On-line Optimization of European XFEL with OCELOT

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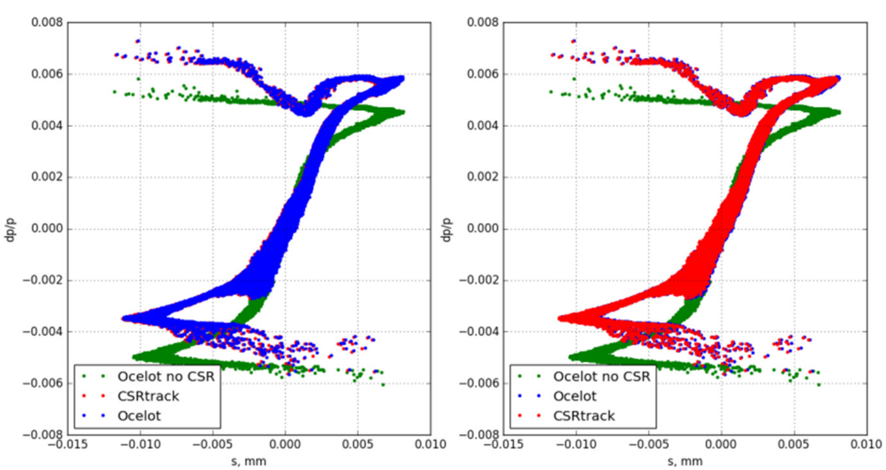
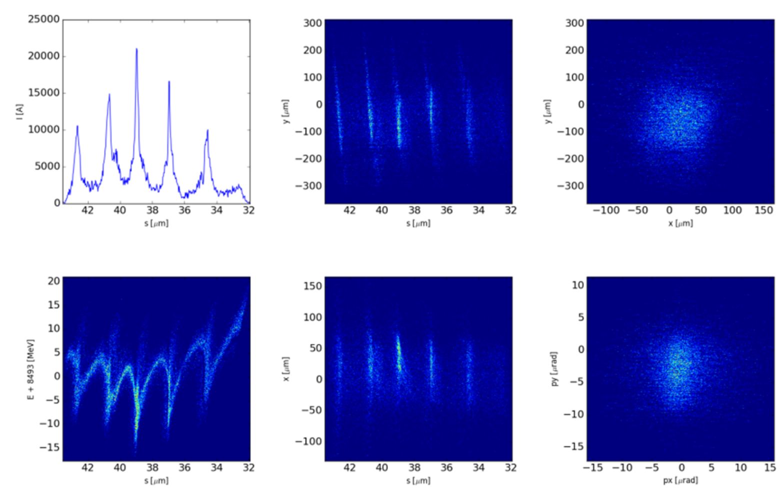
OCELOT concept

- Started as simulation project (Undulator radiation, FEL) at European XFEL
- FELs are notorious for difficulty in model-to-measurement comparison (short pulse length, small emittances, synchronization - diagnostics non-trivial) and need of manual retuning. This puts a limit on the merit of simulations (such as taper optimization).
- Branched into more on-line control-oriented development
- Resulting concept of generic simulation/controls framework/library, featuring

Electron beam physics models **X-ray physics models** **On-line Controls**

Advanced GUI **Data-centric (statistics, ML)**





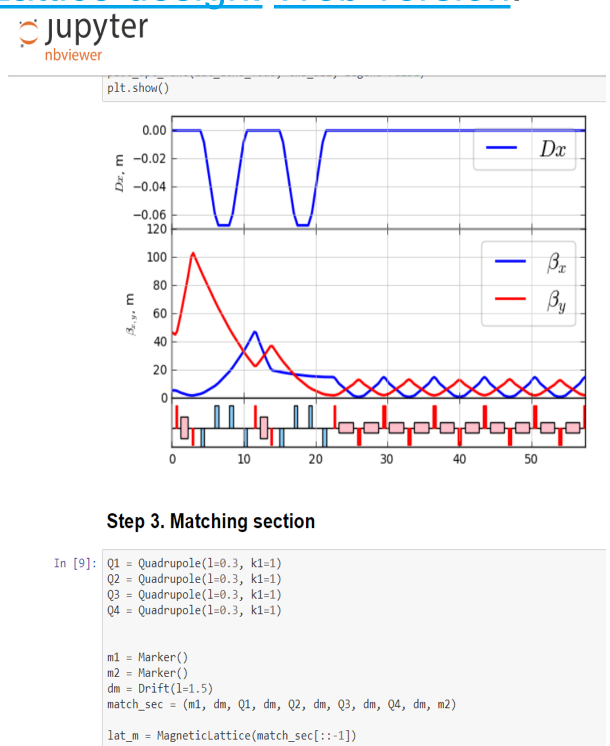
OCELOT technical concept

- Everything in python. Focus on simplicity
  - No API to other languages
  - Everything is a python object, no (additional) input language, no parsing, no data standards, free serialization. Implement only physics
  - Parsers however easily implementable (included ELEGANT, MAD-X, GENESIS)
- Abundant numerical libraries
  - *Numpy, scipy, matplotlib, mpi4py*
  - *Scikit-learn* for machine learning
- Not a standalone application but a python library + a set of tools
- Code optimized when possible, but simplicity and usability has priority over speed
- Modular physics process architecture (concept similar to *Geant4*)
- Open source

OCELOT details

- Single-particle electron optics
- Beam dynamics in linacs
  - Wakes, CSR, Space charge
  - 2^{nd} order tracking
- X-ray optics
  - Fourier optics
  - Dynamic diffraction (Bragg)
- Synchrotron radiation
  - UR/SR solvers
- FEL calculations
  - Integrates Genesis
- *Controls interface and optimization tools*

- Tutorials on https://github.com/ocelot-collab/ocelot:
  - Tutorial N1. Linear optics. Web version.
  - Tutorial N2. Tracking. Web version.
  - Tutorial N3. Space Charge. Web version.
  - Tutorial N4. Wakefields. Web version.
  - Tutorial N5. CSR. Web version.
  - Tutorial N6. RF Coupler Kick. Web version.
  - Tutorial N7. Lattice design. Web version.



