PROGRESS IN AUTOMATIC SOFTWARE-BASED OPTIMIZATION OF ACCELERATOR PERFORMANCE*

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Abstract

At modern linac- and storage-ring-based light sources, a certain amount of empirical tuning is used to reach ultimate performance. The possibility to perform such empirical tuning by automatic methods has now been demonstrated by several authors (e.g. I. Agapov et al. in proc IPAC 2015). In this paper we present the progress in development of our automatic optimization software based on Ocelot, its applications to SASE FEL optimization at FLASH and LCLS and its potential for storage ring optimization.

INTRODUCTION

The tuning of accelerator facility performance is required, as a rule, after any transient process e.g. switching of operational mode or daily/seasonal temperature changes. It involves various types of feedbacks (e.g. RF parameters, currents of magnet elements and so on) or well-defined procedures as orbit correction using response matrix. In addition, a 'high'-level automatic control is available, which saves and restores the optimal machine parameters for every particular operational mode. However, due to various reasons like the hysteresis of magnetic elements and/or temperature drifts, even after applying these multi-level automatic tuning procedures the accelerator performance is not optimal: the final tuning still requires a fine manual work by an operator, which is a most time-consuming procedure that can last a few hours.

We developed empirical optimization methods and software based on Ocelot [1], which were initially conceived for SASE tuning optimization at FEL facilities. Our approach and software was successfully tested at the FLASH [2] facility (details of first results can be found in [3]) and later at LCLS [4] (see below "SASE optimization at LCLS"), and subsequently extended for storage ring applications. In particular, it was used for beam injection optimization at the booster of the Siberia-2 Light source [5] (NRC Kurchatov Institute, Moscow).

OPTIMIZATION TECHNIQUE

Optimization procedures roughly mimic what a human operator does, but uses a function optimizer which can run faster, more effectively, and along several dimensions simultaneously. Our optimizer reads the target signal (e.g. the signal from a SASE detector) and executes *Sequences* of *Actions*, which control actuator devices, see Fig. 1.

An Action is not just a list of devices used during the optimization process, but also contains the limits of variation for every device, the optimization method used, the number of iterations allowed, and the target signal for minimization/maximization. The target can be as mentioned above, the SASE level measured using various types of detectors, but also, for instance, the FEL spectrum, the photon beam positions, Beam Loss Monitors (BLMs) signals, the electron orbit, or a combination of any of these. The optimizer can, in principle, obtain information which is unavailable to the diagnostics from an online model of the accelerator.

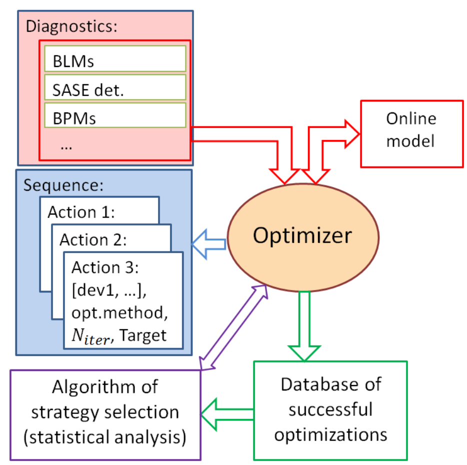

Figure 1: Scheme of the optimization tool.

In practice, universally effective *Actions* and *Sequences* do not exist. In order to define most effective *Actions* and *Sequences* for every particular operation mode, we developed and implemented a *Database of successful optimization* for statistics collection. In the future, information from this *Database* will be used by an *Algorithm of strategy selection* and will result in recommendations to the operators about the most effective *Actions* for any given operational mode.

SASE OPTIMIZATION AT FLASH

The objective function used for optimizing the performance of FLASH is proportional to the SASE pulse energy averaged over several bunch trains. Since radiation can cause demagnetisation of undulators, a beam loss penalty is always added. It is a nonlinear function that is zero when losses are well below threshold and grow rapidly when the maximum BLM reading exceeds 0.7 of the threshold value. With such penalty beam losses never occurred during our tests. Therefore, as concerns radiation

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damage, the use of our optimization procedure turns out to be safer than manual tuning.

Optimization is usually performed with the Nelder-Mead Simplex method, although other methods can be used too, see e.g. the tests at the LCLS described in the next section.

An example of evolution of SASE power and steerer currents during SASE optimization is shown in Fig.2. During this optimisation, two *Actions* were used with two and four devices respectively.

The changes in the electron orbits in the horizontal and vertical planes while *Action1* is performed are shown in Fig.3. Solid lines correspond to the final values.

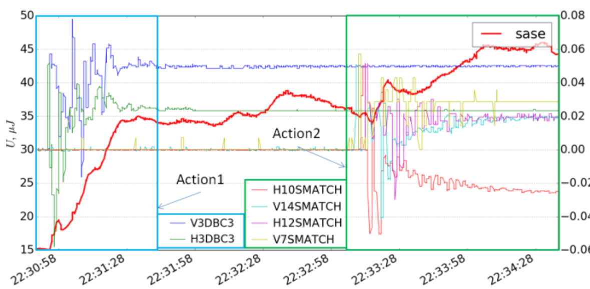

Figure 2: SASE optimization at λ=13.5 nm.

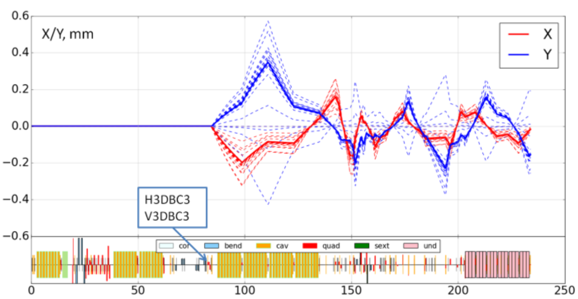

Figure 3: Orbits changing during *Action1*.

