ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUMPA07

ADVANCES IN AUTOMATIC PERFORMANCE OPTIMIZATION AT FERMI

G. Gaio†, M. Lonza, Elettra-Sincrotrone Trieste S.C.p.A., Trieste, Italy
N. Bruchon, L. Saule, University of Trieste , Trieste

Abstract

Despite the large number of feedback loops running simultaneously at the FERMI Free Electron Laser (FEL), they are not sufficient to maintain the optimal working point in the long term, in particular when the machine is tuned in such a way to be more sensitive to drifts of the critical parameters. In order to guarantee the best machine performance, a novel software application which minimizes the shot-to-shot correlation between these critical parameters and the FEL radiation has been implemented. This application, which keeps transversally and longitudinally aligned the seed laser and the electron beam, contrary to many algorithms that inject noise in the system to be optimized, run transparently during the experiment beam times. In this paper we describe the status of the FERMI optimizers and present a newly developed method to calculate a FEL quality factor starting from the images provided by a photon energy spectrometer which tries to mimic the evaluation of machine physicists, as well as the first results obtained using two model-less algorithms to optimize the FEL performance through maximization of the quality factor.

INTRODUCTION

In a seeded FEL [1], the transverse (horizontal and vertical) and longitudinal (temporal) alignment between the electron bunches and the UV seed laser pulses is fundamental for the quality of the produced FEL photon beam in terms of intensity, pulse energy stability and spectral purity. In order to guarantee the alignment stability, a number of beam-based feedback loops [2] have been deployed over the years and very good results have been obtained in stabilizing the transverse coincidence between electrons and seed laser, which is now in the order of 10 uμ$_{\text{rms}}$. Moreover, continuous advances in the LLRF system of the linac RF plants and in the locking systems of the photo injector and seed lasers, have reduced the average fluctuations of the arrival time between electrons and the seed laser down to 150 fs in a time period of a few hours.

However, the FEL performance in the long term is still affected by a slow decay of the FEL intensity and a consequent increase of the shot-to-shot jitter (e.g., Fig. 1). This is mainly due to a loss of longitudinal and transverse superposition between the electron bunch and the seed laser pulse.

The main cause of the transverse drift is the seed laser pointing which is not completely controllable due to the technical difficulty to place diagnostics inside the undulators.

The origin of longitudinal drifts is more difficult to ascribe to a particular system. The extreme sensitivity of the laser systems to temperature variations, which can affect the timing of the systems, small changes in the distribution of electron charge and energy in the bunches or drifts of the time of flight from the gun to the first bunch compressor are probably the main causes.

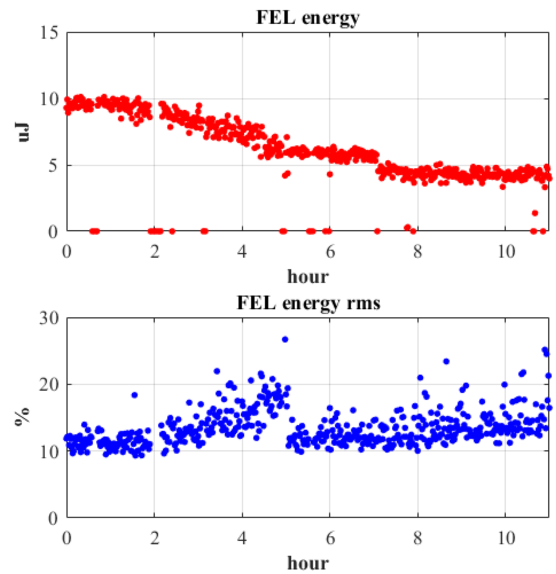

Figure 1: Typical decay of the FEL intensity and increase of the jitter in a time span of 11 hours. The jitter was reduced at the 5th hour by a manual re-optimization of the delay between the seed laser pulses and the electron bunches. The intensity could not be fully recovered because of an ongoing transverse misalignment of the two beams.

A more predictable case in which both the transverse and longitudinal alignment could be perturbed is when the seed laser wavelength (and consequently the FEL wavelength) is intentionally changed by the operators on request by the beamlines. The delay introduced by the Optical Parametric Amplifier (OPA) changes with the laser wavelength and a feed-forward loop implemented to compensate for this variation is not able to completely suppress the residual error. Moreover, by changing the wavelength, the pointing of the seed laser can be disturbed by a variation of shape and intensity of the laser spot measured on the CCD cameras, which affects the calculation of the centroids and induces the pointing feedback to an improper correction.