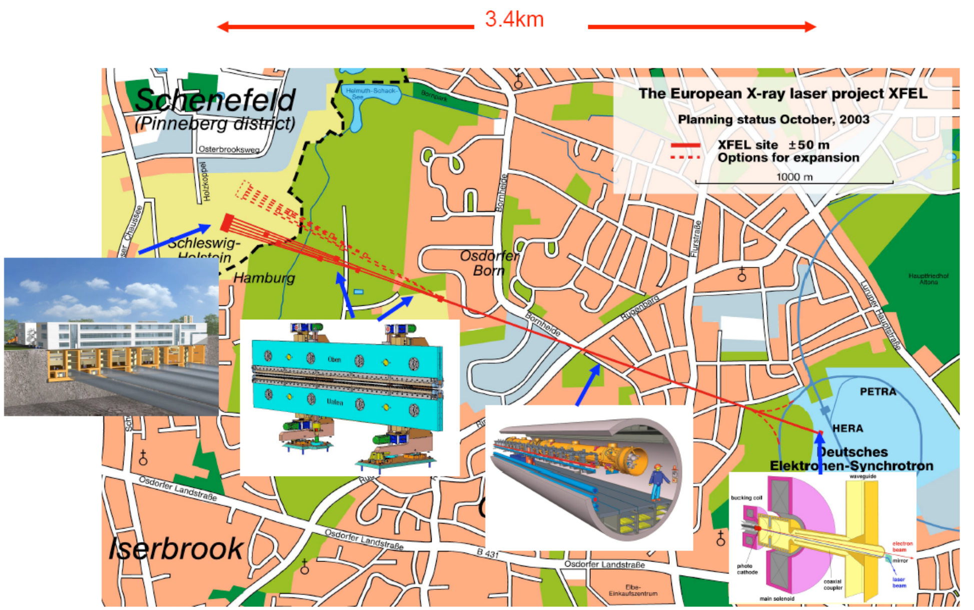
On GitHub https://github.com/ocelot-collab/ocelot

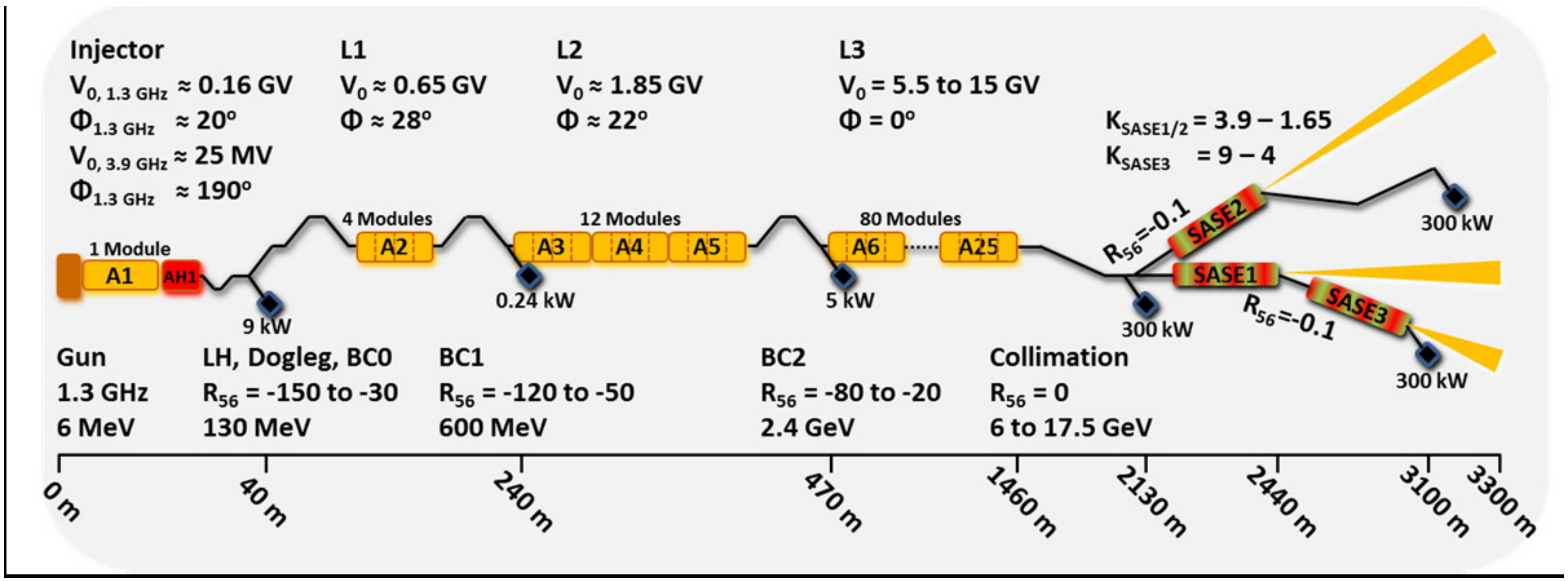
I. Agapov et al., NIM A. 768 2014

The European XFEL in a nutshell

Driven by superconducting linac

- Pulse repetition rate 10 Hz
- Pulse length 600 ms
- #bunches per pulse 2700 -
- Bunch length (compressed) 2-180 fs (FWHM)
- Bunch charge 0.02-1 nC
- Slice emittance 0.4-1.0 mm mrad
- Slice energy spread 4-2 MeV