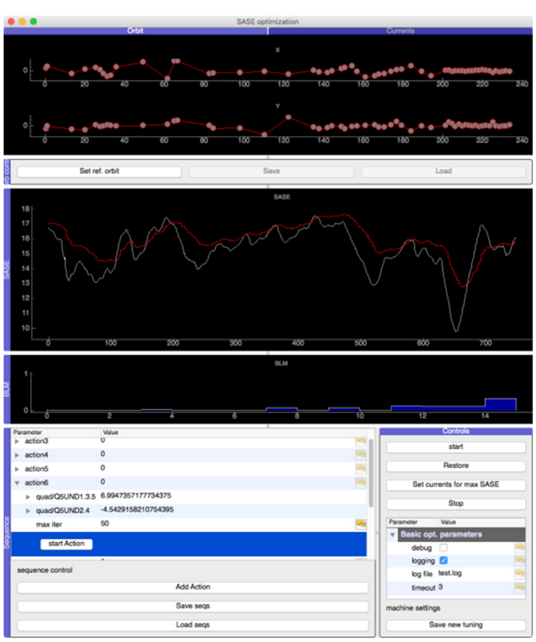

Figure 4: GUI for SASE optimization.

The typical tuning *Sequence* for FLASH consists in performing *Actions* dealing first with launch steerers, then with FODO quadrupoles, matching quadrupoles, steerers between undulators and, finally, tweaking of RF parameters.

A Graphical User Interface (GUI) for SASE optimization was developed and tested at FLASH. The GUI, Fig. 4, allows following in real time the evolution of two SASE signals (fast and slow averaging), BLM signals, electron orbit and signal settings of the actuator devices.

SASE OPTIMIZATION AT LCLS

The Linac Coherent Light Source at SLAC has recently started using the optimization package within Ocelot for standard tuning of the FEL pulse intensity. Previously, efforts have relied on hand tuning by operation staff and single dimensional scans over parameter space. The Ocelot package has allowed fast multi-dimensional optimization to become a routine part of standard machine tune up and recovery.

Several algorithms have been tested including Nelder-Mead Simplex, Conjugate Gradient, Powell's methods and others. The most effective routine has proven to be the Nelder-Mead Simplex, which is currently used as a default for most purposes. A Bayesian optimization method based on Gaussian processes is currently under development [6]. The algorithm is used primarily to tune linac matching quads, though it has also been used to optimize feedback setpoint, steering correctors and dispersion quads on pulse intensity. Other tests have been successfully conducted optimizing function besides pulse intensity, such as steering the linac orbit or maximizing detector counts on a spectrometer signal.

After initial tests with simple scripts, an interface GUI was developed using PyQt in order to keep track of the optimization algorithms path and provide an intuitive method for frequent use. Figure 5 shows the GUI interface after a scan of linac matching quads. The left table is used for selection of scan devices, as well as device setpoint readback and a fast reset option. The top right plot shows a timeseries of the objective function, while the bottom right plot shows a difference plot for scanned devices.

Figure 5: The Ocelot interface GUI after a successful scan of the L3 linac matching quads.

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INJECTION OPTIMIZATION AT SIBERIA-1 STORAGE RING

The Siberia-2 Light Source at the NRC Kurchatov Institute in Moscow is fed by the booster synchrotron Siberia-1, 450 MeV, which also works as independent light source in the VUV and is driven by a 80 MeV injector linac.

Since both the software and the approach described in the previous sections are completely general, they can be applied to a wide variety of optimization problems. In particular, we adapted our software to optimize the injection efficiency of the linac into the Siberia-1 storage ring.

Beam injection optimization is performed in a single-injection mode. In this mode, an electron bunch in the storage ring Siberia-1 is replaced by a new one from the linac, with the repetition rate of 1 Hz. The goal of this single-injection mode is to optimize the overall injector efficiency. After that, an accumulation-injection mode is activated that serves during injector operation.

The most effective *Action* for tuning the overall efficiency is constituted by three devices: I2M1 – the current in the dipole magnet in EOC-1, which is the transport channel from the injector linac to Siberia-1, U2M2 – the voltage in the septum magnet, and I3BM – the current in the main dipole magnet in Siberia-1 (energy matching between linac and storage ring).

A typical tuning is shown in Fig.6. The tuning time is usually about 2-3 minutes. At the moment, the timeout value between the error function evolutions is about 3 s and is defined by the time response of the power supply server. In principle, timeout can be reduced to 1 sec.

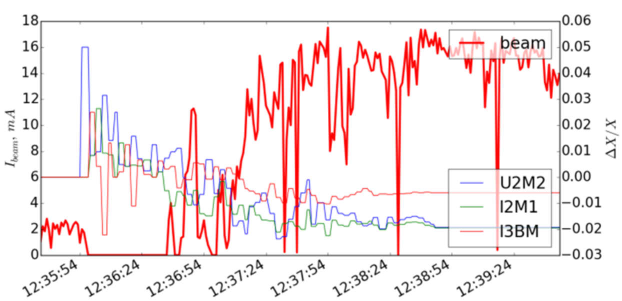

Figure 6: Injection tuning.

In spite of the fact that the current signal is noisy, tuning procedures were successful. Infrequent zero current level on the right part of Fig. 6 (red thick line) is due to wrong gun operation.

CONCLUSION

In this paper we presented simple and robust empirical tuning method and software, which shows good performance as concerns the optimization of SASE FEL signals as well as the other accelerator parameters both at linacs- and storage ring-based facilities. The performance achieved on routine tasks is comparable to that of an experience operator, while a considerable amount of time is saved.

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