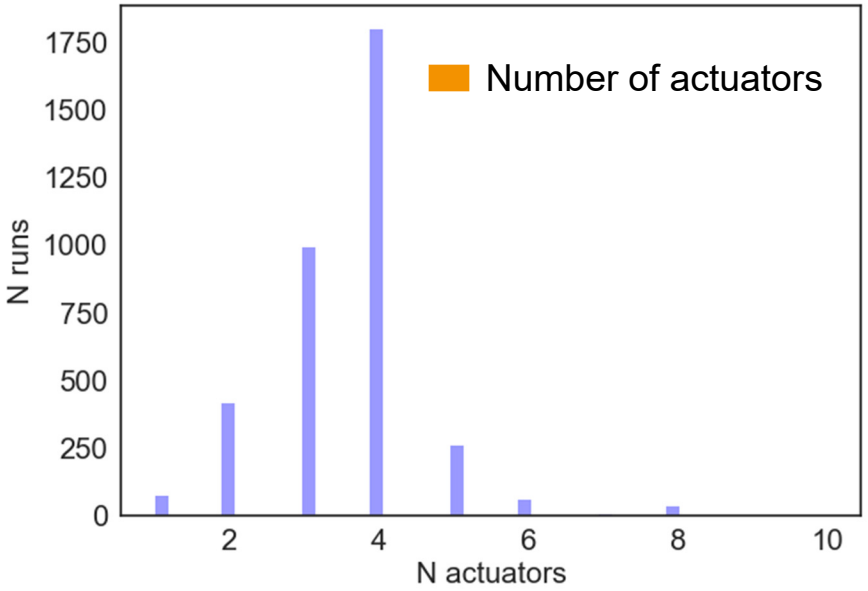


Laser Heater chicane

OCELOT Optimizer: Statistics







In most optimizations 4 devices are used and the average time duration of a single optimization is 3.5 minutes

OCELOT Optimizer: Statistics

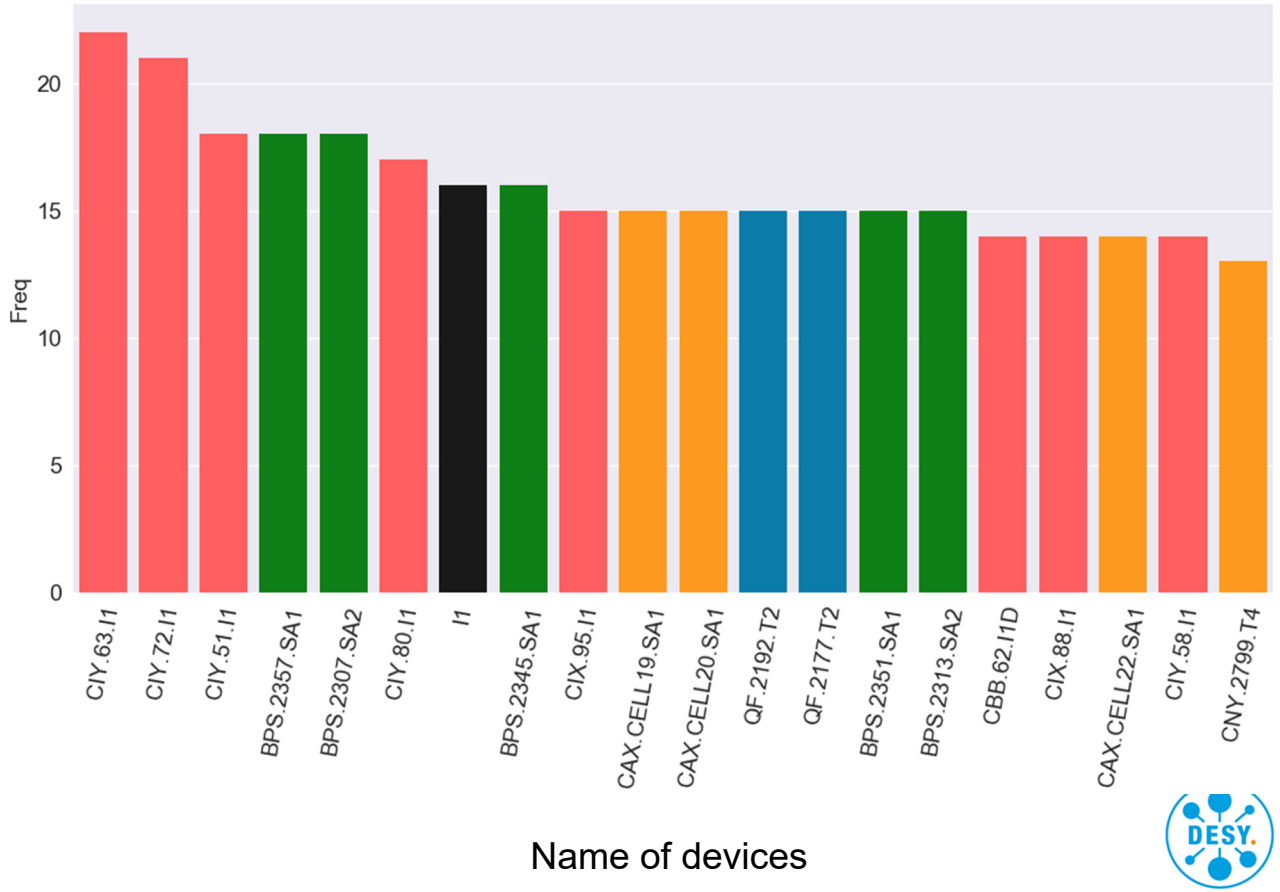
Percentage of “effective” optimization runs

Period	$\frac{\Delta S}{S_0} > 10\%$
Dispersion local minimization	
Statistics for 16 months	62%
FEL pulse energy maximization	
Statistics for 16 months	18%

- Number of unique devices used for optimization
  - FEL optimization: 446 unique devices
  - Dispersion: 28
- Can we identify effective devices for a particular optimization?
- Are hyperparameters of optimization methods optimally adjusted?
- More automation to speed up FEL tuning?

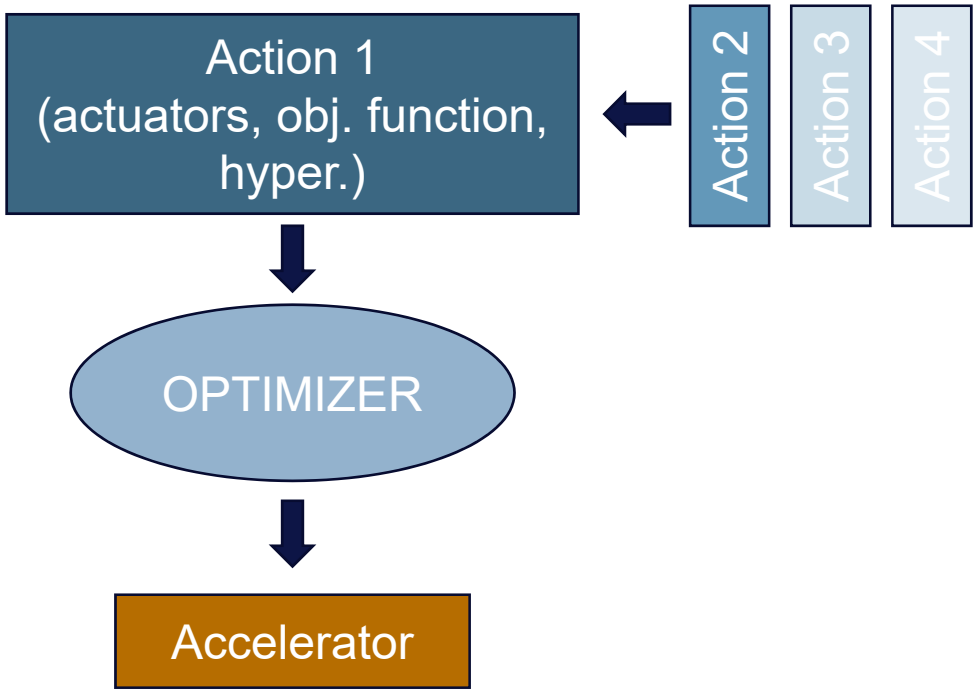
OCELOT Optimizer: FEL optimization. Identifying stricter constraints

- Chart of devices are used in “effective” optimization runs
  - Injector orbit tuning
  - Undulator phase shifters
  - Orbit in undulator
  - Injector energy chirp
  - Undulator matching quads
- In “effective” optimization runs were used 349 unique devices
- More automation. Sequence of optimizations