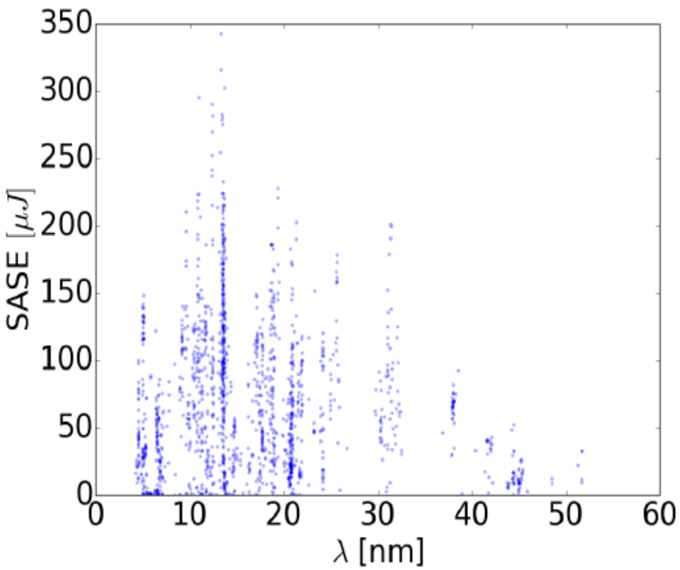




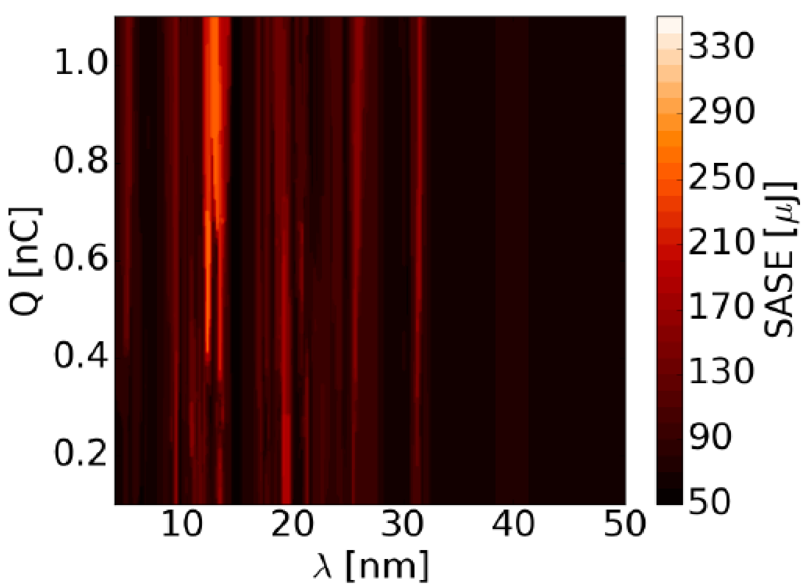
Optimization and tuning

- Even when major technical systems work well, getting close-to-design photon pulse parameters requires manual fine-tuning
- Tuning done with the gun, linac RF voltages and phases, orbit, optics, undulator gaps, phase shifters, ….
- Hundreds of free tuning parameters
- Requires time and expertise, and the results varies depending on operator, time investment and machine conditions
- With increasing complexity and pressure on availability, more automation needed

FLASH 2015 data

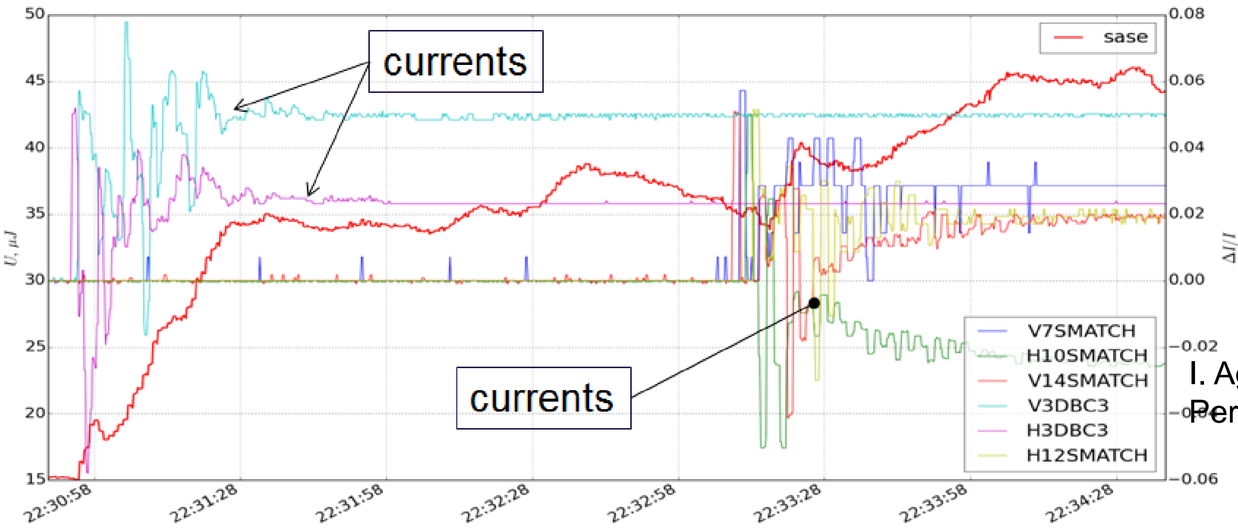


K-means prediction



Optimizer - FLASH

- Undulator orbit, optics matching and compression tweaked empirically at FLASH for SASE tuning
- Implemented a tool that optimizes SASE with a set of actuators with a functional minimization instead of manually
- Major difficulty: parameter setup (signal averaging, device boundaries) and error handling (hardware and software hiccups)