Before the deployment of correlation-based optimizers, no preventive actions were taken during the experiments to recover the machine performance and a re-optimization

† giulio.gaio@elettra.eu

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUMPA07

was normally carried out by the operators only on request by the beamline scientists. The procedure to recover the machine performance in most of the cases is well established. First the operators use a delay line to adjust the arrival time between the seed laser pulses and the electron bunches, then they run an automatic software procedure which restores the transverse overlapping of the laser and the electron beams [3].

CORRELATION MINIMIZER

When the intensity of the FEL is unstable, it is usual to search for machine variables having the same behaviour. Since a seeded FEL is sensitive to a plethora of variables, the real causes of the FEL instabilities are difficult to identify. This is particularly true when the machine is not optimally tuned and the dependency on parameters usually not critical is higher. In this case the real causes of FEL instabilities could be masked or mixed with each other. This occurs, for example, when the dispersion of the electron beam is not optimized or when RF plants are working far from the crest. In both cases the electron trajectory is strongly affected by the energy jitter of the linac. In this condition, if the resonance energy of the undulators is not perfectly matched with the electron energy, the electron trajectory instability is well correlated with the FEL intensity suggesting wrongly a non-optimal alignment of the electrons in the undulators. For this reason the concept of correlation, even if powerful, has to be taken with particular care and the variables used for the optimization should be selected case by case.

There are many correlation indexes used to measure the dependency between two variables. The most popular is the Pearson correlation coefficient [4] which measures the linear correlation.

After a machine optimization, most of the critical variables used to maximize the FEL performance have low correlation with it because we assume to be on a maximum of the non-linear relationship between the variables and the FEL parameter to optimize. The goal is to keep this correlation low in time. To accomplish this task a new software application called "correlation minimizer" has been developed and is currently used to keep transversally and longitudinally aligned the electron and the seed laser beams.

Software Application

The main goal of this application is not to maximize the performance of the FEL by exploring the variables space following a defined strategy [5, 6], but to slightly adjust these variables in order to maintain the machine in a good working point previously found. For doing that we exploit the natural jitter of the variables by analysing their shot-to-shot correlation with the FEL output. In this way we don't introduce any perturbation that could disrupt the experiments.

In this application three variables have to be defined:

- **Target**: the objective function to maximize, which is usually the FEL energy or a combination of FEL parameters.
- **Sensor**: the variable whose correlation with the target has to be minimized.
- **Actuator**: the variable used to change the sensor value.

The correlation minimizer acquires synchronously the last N shots-to-shot values of sensor and target, calculates the correlation coefficient and moves the actuator in the direction to increase the target. In the case of positive correlation (an increase of the sensor corresponds to an increase of the target) the actuator is moved to increase the sensor value and the opposite if the correlation is negative. The goal of this procedure is to approach the maximum of the target and consequently reduce, and eventually keep, the correlation to zero.

Figure 2 shows the graphical panel used to control the correlation minimizer.

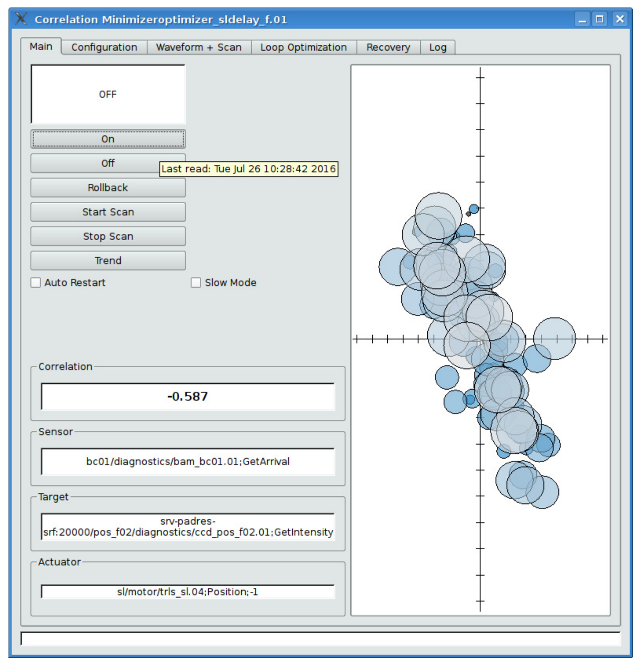

Figure 2: Graphical interface of the correlation minimizer. The spots on the right represent the relationship between the target (vertical axis) and the sensor (horizontal axis). The spots are big for the most recent samples and get smaller as the samples become older. In the example of the figure the correlation is almost linear and the correlation index is -0.587.