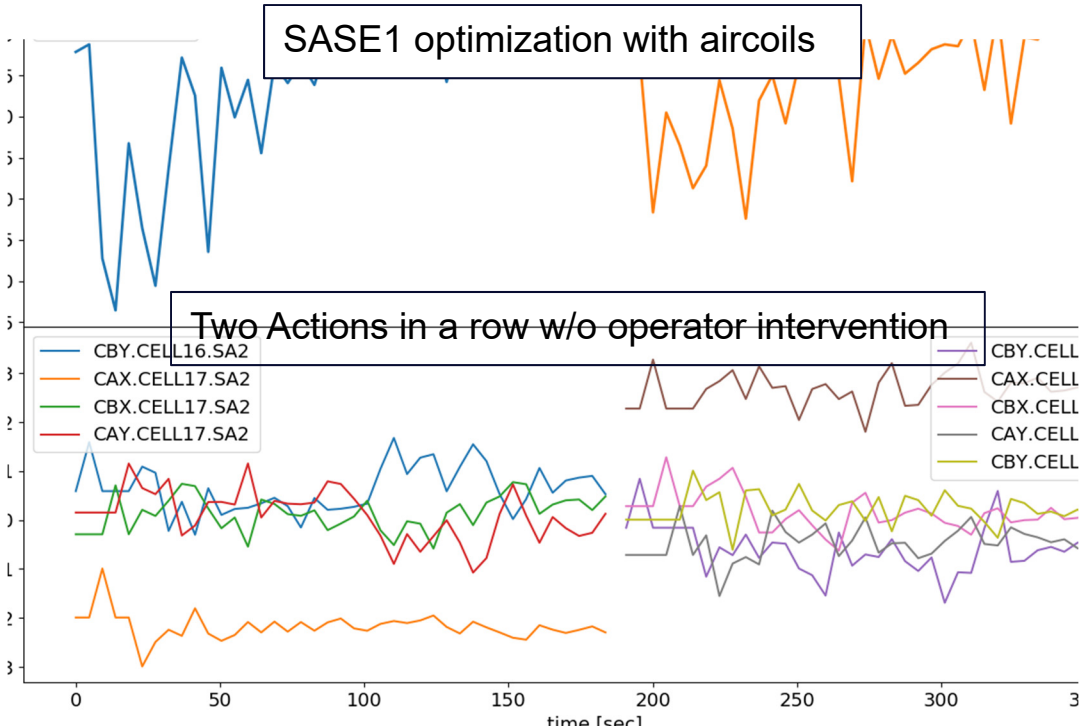


Sequence of optimizations: automatic optimization

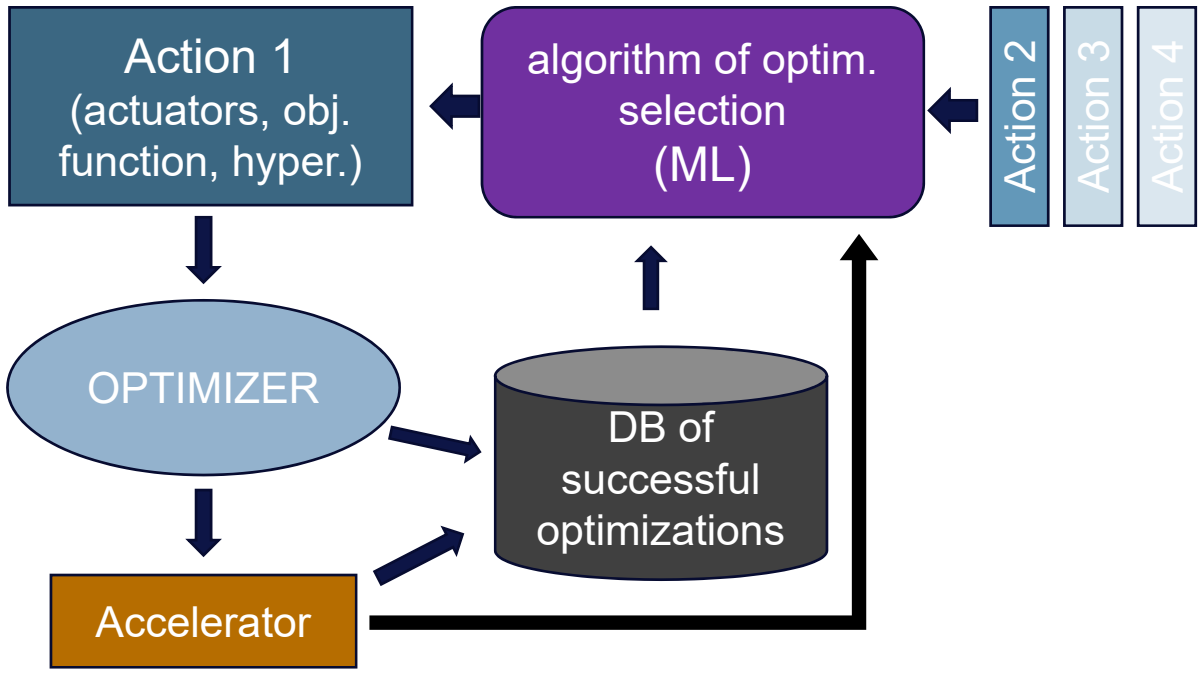
- Optimization with small number of actuators (4-6) is more efficient than with many due to noise and slow drifts



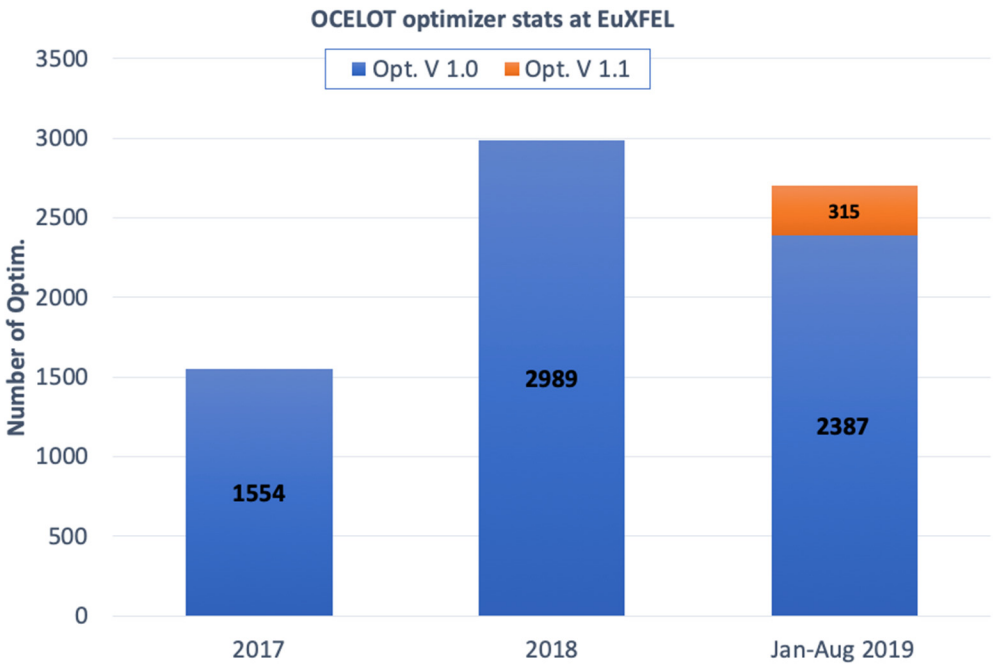
- New version (v1.1) was deployed
- Predefined sequence of optimization
  - without operator intervention
  - Optimizer monitors machine state – paused optimization if necessary.



Sequence of optimizations: even more automation with ML?



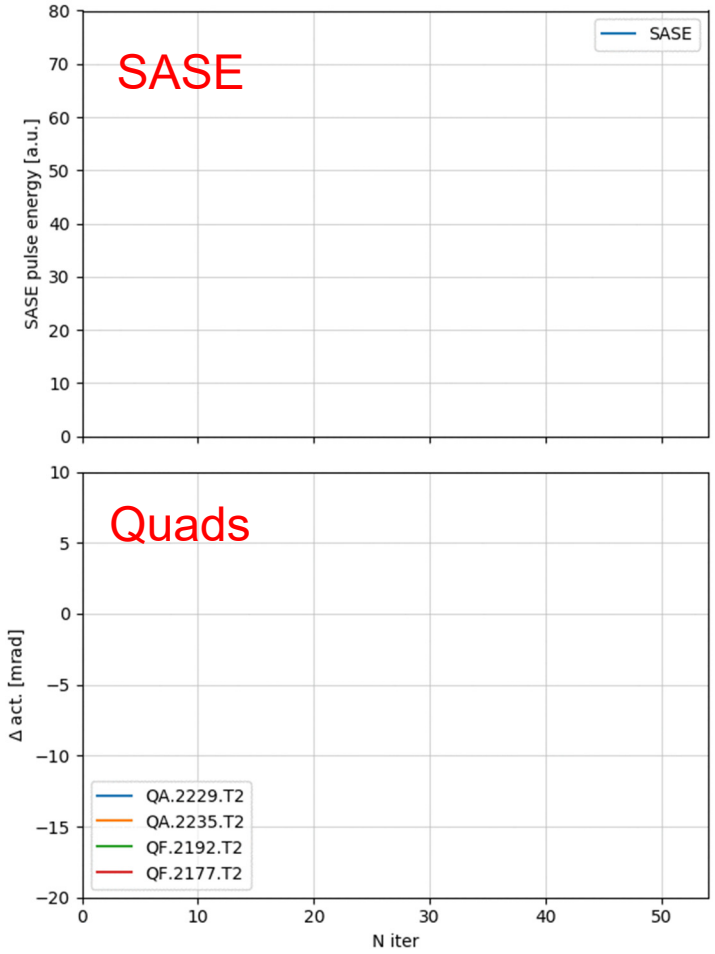
More logged DOOCS channels about machine state



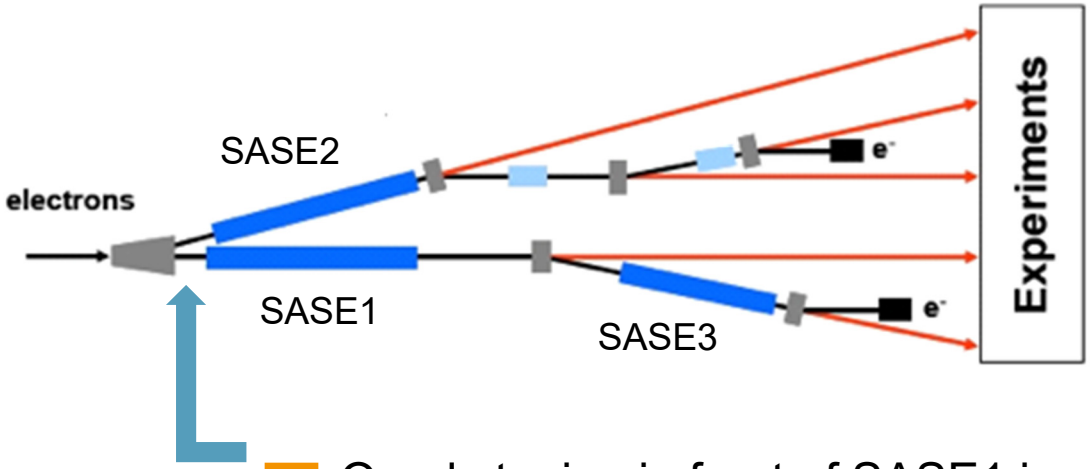
I. Agapov, G. Geloni, S. Tomin, I. Zagorodnov. arXiv:1704.02335, 2017