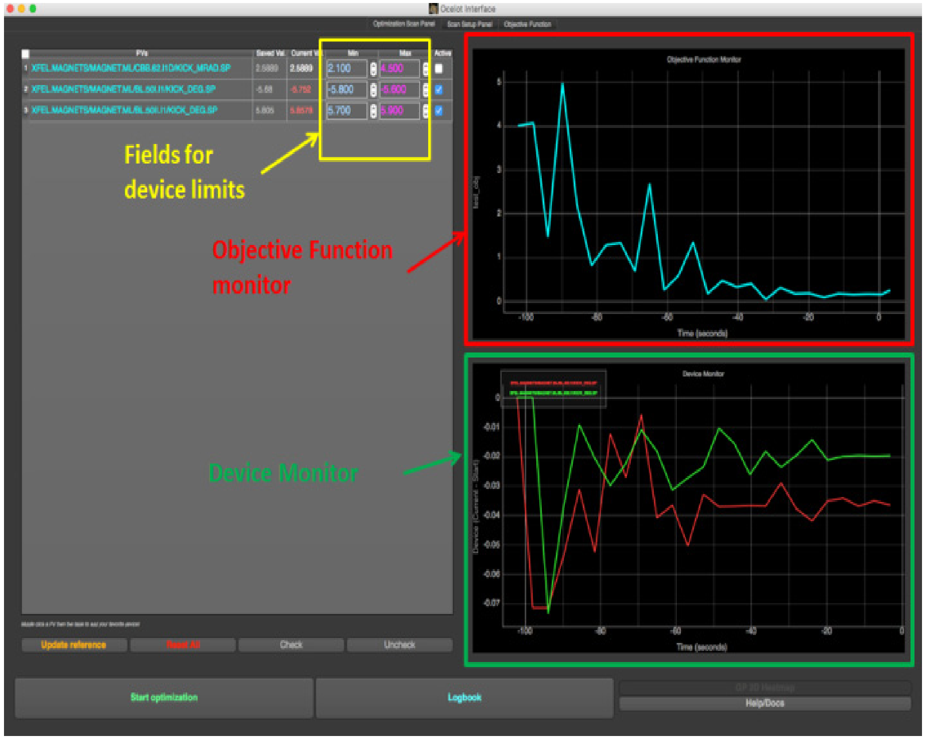


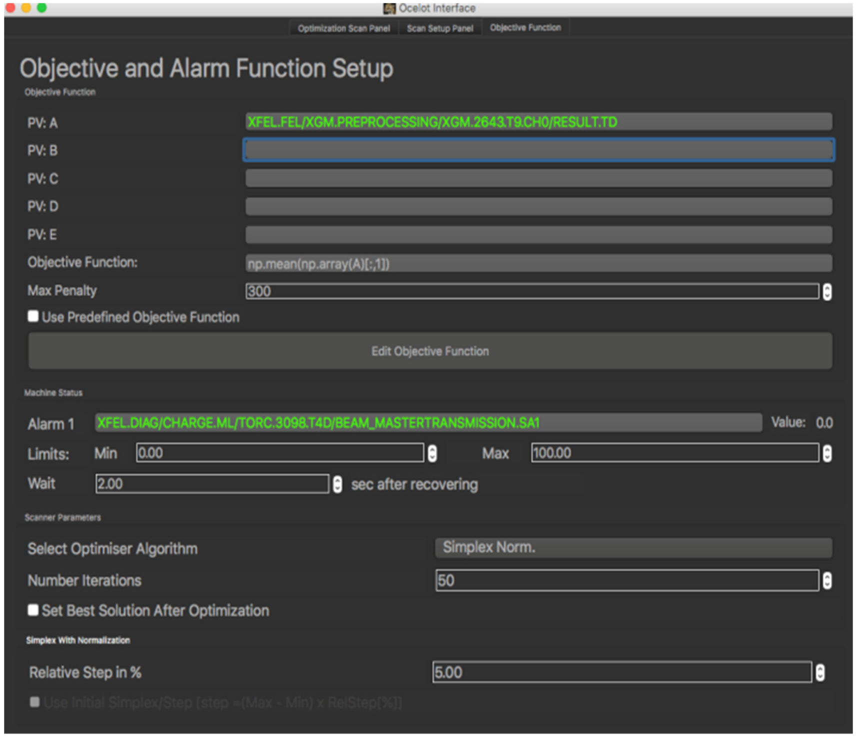
Example with 4 correctors
$\lambda = 10.4\ nm$

I. Agapov et al. Statistical Optimization of FEL Performance. IPAC15.

Generic optimizer - XFEL.EU

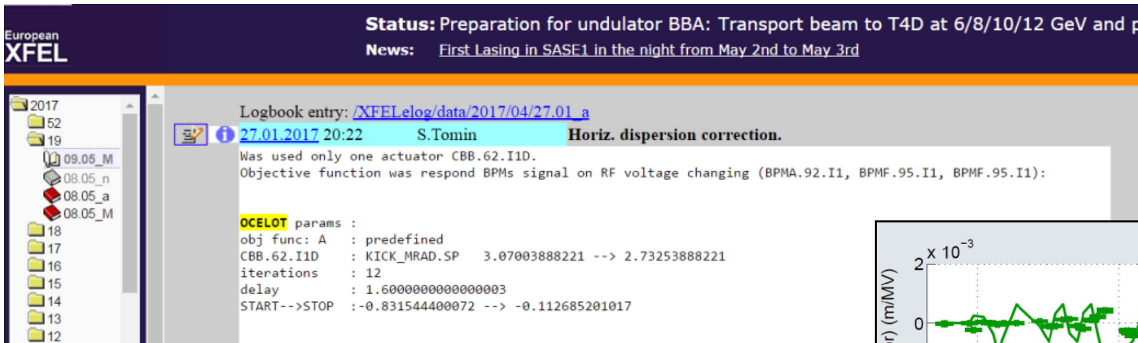
- Sequence of actions / decision tree implemented initially
- However development shifted towards making the tool more universal and useful for ad-hoc tasks (important for commissioning)
- Concentrated on single actions and developed generic GUI
- Deployed for European XFEL