Although the usage of the Pearson coefficient naturally drives the correlation minimizer in such a way to maximize the target, in some experiments the FEL energy stability is more important than its absolute value. In this case we adopt an alternative index described below, which takes into account also the energy jitter.

Similarly to the method based on correlation, N shot-to-shot samples are acquired from both sensor and target. The couples (t_i,s_i) are sorted by the sensor values. Then the sorted couples are divided into two groups: the first group A containing N/2 couples $(t^s_i,s^s_i)_{i=1..N/2}$ with the highest sensor values and another group B containing the rest N/2 couples $(t^s_i,s^s_i)_{i=N/2+1..N}$.
For each of the groups an index is calculated as:

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUMPA07

$$T = \frac{avg(t_i^s)}{(1+std(t_i^s))^X}$$

where *avg* is the average function and *std* the is standard deviation.

If T(A) > T(B) then the actuator is changed so to increase the sensor value, otherwise the actuator is moved in the opposite direction.

The exponent "X" can be used to tune the optimization strategy between "maximum search" (X = 0) or "balanced search" (X > 0, usually = 1) that takes into account the target noise magnitude.

LONGITUDINAL OPTIMIZATION

In order to search the longitudinal position of the seed laser pulse inside the electron bunch that gives the highest FEL energy, the laser can be moved along the electron bunch by means of a mechanical delay line. When the seed laser pulse overlaps the head of the electron bunch, the correlation between the electron arrival time and the FEL energy is positive. In fact an increase of the arrival time moves the bunch ahead, thus moving the seed laser into the core of the electron bunch with the effect of an increase in FEL energy. The opposite effect (negative correlation) happens when the seed is on the tail of the bunch. It is therefore obvious that if we want to maximize the FEL energy we have to move the delay line accordingly to the sign of the correlation between electron bunch arrival time and the FEL energy.

In the longitudinal alignment optimization, the configuration of the correlation minimizer is:

- **Target**: FEL energy measured by a gas ionization monitor or by a photon energy spectrometer.
- **Sensor**: bunch arrival time measured after the first bunch compressor or in front the undulators.
- **Actuator**: mechanical delay line used to align longitudinally the seed laser with the electron beam.

The number of samples N and the step size depends on how fast is the instability of the FEL. Typically N varies from a minimum of 100 to a maximum of 500, while the step is usually between 5 and 20 fs. The correction period is in the range 1.5-3 s.

In general the correlation minimizer automatically brings the seed laser pulse close the head of the electron bunch because of a peak in charge density. In this region the FEL has the maximum intensity but also more jitter in energy, spectral purity and wavelength. In this case it can be appropriate to adopt the alternative correlation index with X=1 (balanced search). Figure 3 is an example of automatic optimization.

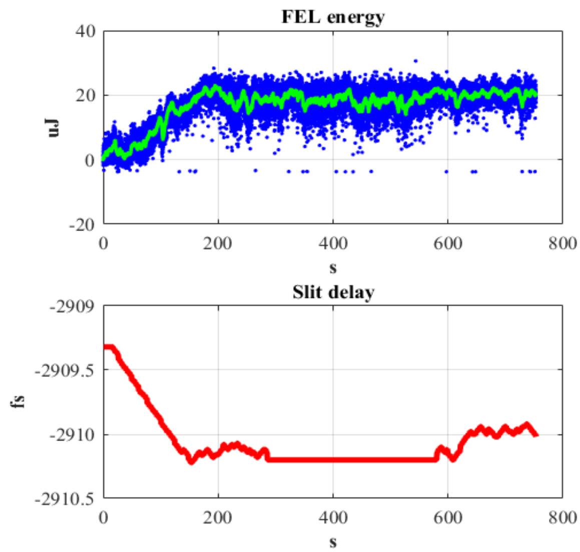

Figure 3: Example of automatic optimization of the delay between the seed laser pulse and the electron bunch using the correlation minimizer acting on the delay line. After reaching the maximum the minimizer is turned off. At 580 s the minimizer is switched on again in "balanced search" mode which decreased the FEL energy *rms* from 16% to 10%.

TRANSVERSE OPTIMIZATION

At FERMI, an automatic tool assists the operator in aligning transversally the seed laser with the electrons. However, it can be run only in agreement with the beamlines scientists because it produces perturbations that can disturb the experiments.

In order to maintain a good transverse overlap with the electron bunch during the experiments, four correlation minimizers are applied simultaneously to optimize separately the four set points (horizontal and vertical position on two CCD cameras) of the seed laser pointing feedback.