Hyperparameters. Beam matching

SASE optimization with 4 quads



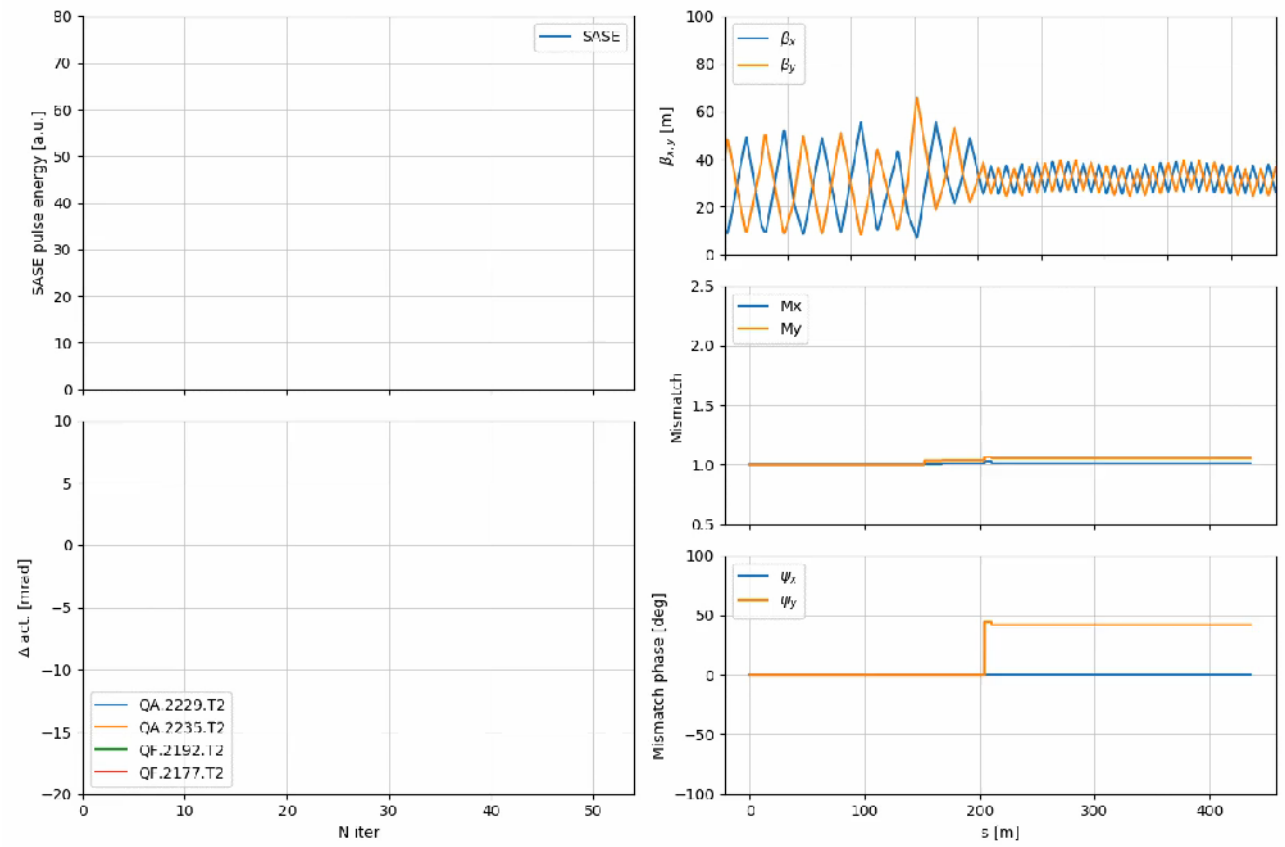
- Initial quad step
- Group of quads

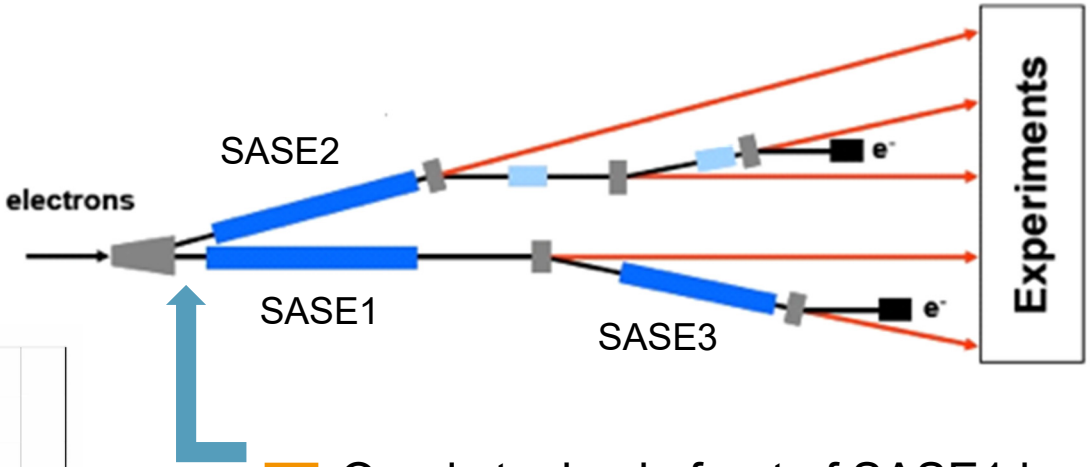


- Quads tuning in front of SASE1 is one of the steps of standard optimization procedure with Optimizer.
- Hyperparameters, such as initial steps, number of iterations, were corrected as experience increased.

Hyperparameters. Beam matching

SASE optimization with 4 quads





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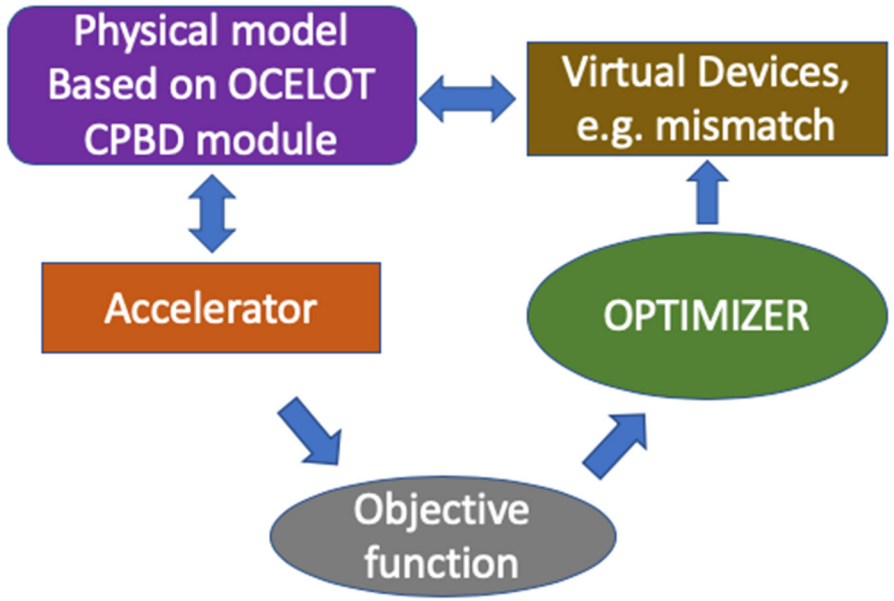
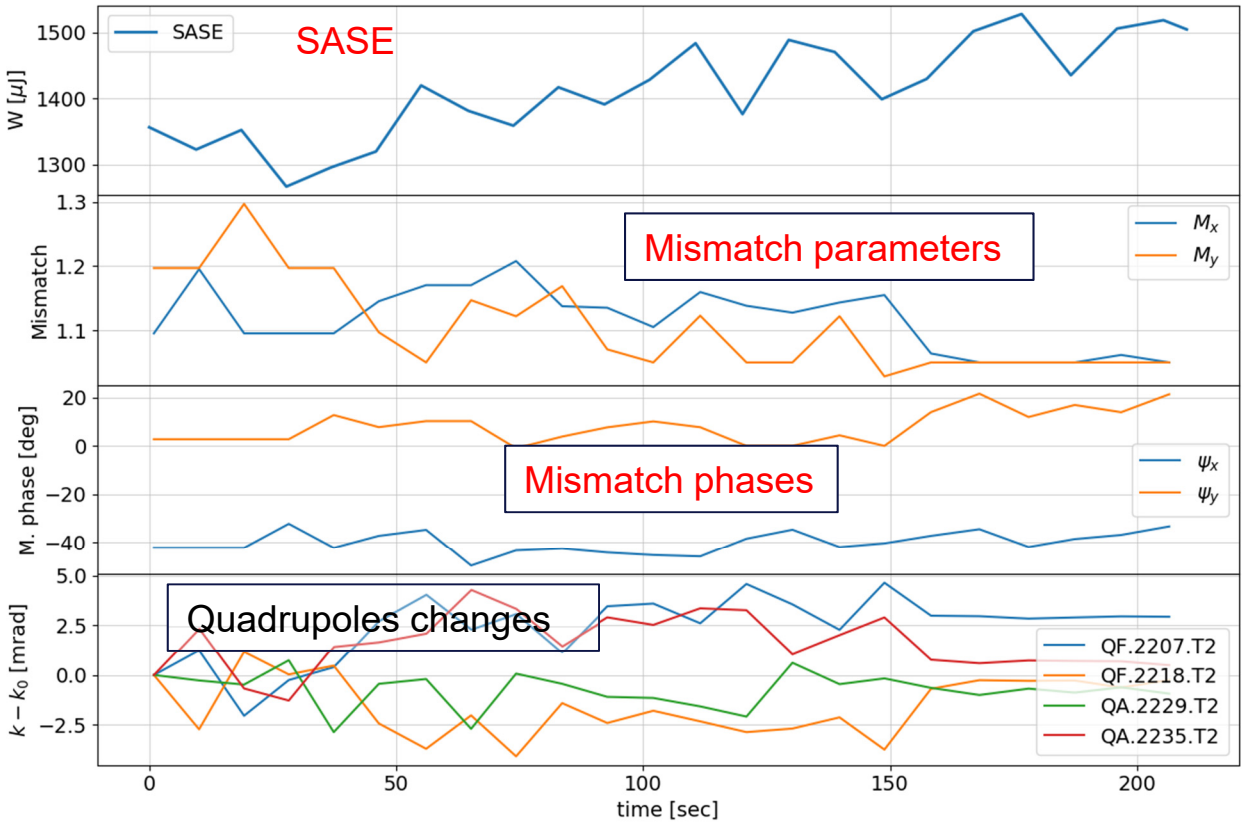
Beta mismatch parameter* optimization



- OCELOT beam dynamics module is already used for orbit correction
- Bounds and hyperparameters are defined
- Only 4 actuators are used while number of quads can be more - reduction of dimensionality in some cases

SASE pulse energy opt. 25 iterations



* M. Sands, SLAC-AP-85 1991

Model-dependent optimizations

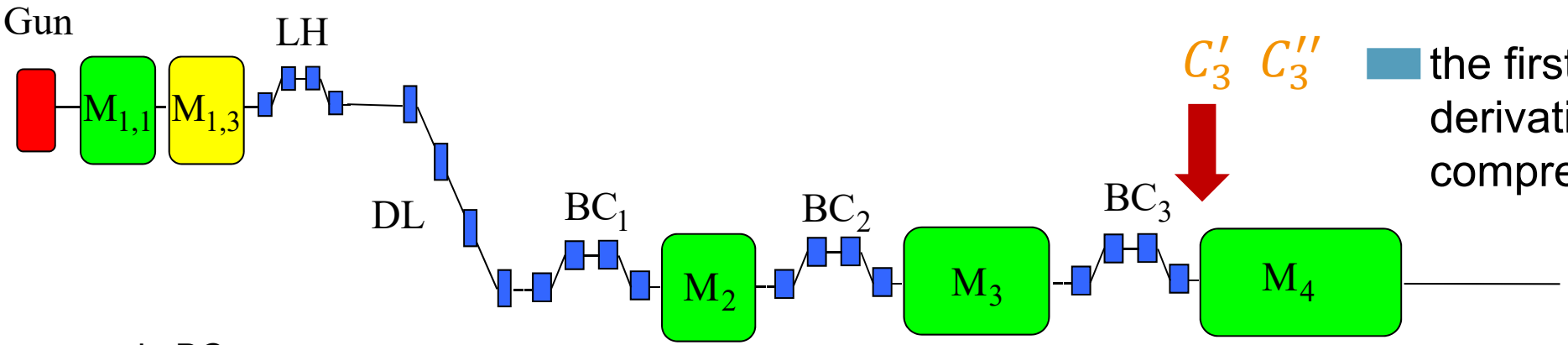
- Model-dependent optimizations use/construct a regression model which can predict result.
  - Mathematical/physical accelerator model
  - Model based on data analysis (statistic, ML)

- Compression scenarios optimization

- Adaptive orbit feedback

Bunch compression optimization

Working point (11 parameters of longitudinal beam dynamics)



- the first and the second derivatives of the global compression

- energy in BC:
- Deflection compaction factor:
- compression factor:

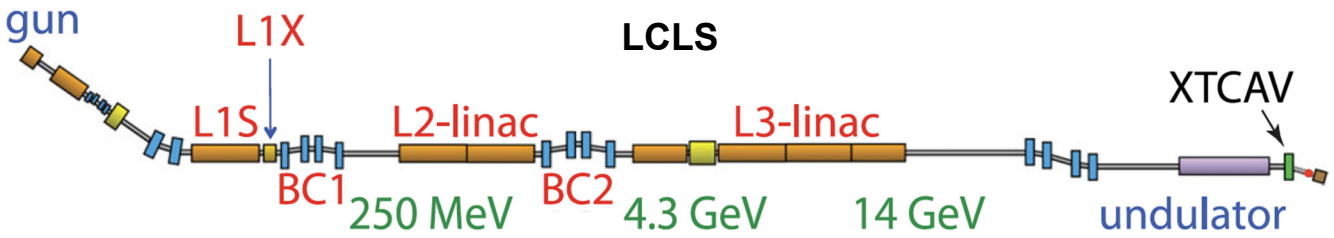
$E_1 = 130$ MeV
$R_{56}^1 = ?$
$C_1 = ?$

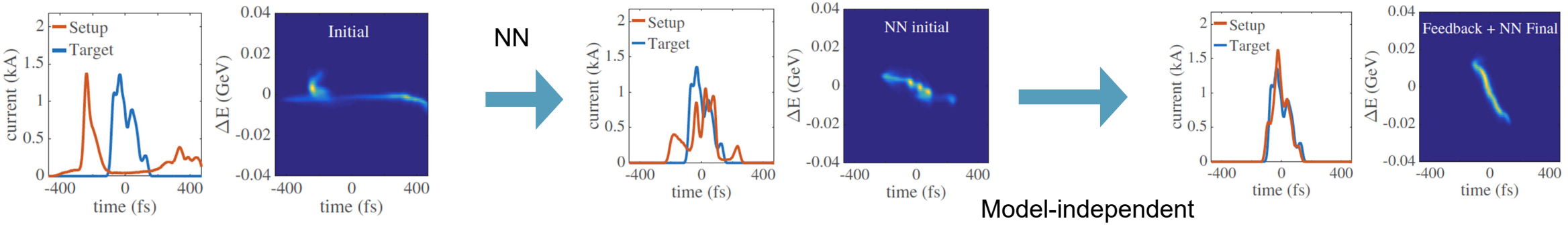
$E_2 = 700$ MeV
$R_{56}^2 = ?$
$C_2 = ?$

$E_3 = 2400$ MeV
$R_{56}^3 = ?$
$C_3 = I_{\text{final}}/I_{\text{gun}}$

- Set, control and recovering a working point

Model-independent and ML methods for control of longitudinal beam dynamics



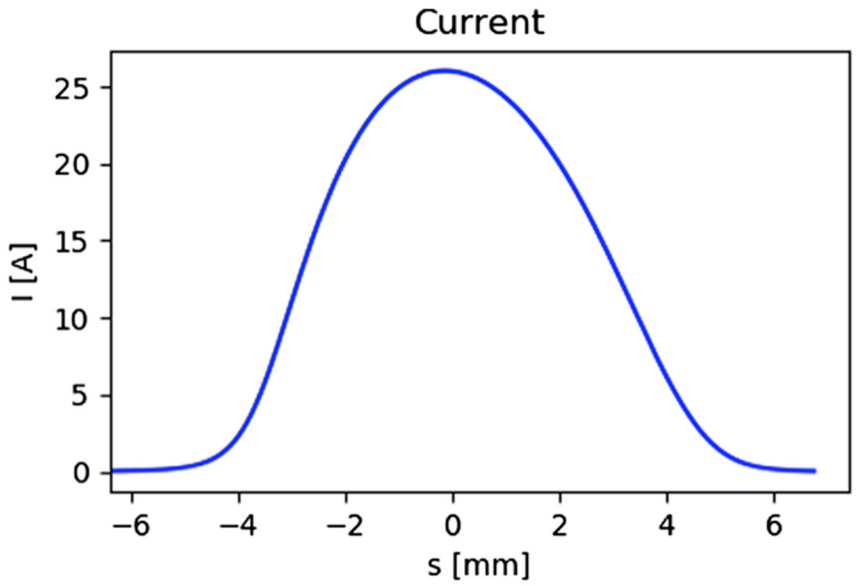


PHYSICAL REVIEW LETTERS **121,** 044801 (2018)

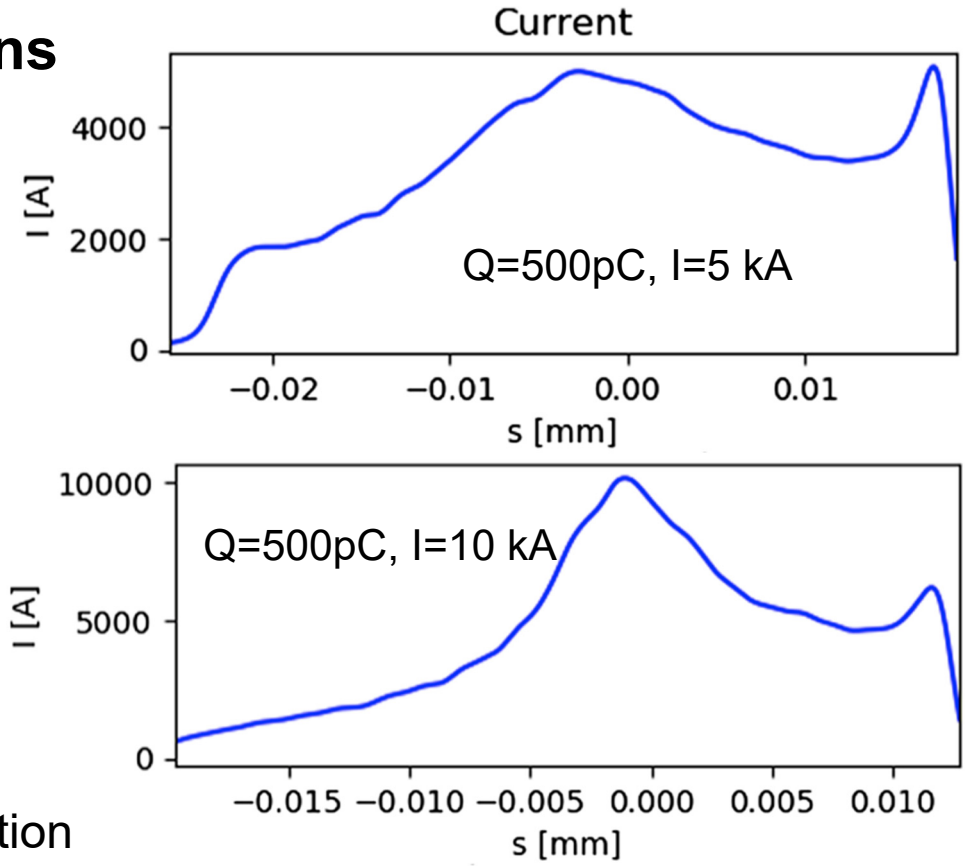
Demonstration of Model-Independent Control of the Longitudinal Phase Space of Electron Beams in the Linac-Coherent Light Source with Femtosecond Resolution

Alexander Scheinker,[1,*] Auralee Edelen,[2] Dorian Bohler,[2] Claudio Emma,[2] and Alberto Lutman[2]
[1]*Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545, USA*
[2]*SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA*

Model-dependent compression tuning. Simulations



5 – 10 iterations with CSR, SC, wakes



1. $f_{n-1} = A_x(x_{n-1})$
2. $\Delta f_{n-1} = f_0 - f_{n-1}$
3. $g_n = g_{n-1} + \Delta f_{n-1},$
4. $x_n = A_0^{-1}(g_n)$

$f = A_x(x)$ non-linear transformation of the RF parameters (x) to compression parameters (f)

I. Zagorodnov and M. Dohlus, Phys. Rev. ST Accel. Beams 14, 014403 (2011).

I. Zagorodnov, M. Dohlus, and S. Tomin, Phys. Rev. Accel. Beams 22, 024401, 2019.

Adaptive Feedback

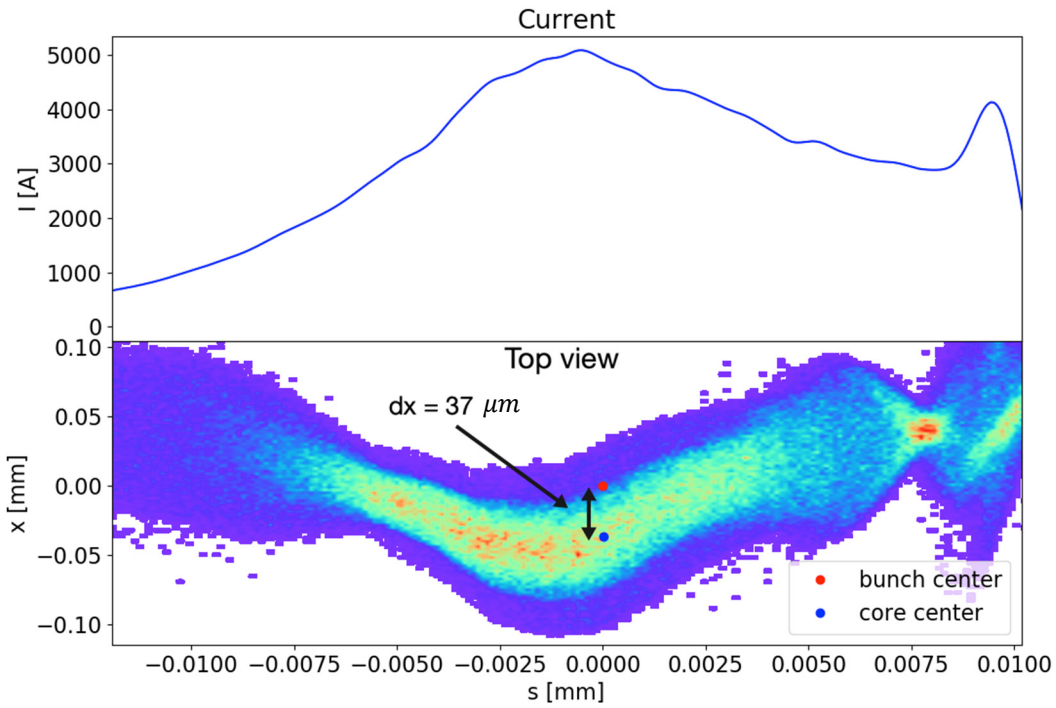
- The "Adaptive Feedback" is a statistical optimizer exploiting the orbit jitter and its correlation with a fast FEL intensity signal (shot-to-shot resolution) to optimize the undulator launch orbit

G. Gaio, M. Lonza, Automatic FEL Optimization at FERMI, Proc. of ICALEPCS2015

Adaptive Feedback

- The "Adaptive Feedback" is a statistical optimizer exploiting the orbit jitter and its correlation with a fast FEL intensity signal (shot-to-shot resolution) to optimize the undulator launch orbit
- Correcting the orbit to zero BPM positions does not always mean a straight line for lasing slice