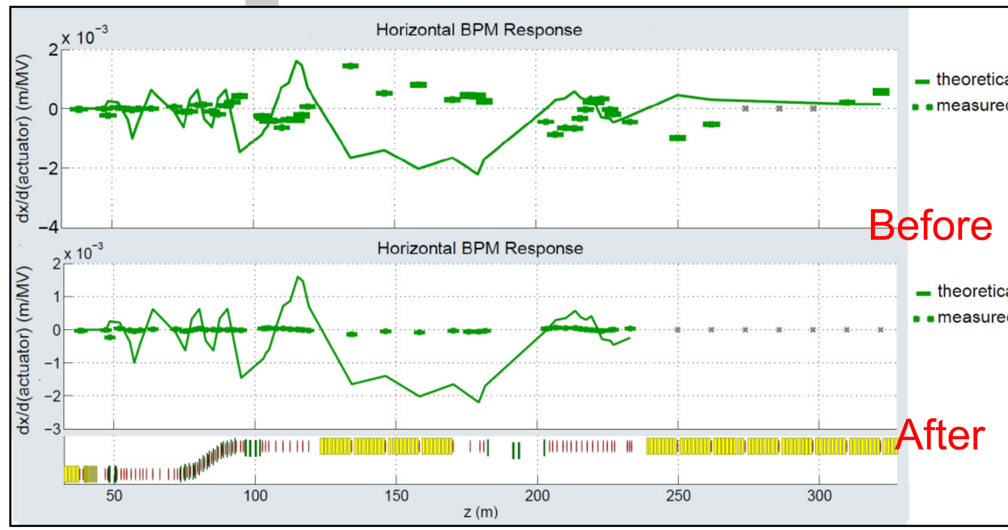




Dispersion correction - XFEL.EU

Alternative to response-matrix-based correction

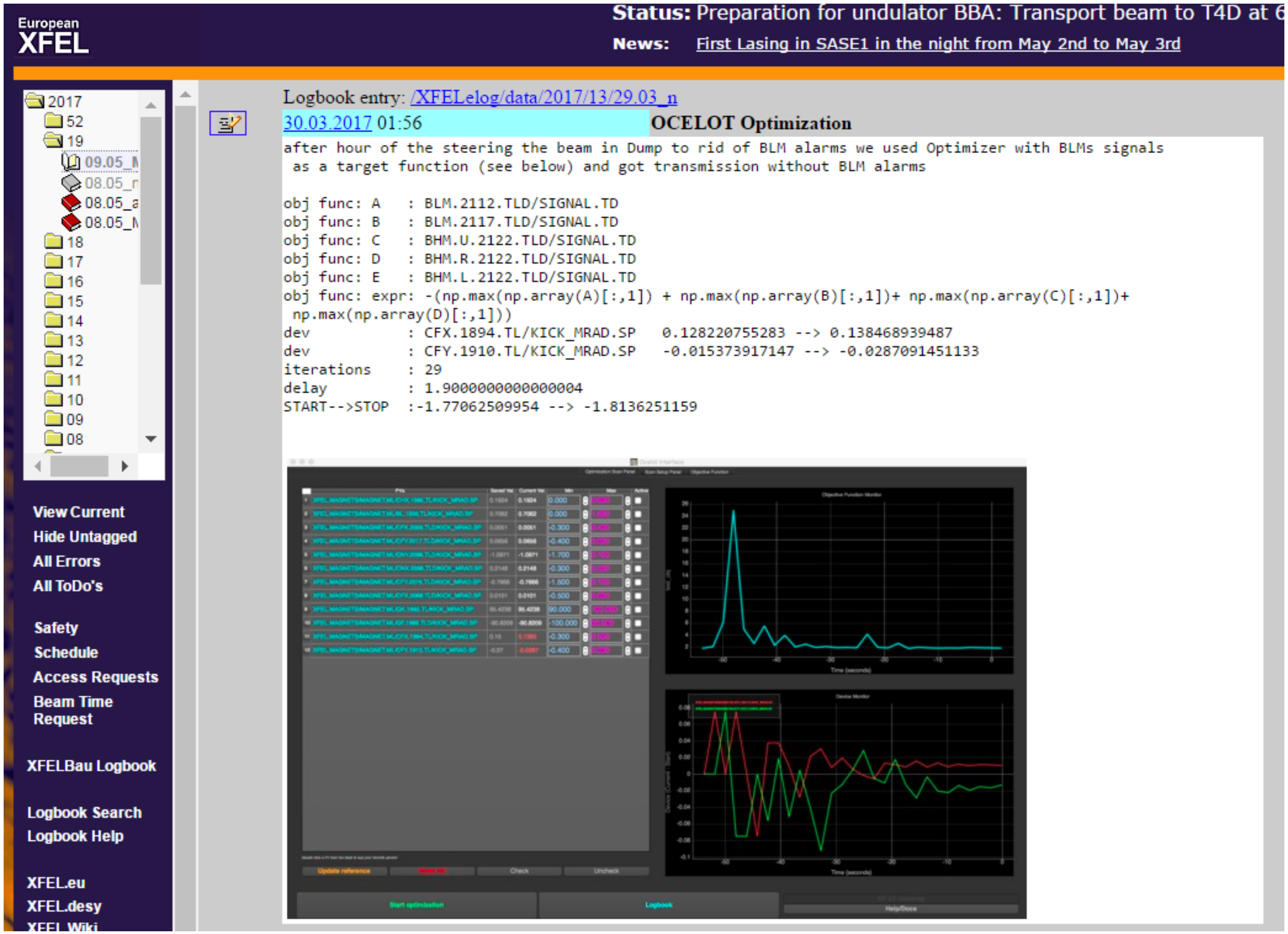




Dispersion compensation from I1D dump magnet (compensation with one actuator)

