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STATUS OF AUTOMATED OPTIMIZATION PROCEDURES AT THE EUROPEAN XFEL ACCELERATOR

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Abstract

The European XFEL is in the operational stage since fall 2017. Since then, tuning of the FEL performance (e.g. of the photon pulse energy) has become increasingly important. Due to a large number of parameters to which FEL facilities are highly sensitive and their complex correlations, controlling and optimizing them in a speedy manner is becoming a very important and challenging task. Several automated optimization procedures were developed to optimize the FEL beam quality. In this work, we present the status and the results of these activities, as well as the optimization statistics.

INTRODUCTION

The European XFEL [1] belongs to the family of the Hard X-Ray FEL facilities along with LCLS [2], SACLA [3], SwissFEL [4], and PAL-XFEL [5] and it has the highest electron beam energy up to 17.5 GeV among them. The superconducting technology used for the linac of European XFEL allows producing up to 27000 electron bunches/second in the burst mode with 10 Hz. The beam switchyard containing of fast kickers and DC septa [6] distributes the electron bunches between three SASE undulator lines aiming to deliver X-rays from 0.25 to up to 25 keV.

The multi-user operation places high demands on the availability and quality of the electron and photon beam that should be achieved in as short a time as possible. The Hard X-Ray FEL performance is highly sensitive to many accelerator parameters including e.g. the orbit inside the undulator, RF parameters (see e.g. [7]) and many others.

A wide variety of high-level control applications and procedures have been developed to setup the machine and reduce the required tuning time. This includes beam based alignment, electron beam phase space tomography [8], an orbit correction tool [9], and many others. Despite of that, getting the best machine performance requires significant efforts of machine parameter tuning and human expertise.

The magnet imperfection and misalignment, the temperature gradients and residual magnetic fields, etc, are unavoidable companions of the large-scale FEL facilities which inevitably leads to deviations of machine parameters from the reference values. Most of these deviations can be detected by comprehensive diagnostics and subsequently compensated. However, such diagnostics are not always available online or in an accelerator part of interest. For example, a routinely using a procedure of projected beam optics matching may not provide the same matching to the central slice, see Fig. 1. To overcome this, beam phase space tomography [7] and matching of the bunch slice of interest can be used. However, this is currently not often possible due to time constraints and not available after the main linac.

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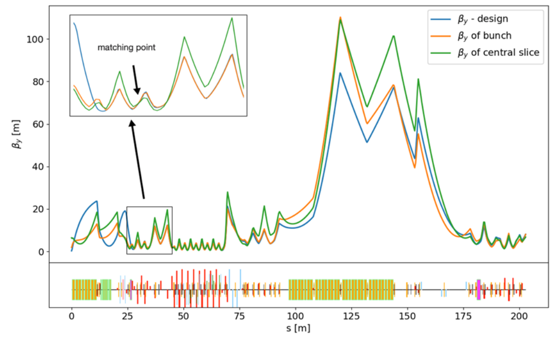

Figure 1: β_y of the first 200 m of the EuXFEL accelerator: design β_y (blue line), β_y of whole bunch from tracking with SC. (orange line), β_y of the central slice (green).

Figure 1 shows the vertical beta functions of the first 200 m of EuXFEL accelerator for three cases: the design β_y, the β_y of the whole beam (the projected beam was matched ~32 m after the gun cathode at $E_{beam} = 130$ MeV) and β_y of the central slice of the beam. The two last cases were obtained from tracking of $2 \cdot 10^6$ macroparticles (500 pC) with space charge (SC) effect using OCELOT [10, 11]. The beta function of the entire beam eventually diverges relative to the design after matching due to space charge effects, while the beta function of the center slice is also different.

A few tools [9] including the OCELOT Optimizer and the statistical undulator launch orbit optimization tool (or "Adaptive Feedback") have been developed to automatize several tuning procedures. Here we report the status of development of these tools and present the analysis of the optimization data for more than one year of operation.

THE OCELOT OPTIMIZER

The OCELOT Optimizer was developed and deployed in the EuXFEL control room at the beginning of 2017. It is the next generation of the SASE optimizer developed for FLASH [12]. The tool optimizes a configurable objective function, e.g. FEL pulse energy, by tweaking actuators using an optimization algorithm, e.g. Nelder-Mead algorithm [13]. A detailed description of the tool, as well as some examples of its use during the commissioning of the European XFEL [14] and the first deliveries of the photon beam to users, were presented in [9]. Since then we collected experience of almost two years. The application statistics is shown in Fig. 2. Each optimization is logged including an

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objective function and actuator changes during optimization and can be analyzed afterwards. We excluded the data from 2017 from the analysis due to the specifics of commissioning and analyzed data from 2018 and the first 4 months of 2019. As it can be seen from Fig. 2, the majority of optimizations are dedicated to FEL pulse energy maximization denoted as "SASE" and a small fraction of it to local dispersion minimization in the injector denoted as "Disp.". The remaining optimizations, about 10%, were ignored due to incomplete data in the log files. It should be noted that all optimizations were performed using the Nelder-Mead algorithm [13].