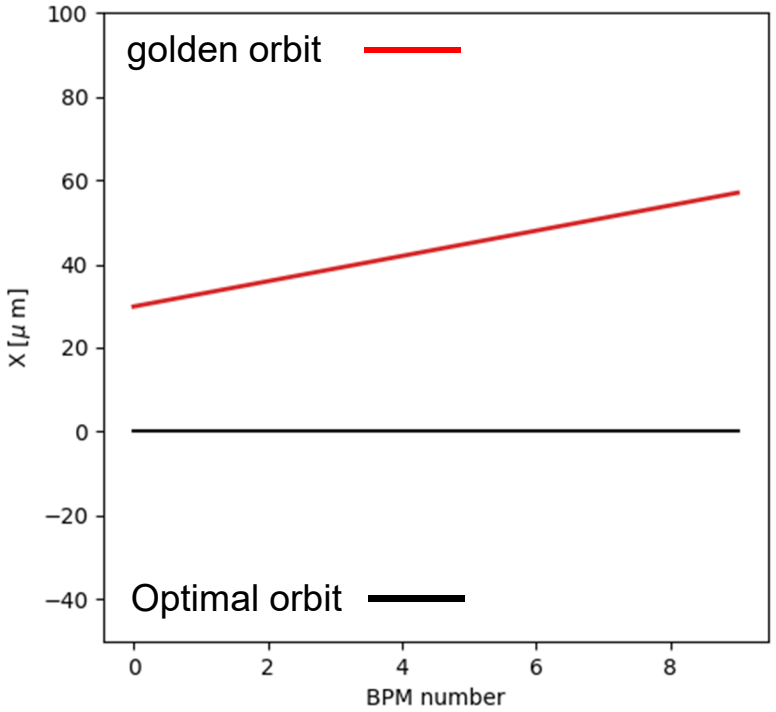
Current and top view of the electron beam (250 pC, 17.5 GeV) in front of SASE2 undulator. Simulation result



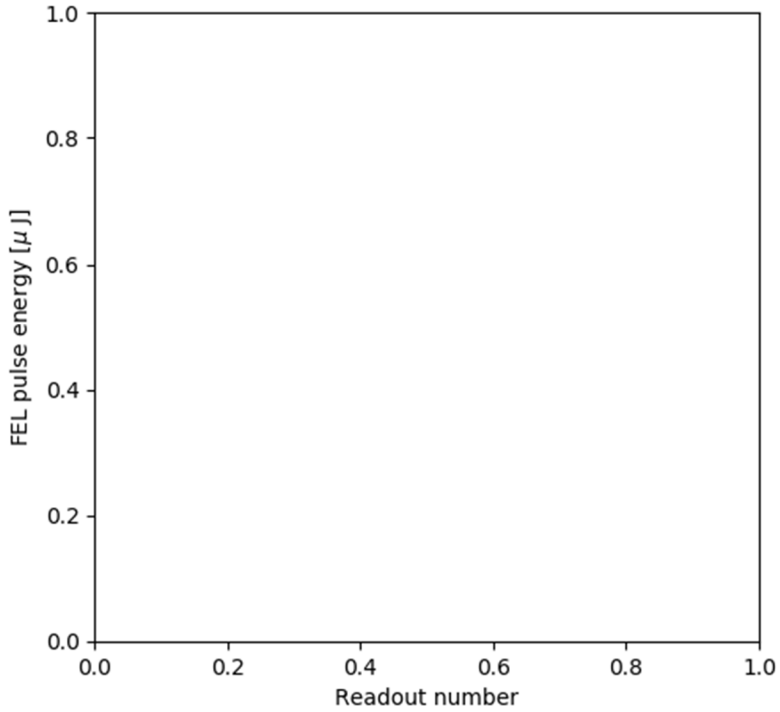
M. Dohlus, S. Tomin, and I.Zagorodnov, "Beam Dynamics at the European XFEL up to SASE4/5", Workshop „Shaping the Future of the European XFEL: Options for the SASE4/5 Tunnels"

Adaptive Feedback: how it works

Horizontal orbit in undulator



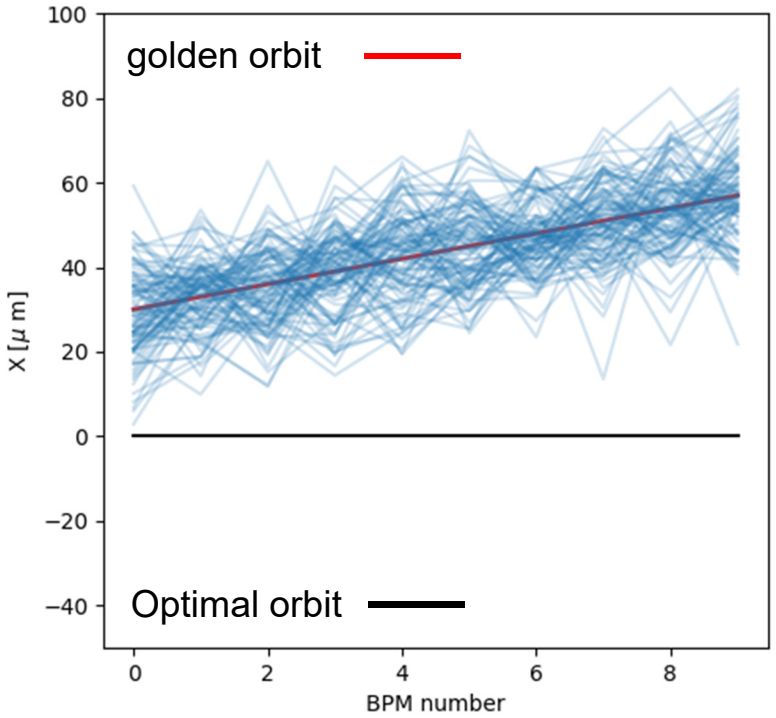
FEL pulse energy



Iteration #1

Adaptive Feedback: how it works

Horizontal orbit in undulator



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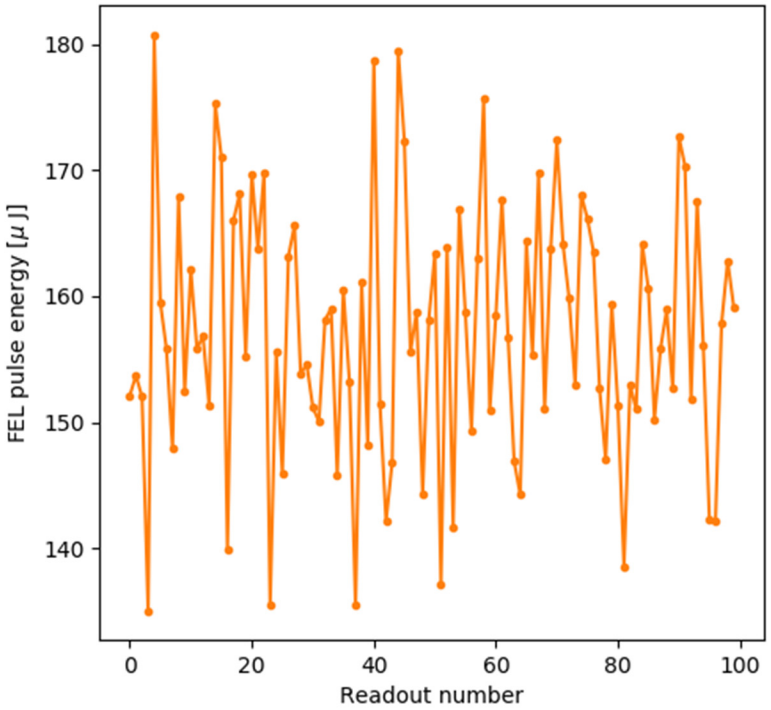

Iteration #1

Adaptive Feedback: how it works

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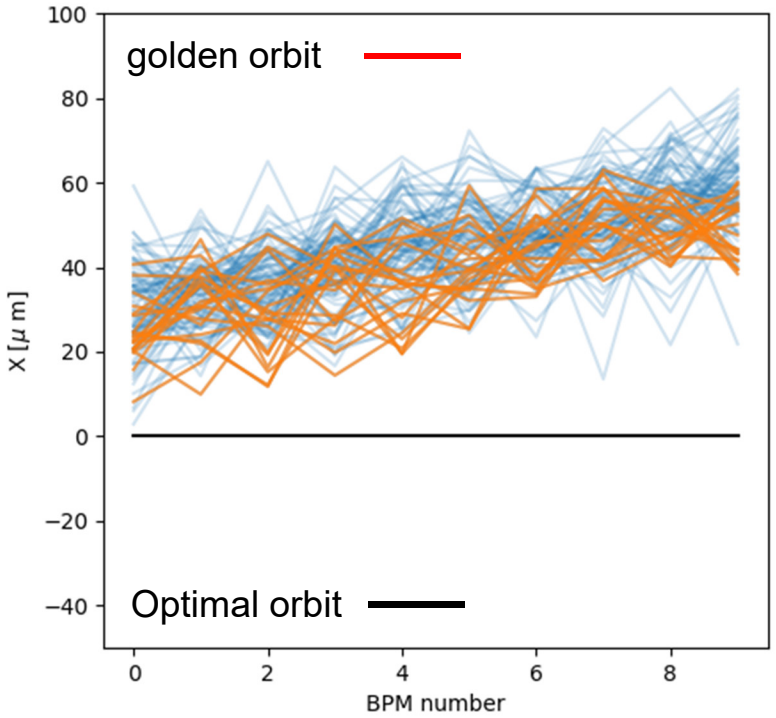
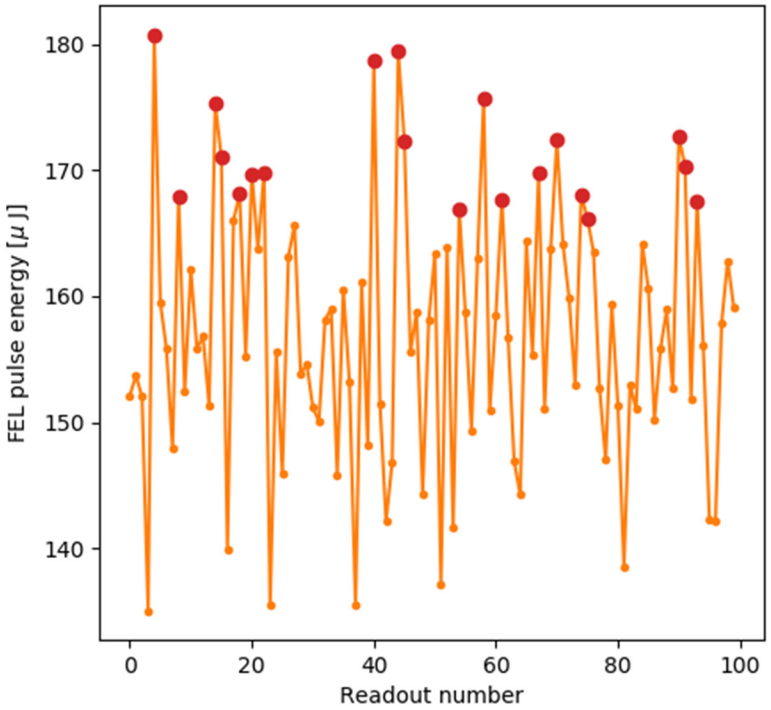