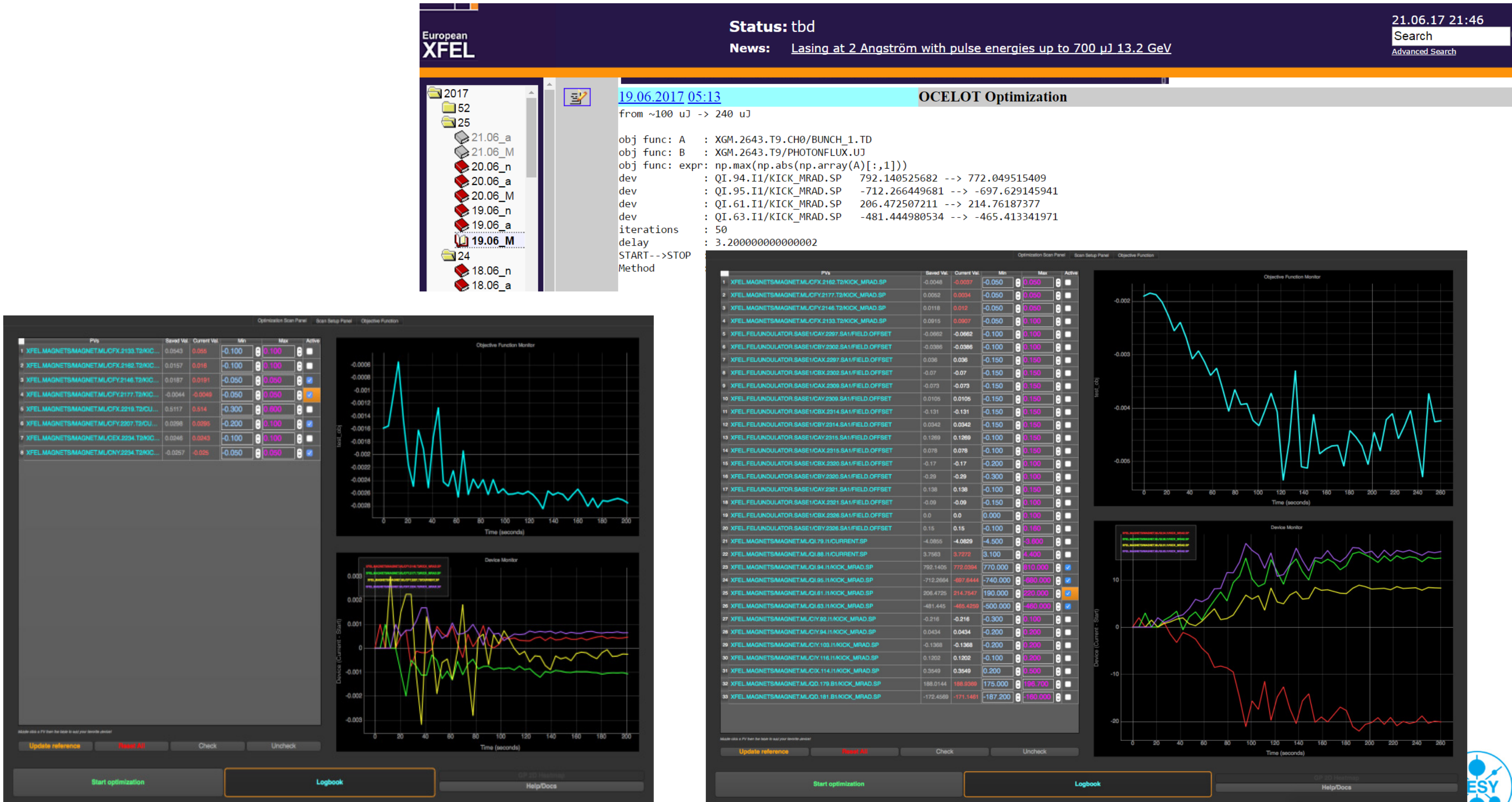
Beam losses and orbit - XFEL.EU

Minimization of the beam losses and keeping reasonable orbit in the TLD



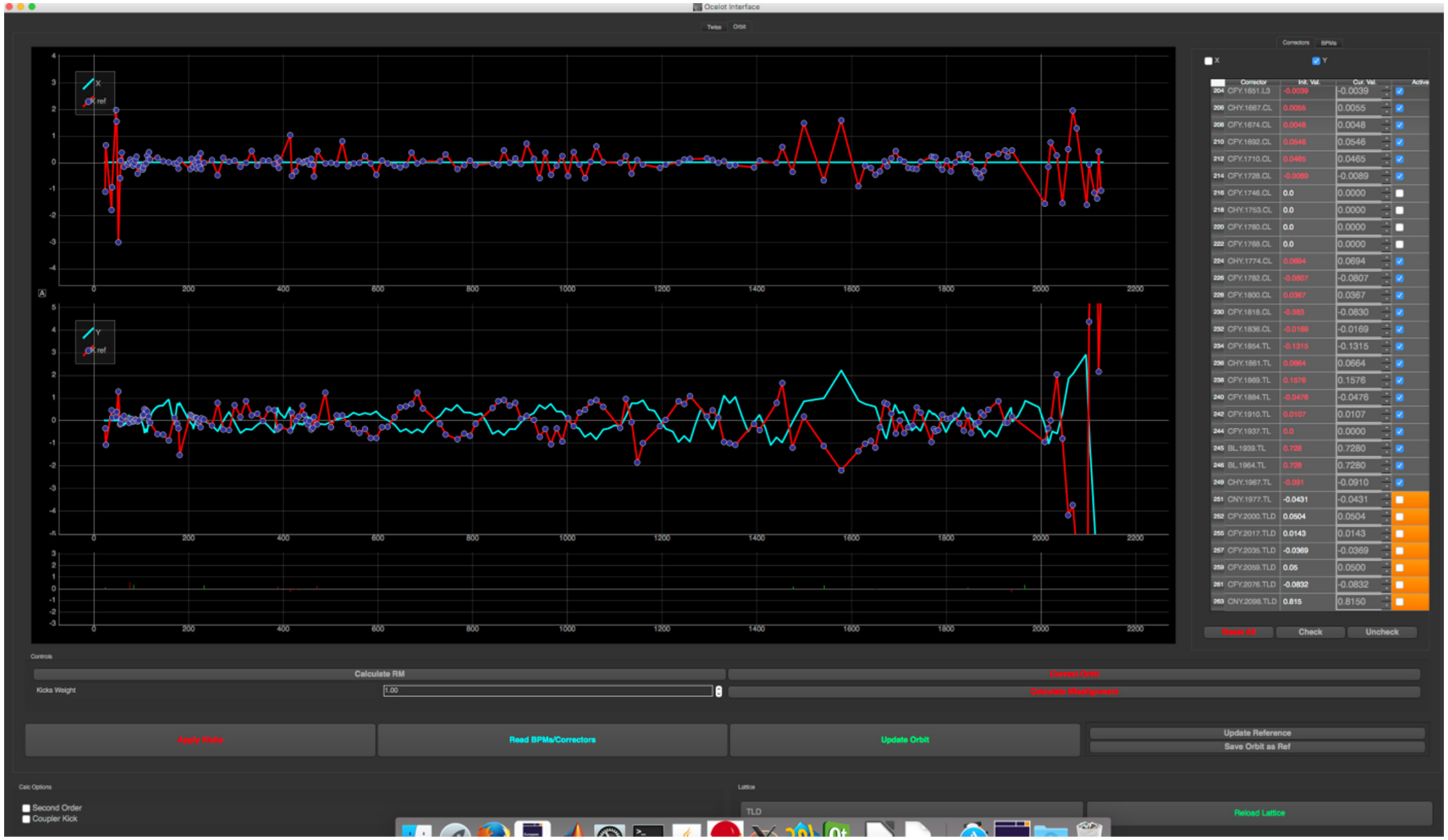
SASE optimization - XFEL.EU

- Example: 4 quads in the Injector DogLeg SASE level was increased from 100 uJ up to 240 uJ
- Routinely used with 4 launch steerers