The correlation minimizer configuration is the following:

- **Target**: FEL energy measured by a gas ionization monitor.
- **Sensor**: vertical and horizontal position of the seed laser spot on two CCD cameras.
- **Actuator**: set points of the seed laser pointing feedback.

An example of optimization is reported in Figure 4.

If the seed laser beam is too stable to allow measuring the correlation, the gain of the laser pointing feedback is slightly increased, which produces a fast low-amplitude noise which is ideal for the shot-to-shot correlation measurements. Typically the number of samples acquired for correlation calculation is between 300 and 600, the step is in the range 5 to 10 μm, the correction period is 2 s.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUMPA07

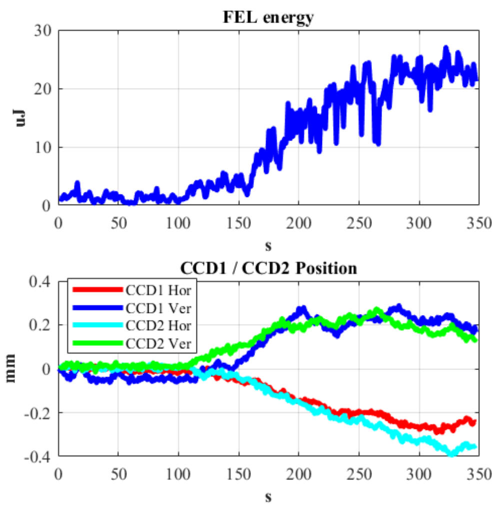

Figure 4: Automatic optimization based on four correlation minimizers working on the set points of the seed laser pointing feedback.

LONG TERM PERFORMANCE

In single-stage single-color FEL mode [7, 8] the usage of the correlation minimizers during user experiments is well established and contributes effectively to obtain and maintain a FEL with good quality.

Figure 5 shows the FEL performance in a period of 48 hours with the transverse alignment optimizer active.

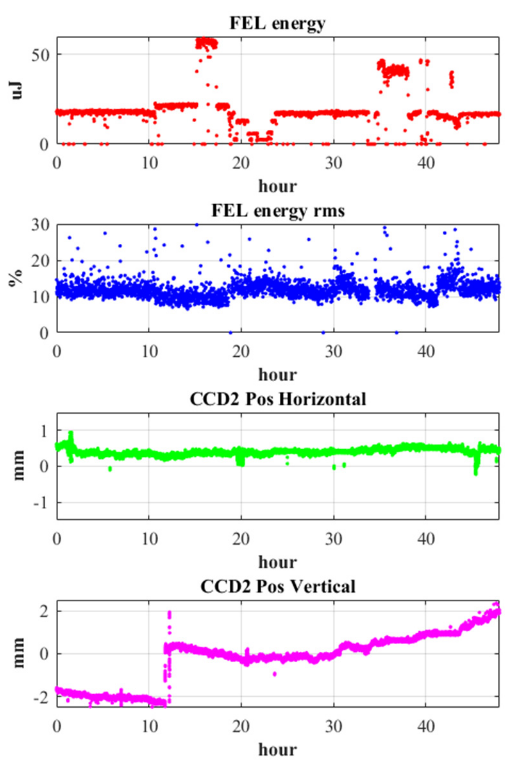

Figure 5: Performance of the FEL in a period of 48 hours with automatic optimization of the seed laser pointing. The third and fourth plots are the values of the sensors used for the optimization.

In this case the optimization of the laser pointing has been limited only to the second CCD camera because it is the most correlated with the FEL. The sharp steps of the FEL energy (red line) are due to changes of the photon filters made by the beamline scientists. At hour 12 the spot of the laser was vertically re-aligned (purple line) because it was going out of the camera field of view. At hour 41 the correlation minimizers were switched off producing a decay of the intensity (red line), then recovered by switching on again the optimizer.

During this 48-hour period the minimizer was able to change autonomously the set point of the seed laser pointing feedback by a total of 2 mm and to effectively keep the FEL energy and jitter at optimum values.

FEL QUALITY FACTOR

In the process of machine optimization carried out by FEL experts or operators during the machine setup, the quality of the photon beam energy spectrum is often taken as a reference. In fact, high intensity and low shot-to-shot jitter are not the only good characteristics of a seeded FEL; also a single line spectrum with narrow bandwidth and good wavelength stability plays a fundamental role in most of the experiments. For this reason some effort has been dedicated to develop an algorithm to automatically analyse the spectrum and use its overall quality as the objective function in an automatic optimization procedure. The FERMI high resolution photon energy spectrometer has been used for this purpose [9].