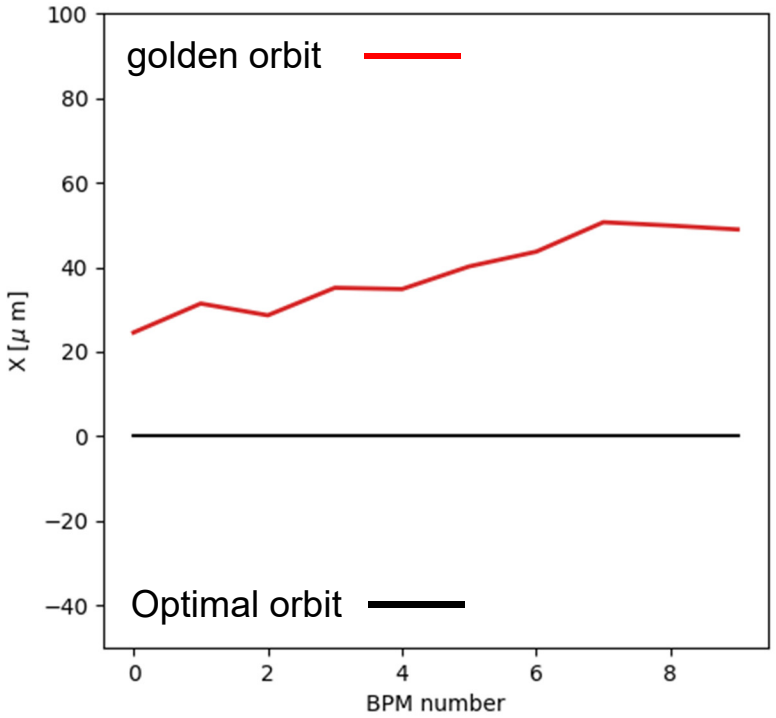
FEL pulse energy



Iteration #1

Adaptive Feedback: how it works

Horizontal orbit in undulator



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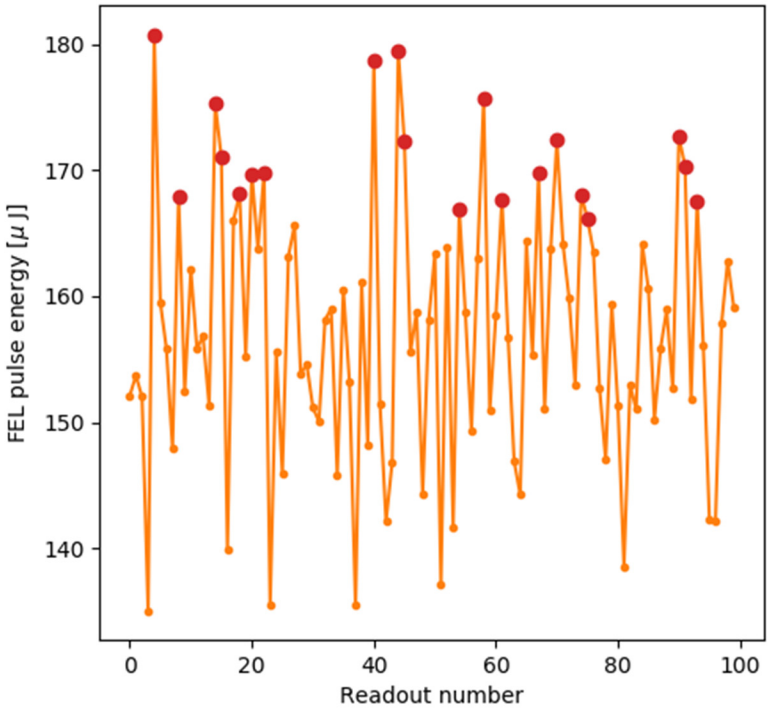

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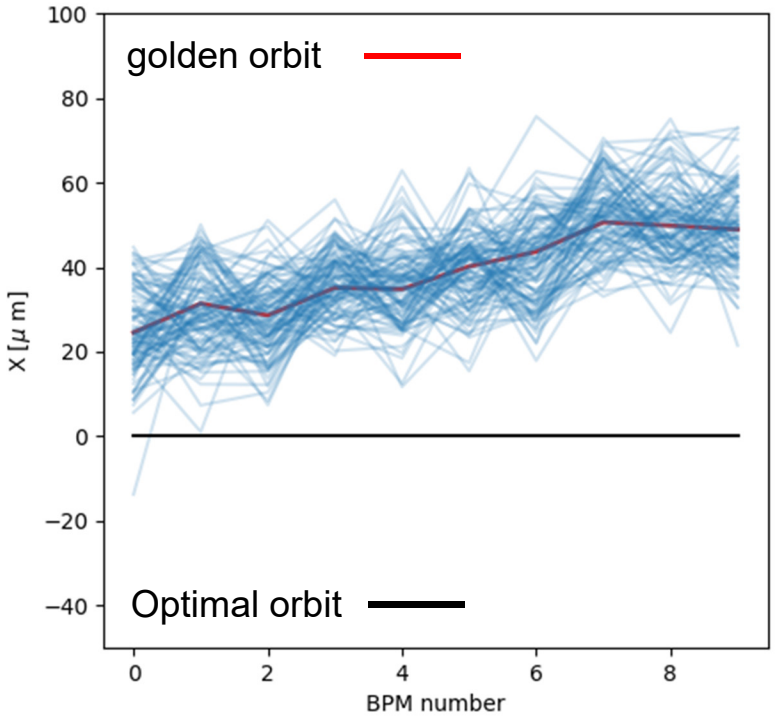
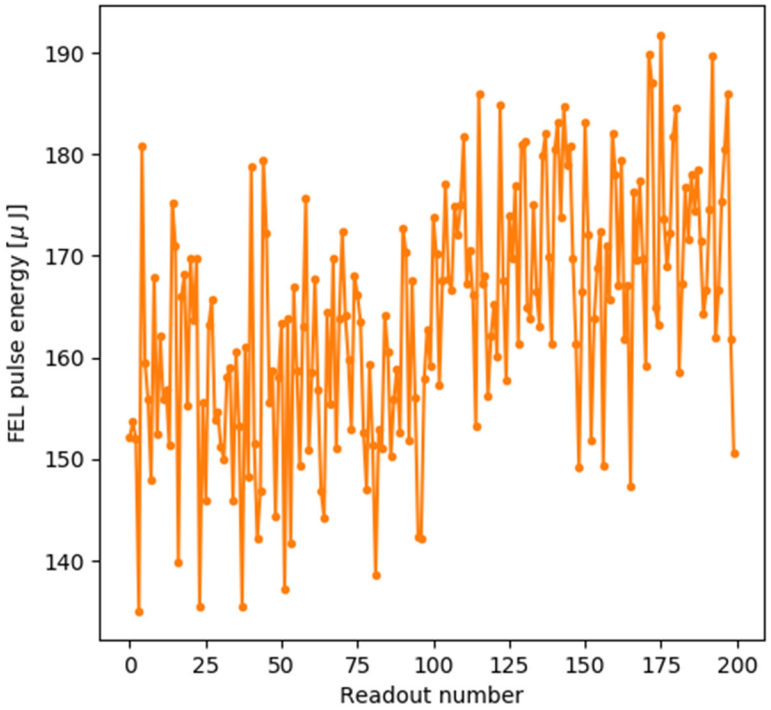