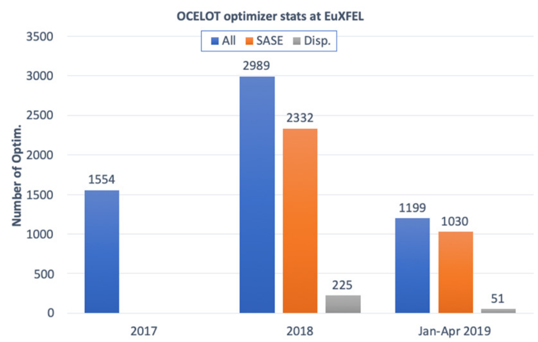

Figure 2: Number of OCELOT optimization starting from 2018 to the end of April 2019.

Figure 3 shows the analysis of combined data for 16 months (>3600 entries). It shows that the average duration of optimizations is around 3.5 min and most popular configurations use 4 or 3 actuators.

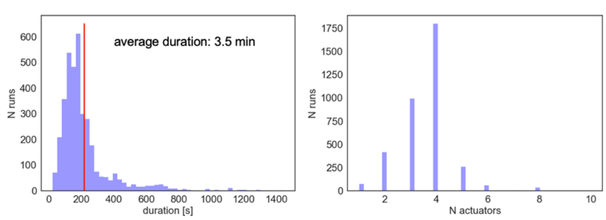

Figure 3: Distribution of optimizations duration (left) and number of actuators used in individual optimizations (right) for 16 months of usage.

Processing of the dispersion minimization logs shows that the majority of the optimizations is successful (decrease in $\sum \eta_{BPM}$ value by >10% from the initial, η_{BPM} is the dispersion at a BPM position), the success rate of 60% in 2018 and 73% in 2019. However, the situation is reversed for SASE pulse energy maximization, see Table 1. Here we defined the "successful" SASE optimization as $\frac{\Delta S}{S_0} > 10\%$, where S_0 is SASE pulse energy in μJ at the beginning of the optimization and $\Delta S = S_{last} - S_0$ is the difference between the final pulse energy and S_0. Another criterion for "successful" SASE optimization is shown in Table 1.

It should be noted that other optimization attempts marked as "unsuccessful" do, in the vast majority of the cases, not make the target function smaller. The high rate of "unsuccessful" optimizations can be explained by:

- Optimizer hyperparameters are not optimal (e.g. initial step of the actuator or the averaging period of the SASE signal),
- Actuators are already in the optimal position at the moment of an optimization start.

Table 1: Percentage of "Successful" SASE Optimizations

Period	$\frac{\Delta S}{S_0} > 10\%$	$\Delta S > 10\ \mu J$
2018	19%	20%
Jan-Apr 2019	17%	25%

The validity of the last point is also confirmed by the statistics: 446 unique devices were used for SASE pulse energy maximization but only 28 actuators were applied for the dispersion optimization. In order to shed some light on this situation we analyzed the logged data and present the most frequently used devices in the "successful" SASE and dispersion optimizations in Figs. 4 and 5.

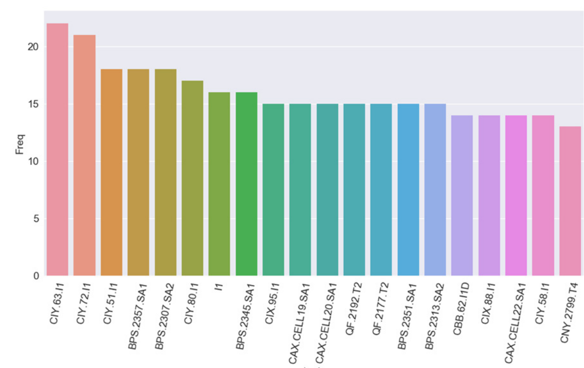

Figure 4: 20 most frequently used devices in the "successful" SASE optimizations.

As we can see, the injector orbit tuning (".I1") is an important part of optimization procedure, as well as phase-shifters tuning ("BPS."), bunch compression settings with the energy chirp of the injector ("I1"), and matching quads upstream the undulators ("QF."). Also, undulator aircoils are used for orbit tweaking ("CAX.") and the gun air coil quadrupole magnets which are not on the chart but are among the 30 most frequently used devices.

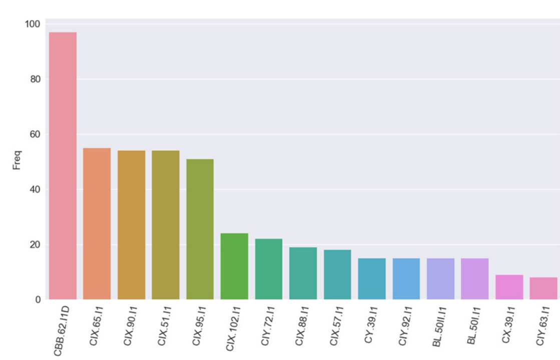

Figure 5: 15 most frequently used devices in the "successful" dispersion optimizations.