The FEL Quality Factor (*FELQFactor*) is an index which summarizes in a number the most important features of the spectrum. The idea was to develop an algorithm capable of evaluating the spectrum image as an expert does. The *FELQFactor* has been used in some preliminary machine optimization tests in which the dispersive section and the delay between the seed laser and the electrons had to be optimized. Two optimization algorithms have been used: Descent Gradient and Extremum Seeking [10]. Figure 6 shows an example of the results; the image on the left represents the initial spectrum, while the spectrum after optimization is depicted on the right.

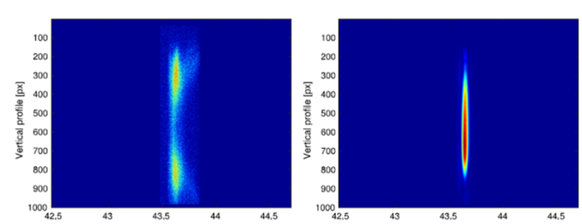

Figure 6: FEL spectrum before (left) and after (right) optimization based on the *FELQFactor* index. The horizontal axis in the images is the photon energy, while the vertical axis represents the vertical photon beam distribution.

Due to the complex data processing required, at present the *FELQFactor* cannot be calculated at the machine repetition rate of 50 Hz, which is mandatory for the corre-

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-TUMPA07

lation-based optimization tools. A basic simplified version of the algorithm able to work shot-by-shot has been successfully tested with a correlation minimizer, encouraging us to proceed with the development of a faster *FELQFactor* implementation.

Currently the main operational problem is that the spectrometer is a shared resource used both for machine optimization (e.g. correlation minimizers) and experimental data normalization, each of them requiring different spectrometer settings most of the time.

CONCLUSION

At FERMI research in the field of automatic optimization is in progress. In the last two years, several software tools have been successfully developed to keep automatically the FEL in a good shape during user experiments by acting continuously and transparently on the longitudinal and transverse alignment of the seed laser with the electron beam. They are routinely used during FEL operations, although further work and additional operating experience are necessary in order to develop robust and reliable tools to be used also in non-standard FEL configurations [7, 8]. With this regard, a novel algorithm has been recently developed to provide automatic human-like evaluations of the FEL energy spectrum quality. The first tests are promising and encourage us to proceed investing further effort in this direction.

ACKNOWLEDGEMENT

We would like to thank Prof. G. Fenu and Prof. F. Pellegrino from University of Trieste for the fruitful collaboration and insights on the development of the *FELQFactor* index and its use for the optimization algorithms.

REFERENCES

[1] E. Allaria *et al.*, “Highly coherent and stable pulses from the FERMI seeded free electron laser in the extreme ultraviolet”, Nat. Photon. 6 (10) (2012) 699–704.

[2] G. Gaio, M. Lonza, “Evolution of the FERMI beam based feedbacks”, *Proc. 13th Int. Conf. on Accelerator and Large Experimental Physics Control Systems*, ICALEPCS’11, Grenoble, France, October 2011.

[3] G. Gaio, M. Lonza, “Automatic FEL Optimization at FERMI”, *Proc. 15th Int. Conf. on Accelerator and Large Experimental Physics Control Systems*, ICALEPCS’15, Melbourne, Australia, October 2015.

[4] K. Pearson, “Notes on regression and inheritance in the case of two parents”, *Proceedings of the Royal Society of London*, 1895, 58 : 240–242.

[5] M. McIntire, T. Cope, S. Ermon, D. Ratner, “Bayesian optimization of FEL performance at LCLS”, *Proceedings of the 7th International Particle Accelerator Conference*, IPAC’16, Busan, Korea, June 2016.

[6] Ilya Agapov, G. Geloni, S. Tomin, I. Zagorodnov, “Automatic tuning of Free Electron Lasers”, ArXiv:1704.02335 (2017).

[7] E. Allaria, *et al.*, “Two-stage seeded soft-X-ray free-electron laser”, Nat. Photon. 7 (11) (2013) 913–918.

[8] E. Allaria, *et al.*, “Two-colour pump–probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser”, Nat. Commun. 4 (2013).

[9] C. Svetina, D. Cocco, N. Mahne, L. Raimondi, E. Ferrari, M. Zangrando, PRESTO, the on-line photon energy spectrometer at FERMI: design, features and commissioning results, J. Synchrotron. Radiat. 23 (1) (2016) 35–42.

[10] N. Bruchon, *et al.*, “Free-electron laser spectrum evaluation and automatic optimization”, Nuclear Inst. and Methods in Physics Research, A 871 (2017) 20 29.