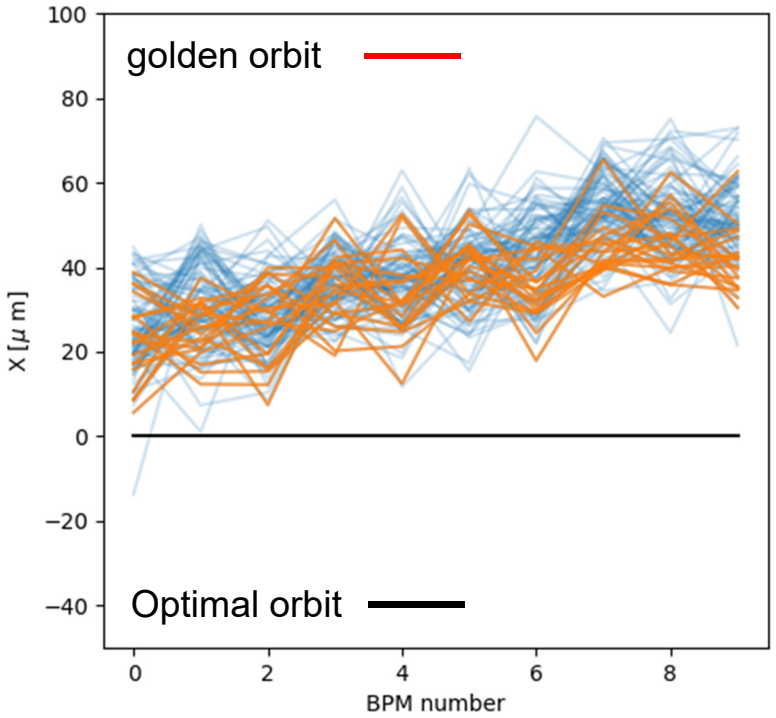
FEL pulse energy



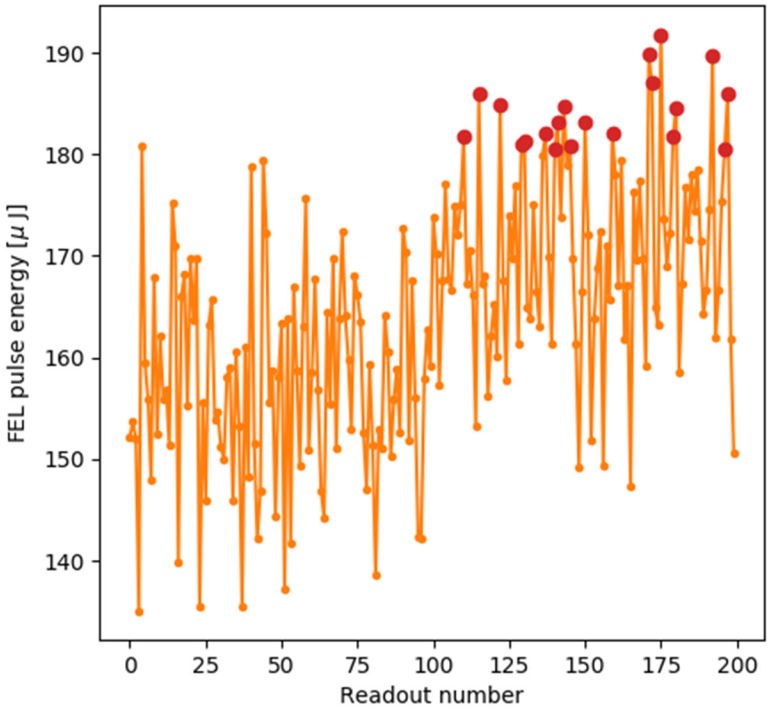
Iteration #2

Adaptive Feedback: how it works

Horizontal orbit in undulator



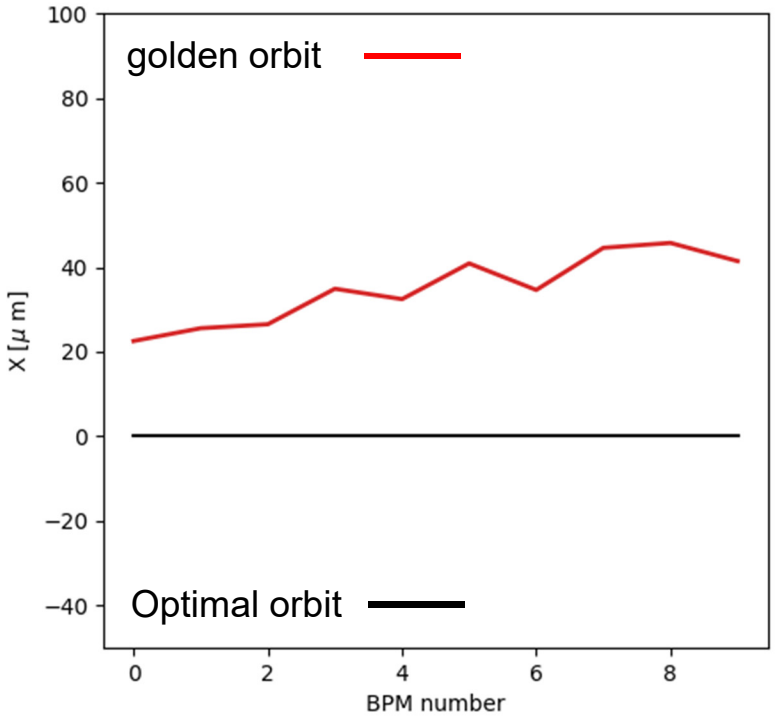
FEL pulse energy



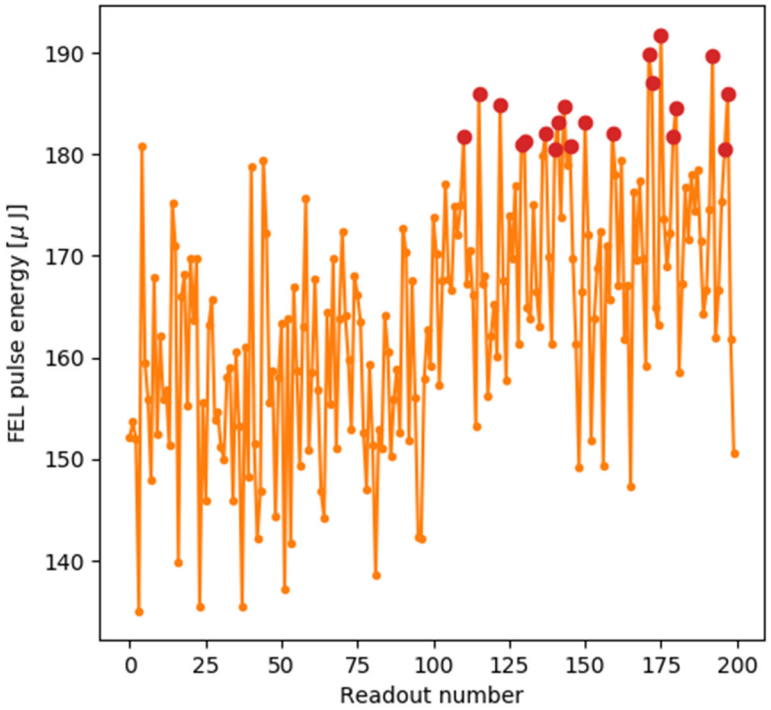
Iteration #2

Adaptive Feedback: how it works

Horizontal orbit in undulator



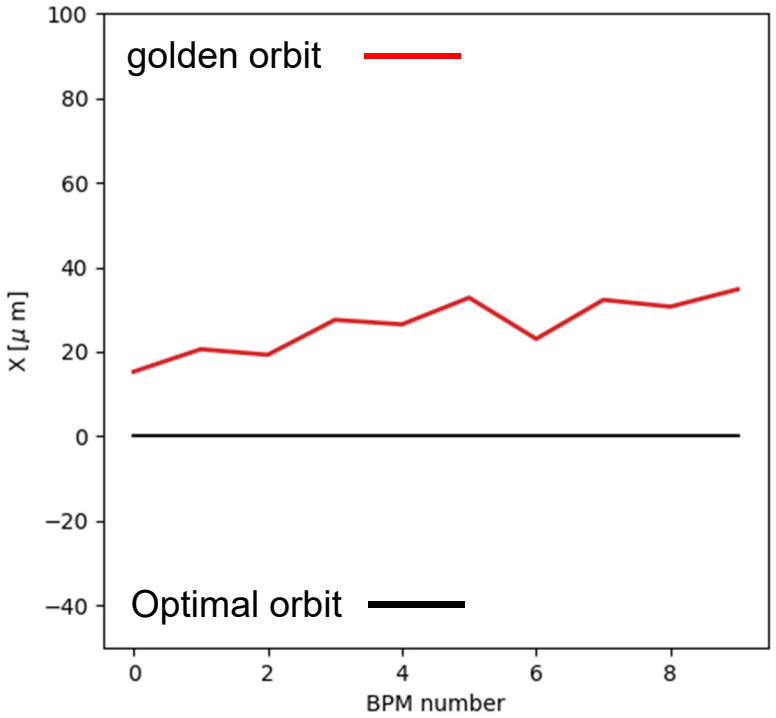
FEL pulse energy



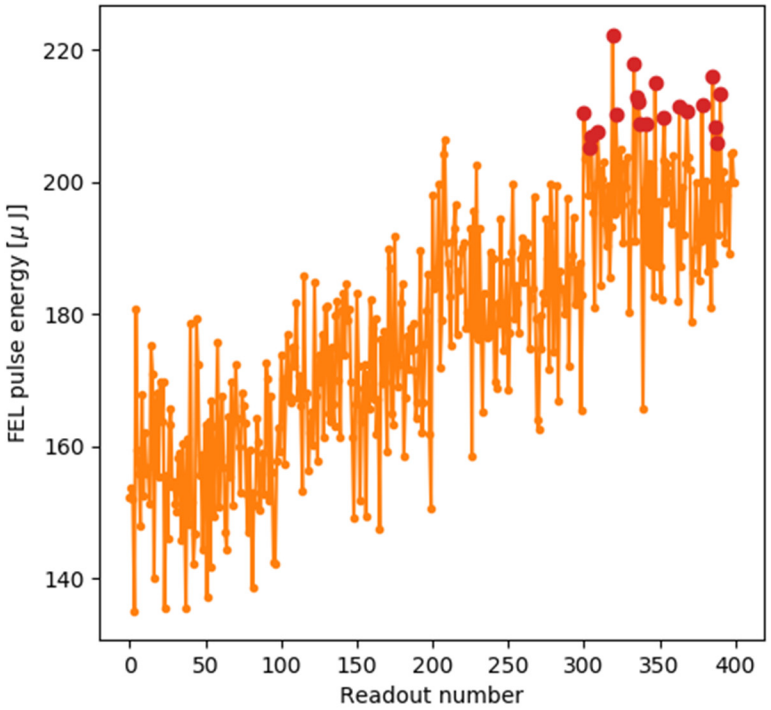
Iteration #2

Adaptive Feedback: how it works

Horizontal orbit in undulator



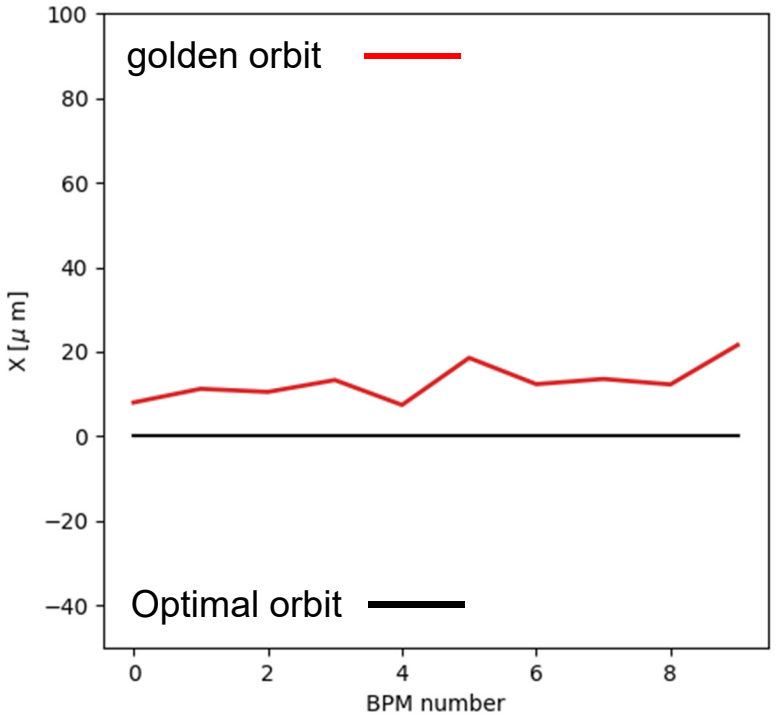
FEL pulse energy



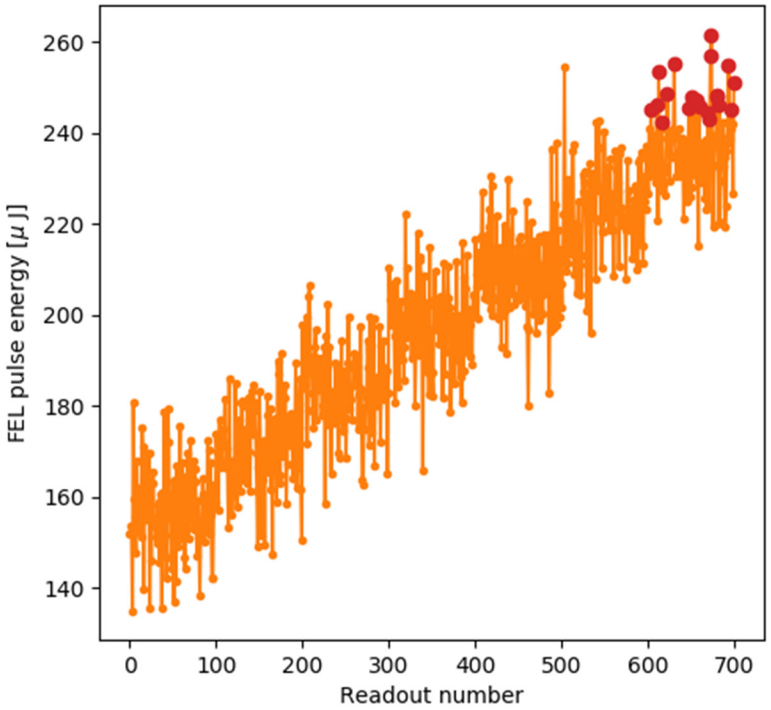
Iteration #4

Adaptive Feedback: how it works

Horizontal orbit in undulator



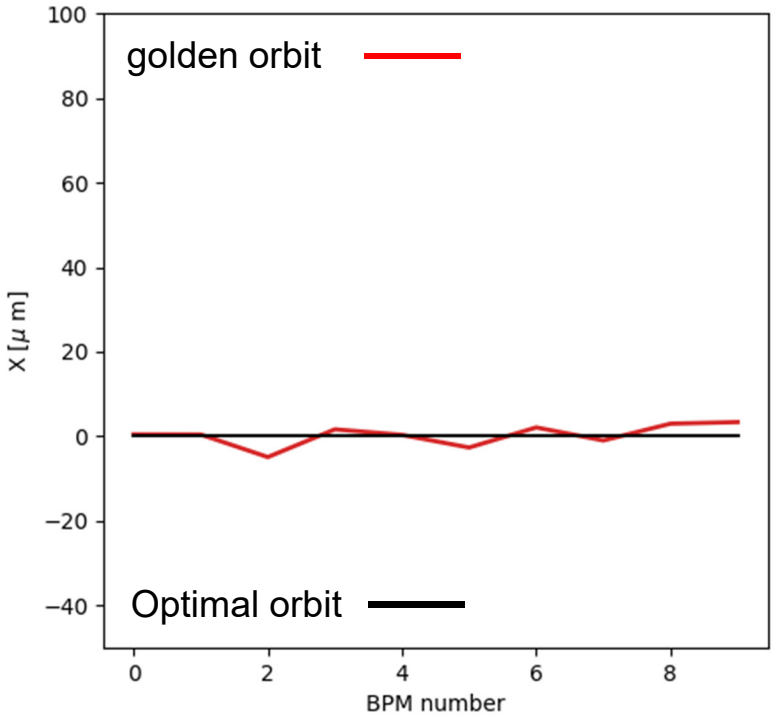
FEL pulse energy



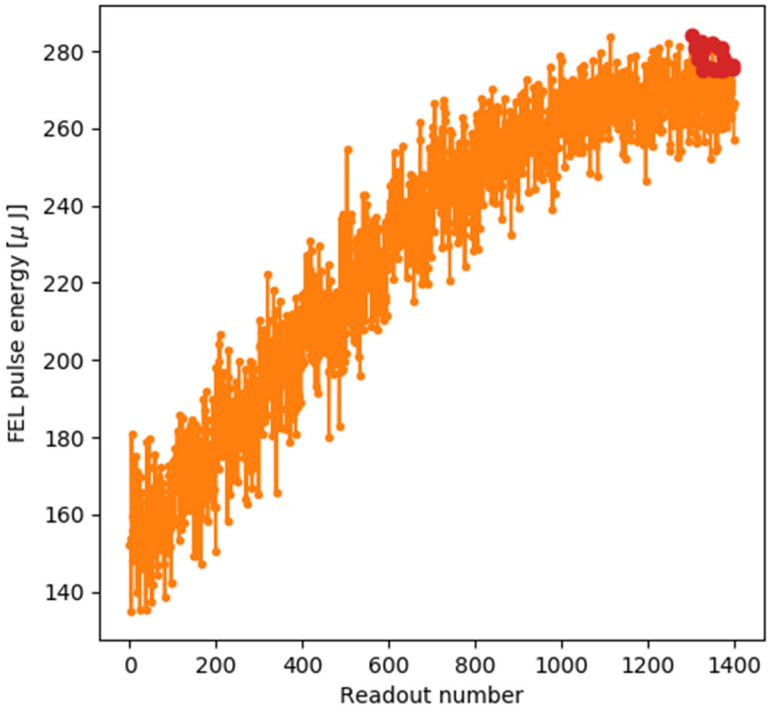
Iteration #7

Adaptive Feedback: how it works

Horizontal orbit in undulator



FEL pulse energy



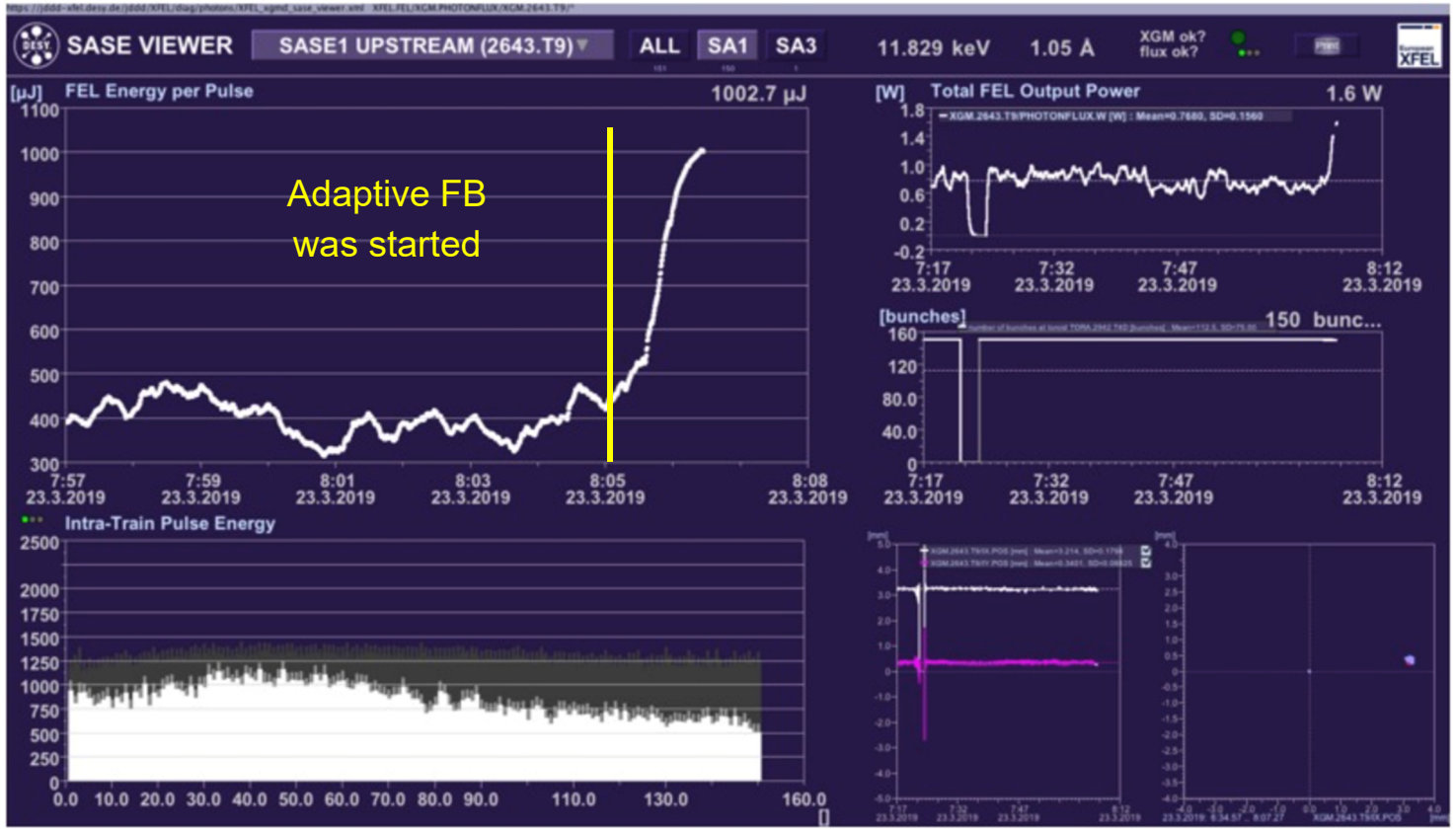
Iteration #14

Adaptive Feedback

Logbook entry: /XFELelog/data/2019/12/23.03_M

23.03.2019 08:06 **XFEL** mscholz, TIS, Artem **XFEL_xgmd_sase_viewer.xml**

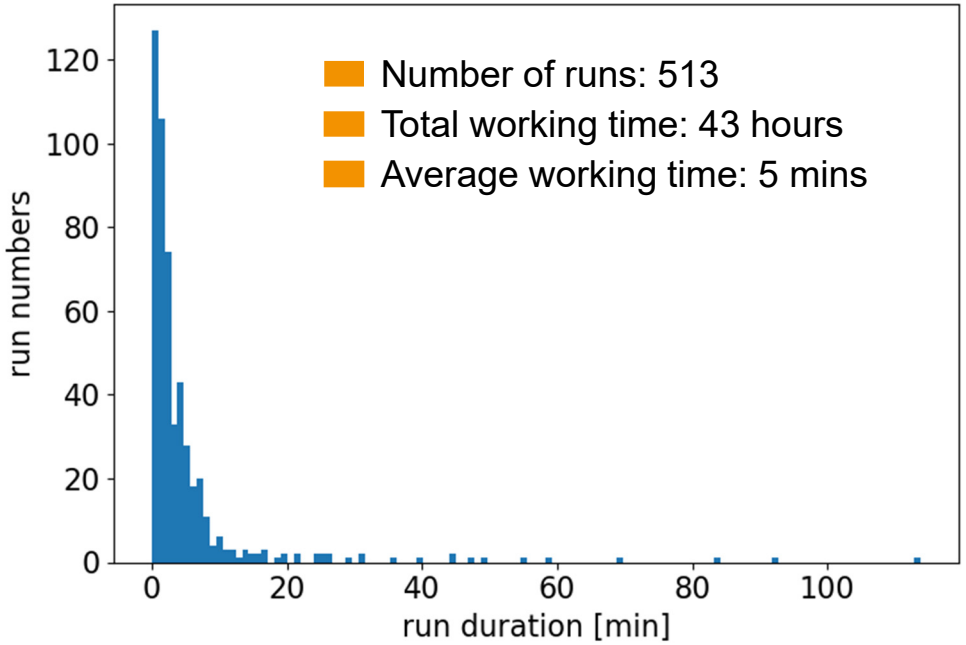
SASE1 signal could be doubles with only starting the **adaptive** FB



Adaptive Feedback statistics

- Adaptive Feedback has become one of the main tools for SASE tuning
- In some cases the adaptive feedback is used as an orbit feedback
- The soft X-Ray FEL pulse energy signal is not sensitive to the orbit jitter in the SASE3 undulator.
  - artificially induced orbit changes have to be used to catch correlations
- Active search?

Statistic of the Adaptive Feedback runs from March 11 to April 7, 2019



Conclusion & outlook

- Model-free optimization methods were widely used during commissioning of the European XFEL and now it is a part of the daily European XFEL operation
- We can apply more automation such as a sequence of optimization without operator intervention. In the future, ML methods will be used to define the sequence
- Accelerator physical model can be used to define hyperparameters.
- Model based iterative method is used in simulations and can be applied to the accelerator to optimize the bunch compression
- A model-based method such as the Adaptive orbit feedback proves extremely useful and more advantageous compared to purely empirical methods.

thanks to all the people who contributed to this work (accelerator team, fel colleagues etc)

…and thank you for your attention!