The chart of devices used for "successful" dispersion optimization agrees with our experience. The "CBB.62.I1D"

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is a compensating winding on the injector dump magnet which is well known as a source of spurious dispersion.

Summing up, we plan to update the recommended configurations for operators using the data from the analysis given here. In addition, the shortcomings of the logged data have been identified. This is typically a lack of data of the machine condition. We plan to fix it for the possible use of machine learning methods in the future.

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. The method proposed in [15] was implemented in OCELOT under the name 'Adaptive Feedback'. Details can be found in [9]. An optimization with the Adaptive Feedback, in general, is compatible with user operation due to slow adjustments of the orbit upstream an undulator (e.g. see Fig. 6). It is usually used after changing e.g. the photon wavelength.

The necessity of such an optimization can be explained by the fact that the trajectory of the lasing bunch slices might not coincide with the trajectory of the center of mass of the bunch. This could be induced e.g. by CSR effects [16] as presented in Fig. 7.

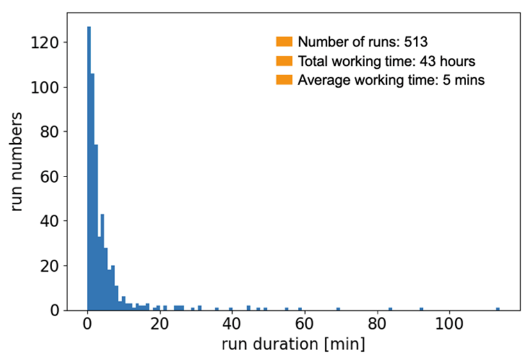

Figure 6: Statistic of the Adaptive Feedback runs from March 11 to April 7, 2019.

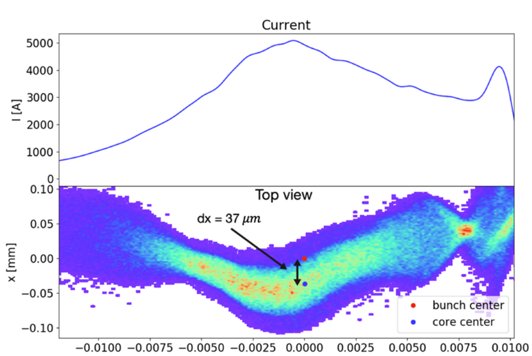

Figure 7: The electron beam parameter in from of SASE2 undulator, the beam energy 14 GeV, 250 pC [16].

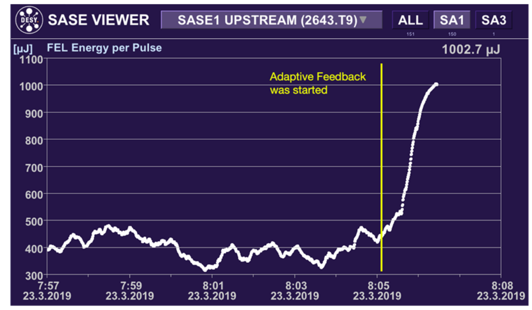

Figure 8: SASE pulse energy during optimization of the launch orbit using the "Adaptive Feedback". Logbook entry March 23, 2019.

One of the examples of a launch orbit optimization with the Adaptive Feedback is shown in Fig. 8. The FEL pulse energy was doubled in 2 minutes of optimization from 450 µJ to 1000 µJ.

Starting as an experimental module within the OCELOT orbit correction tool, the Adaptive Feedback has become one of the main tools for SASE tuning. The statistic of the tool used for less than one month is shown in Fig. 6. The tool was used more than 500 times within a month. The statistic is combined for all SASE undulators (SASE1-3). Also, one can notice that in some cases the adaptive feedback was used for tens of minutes as a replacement of the standard orbit feedback.

It should be noted that the soft X-Ray SASE pulse energy signal is not sensitive to the orbit jitter in the SASE3 undulator. For that reason, artificially induced orbit changes have to be used to catch correlations by the Adaptive Feedback.

DISCUSSION

In this work we presented the status and analysis of statistics data for two tools, the OCELOT Optimizer and the OCELOT Adaptive Feedback.

The Adaptive Feedback is very effective and we do not see the need for major changes in the code in the near future. However, a more complete optimization logging is required for future analysis. And an implementation of an artificial orbit jitter generator for the SASE3 line is under discussion.

The OCELOT Optimizer is efficient compared to manual tuning by the operators. But the data analysis revealed that two problems must be solved to increase the success rate of SASE optimization. First, we need to know what to tune in a particular machine state and, second, the optimizer hyperparameters should also be adapted to the particular machine state (SASE signal deviation) and type of actuators. We are planning to use a machine learning approach for both. However as mentioned above we need more complete data from each optimization including the machine status.

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