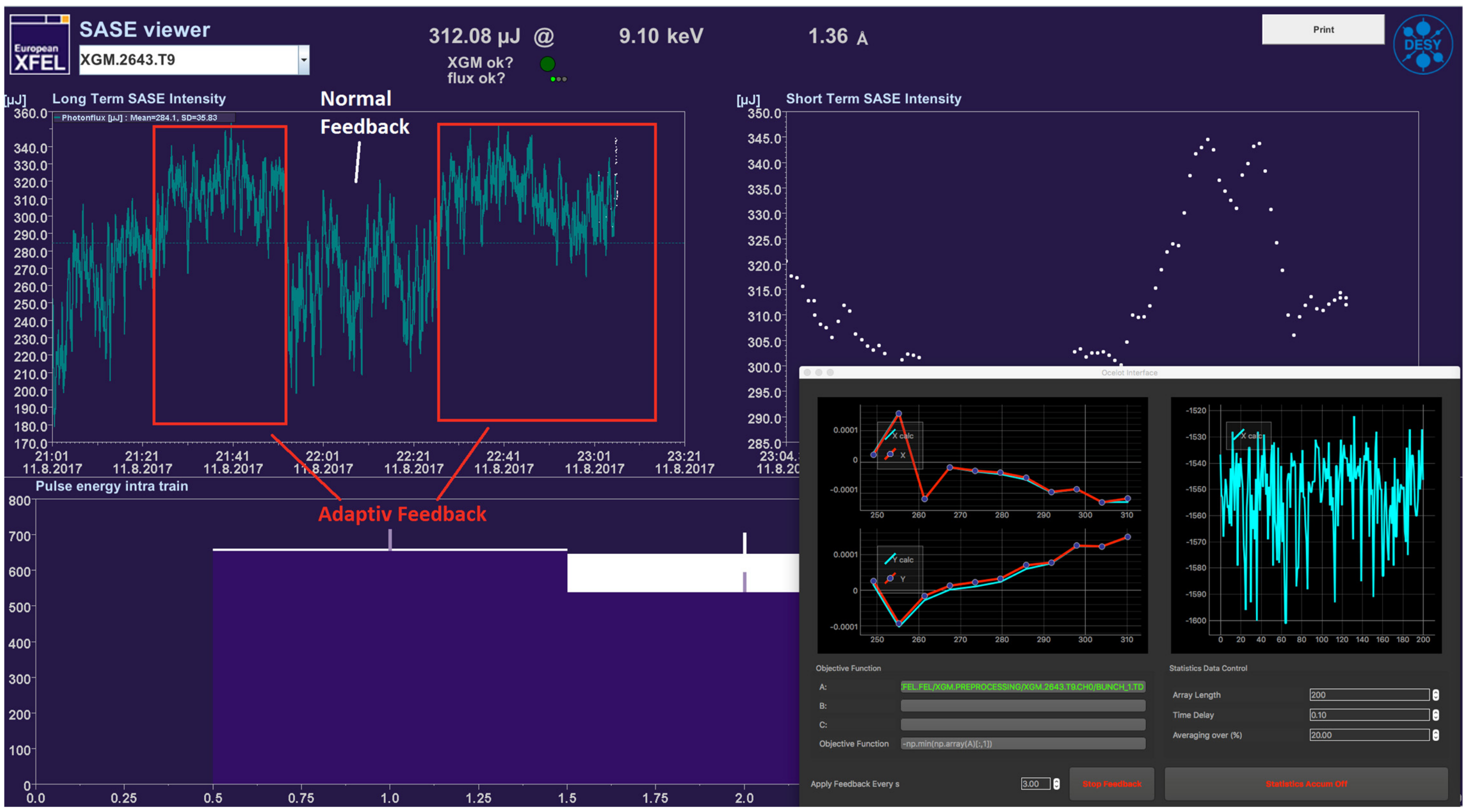
OCELOT orbit correction tool - XFEL.EU

- OCELOT electron optics model for XFEL in place, tools using response matrices can be implemented in the same framework
- Response-matrix (SVD) tool for orbit and dispersion correction implemented and in operation



Adaptive feedback - XFEL.EU

- Optimizer cannot be effectively used during beam delivery
- Implemented "adaptive feedback": Average orbits with best SASE and correct orbit to that value (SVD)
- Works great during user operation



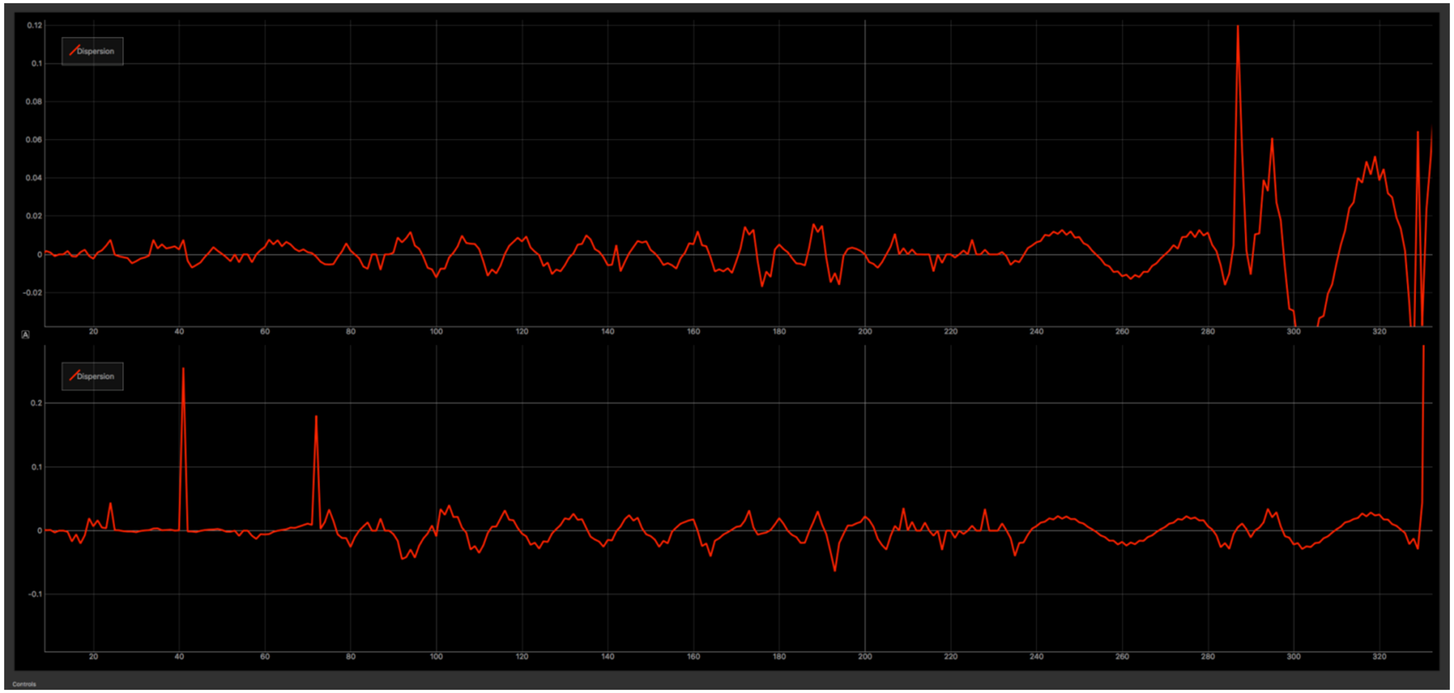
Idea from: G. Gaio, M. Lonza, Automatic FEL Optimization at FERMI, Proc. of ICALEPCS2015

OCELOT on-line model - XFEL.EU

- Read machine parameters (quadrupoles and cavities) and measured beta-functions at a screen (I1, BC1, BC2), compute optics
- Change settings in flight simulator mode
- Possibilities of using such tool for tuning being explored

Correlation tool – XFEL.EU

- In the spirit of data-centric software suite
- Real-time correlations give machine parameters such as dispersion, coupling etc.

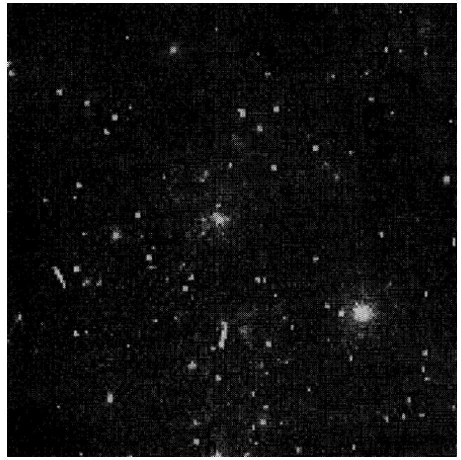


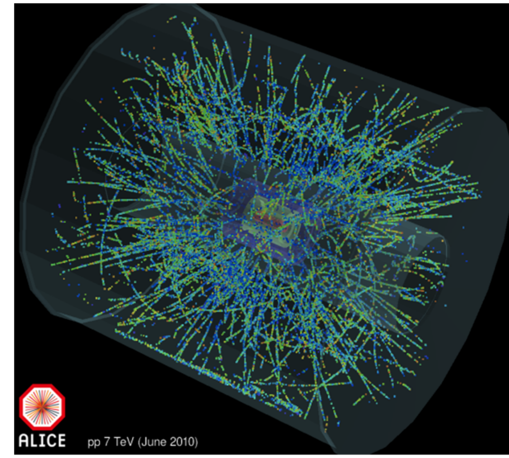
Horizontal dispersion

Vertical dispersion

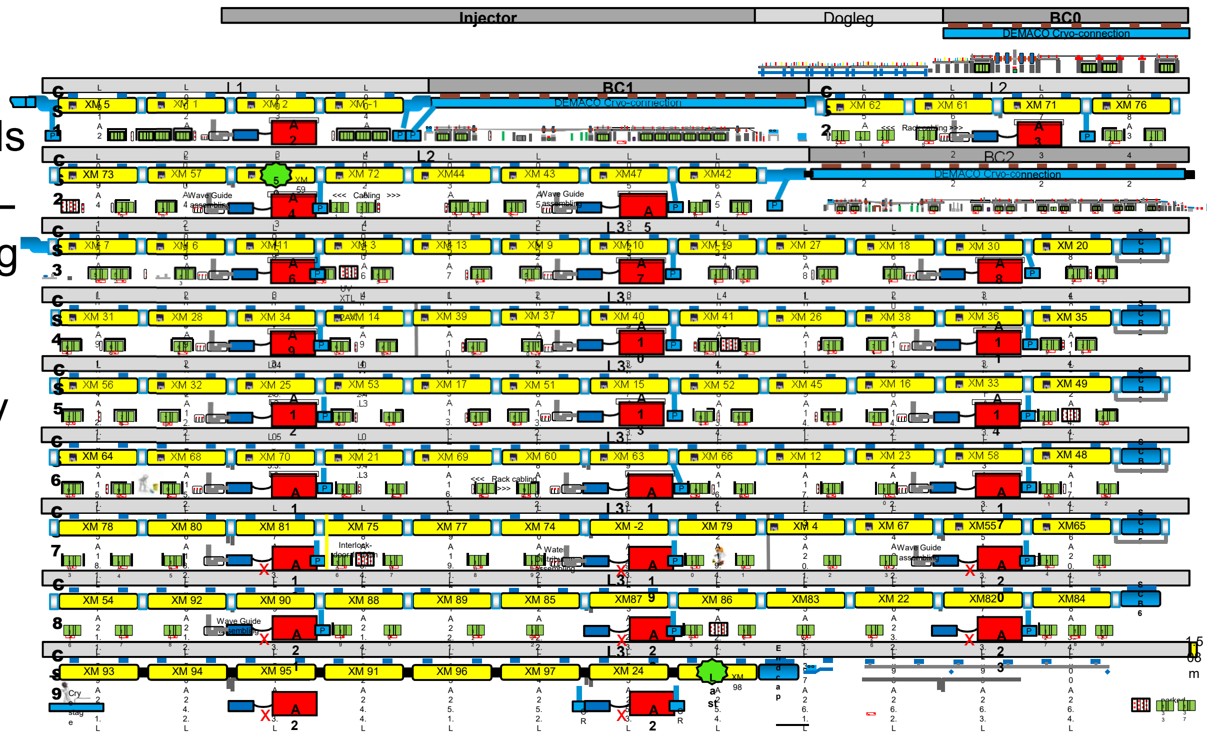
Dealing with data complexity

- ML tools have been long used in astronomy and HEP for pattern recognition/classification problems (data rates prohibitive for visual inspection)





- Boosting advanced data handling/ML techniques tools in accelerator controls for machines like the XFEL is important due to growing complexity



- Failure prediction probably most natural application

- Possibilities of using such methods for tuning being explored

Conclusion and Outlook

- Empirical optimization methods successfully used for European XFEL commissioning and operation
- Corresponding software tools in place, open source and available through OCELOT
- Challenges to reach full tuning automation include
  - Exploiting beam physics models to restrict search space
  - Exploiting statistics and machine learning

https://github.com/ocelot-collab/ocelot