AUTOMATIC FEL OPTIMIZATION AT FERMI

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Abstract

FERMI is a seeded Free Electron Laser (FEL) located in Trieste, Italy. The machine setup and optimization is a non-trivial problem due to the high sensitivity of the FEL process to several machine parameters. In particular, the electron bunch trajectory and its spatial overlap with the seed laser beam represent one of the key aspects to optimize and then preserve during machine operation.

In order to ease the FEL tuning and to guarantee a long term stability of the photon beam, a software process integrated into the feedback systems performs automatic trajectory optimization of both the seed laser and the electron beams. The algorithm implementation, the results and the operational issues are presented.

INTRODUCTION

The FERMI machine setup is a non-trivial task. Although a deeper knowledge of FEL mechanisms in parallel with new diagnostic tools have reduced the time spent for machine tuning, new and more challenging requests coming from the users community have significantly increased the complexity of the accelerator setup and its operation during the experiments.

One of the priorities is the preservation of the FEL radiation quality in the long term. Over the years a number of feedback loops have been added in order to cope with subsystem instabilities [1]. However, even thermal drifts of only a few hundredths of degrees or requested changes of the machine working point tend to move the machine away from the optimum in terms of intensity, stability and spectral radiation purity.

In order to tune the machine for its best performance, a well established sequence of operations has to be carried out. At first, the photon-injector and seed laser systems have to be prepared, transversal and longitudinal electron beam dynamics in the linear accelerator (linac) have to be tuned, and then the FEL tuning process along one of the two undulator chains has to be performed. At the end, the photon beam is driven into the photon beam transport system and aligned in the experimental chamber. Before each users beam time one day is usually dedicated to machine preparation and tuning but, in case of non-standard experiments, up to five days have to be reserved for this task.

The tuning process which is performed by the physicists, in most of the cases consists of a number of manual or automatic scans of actuators versus machine variables, leaving to the physicist the final duty to set actuator to the optimum value. Instead, the optics matching, which imposes the design values of the Twiss functions to the electron beam [2], is completely automatic. There are two main reasons why the optics tuning is performed using the matching program: the first is that the problem is difficult to be managed (up to 6 dimensions in the linac optics). The second reason is that the model in terms of relations between quadrupole strengths and Twiss functions is well known. The availability of a system model reduces the optimization problem to a task that a proper algorithm quickly solves.

However, a system model cannot be always taken for granted. During the commissioning of a new system (e.g. a particle accelerator), the difference of the real system from the model could drive the model based optimization to frustrating results. In order to obtain a correct system model, software based simulators with adaptive and diagnostic capabilities have been developed and are currently supporting operations in several particle accelerators.

Although this kind of software could be applied to the entire FEL from the linac gun to the photon beam in the experimental chamber [3], its usage as an online tool has still to come. In particular, the multiplicity of the systems involved (photo-injector and seed laser beams, electron beam and FEL beam transport) and their nonlinearity have limited the adoption of these tools to only single well known subsystems, leaving to the manual intervention the rest of the machine preparation.

However, the manual tuning, which is a complex task, tends to be inefficient because the expertise of the personnel involved in machine operations is not homogeneous.

FEL PROCESS

The FERMI FEL design is based on an external seeding scheme. Two undulator chains, FEL-1 and FEL-2 operated one at a time, provide radiation in two different ranges, 100-20nm and 20nm-4nm respectively. In the modulator (first undulator) of both undulator chains, an external seeding laser in a tuneable range of 228-265 nm, overlaps in time and space the electron bunch provided by the linac. The resultant energy modulation of the electron bunch is then converted into charge density modulation by a chromatic dispersive section following the modulator. The electron bunch then passes through a series of undulators tuned in magnetic field so that coherent FEL radiation is emitted at one of the harmonics of the seed laser.

In FEL-2 the process is made in two stages. The radiation emitted by the first stage, that is similar to FEL-1, is used as seed in the second stage. In this way the seed laser wavelength is downshifted twice reaching shorter wavelengths.

The undulators and the seed laser are the most important devices involved in the tuning process. A software supervisor [4] taking into account the relations between the undulator magnetic strength, the electron beam energy and the seed laser wavelength, sets the

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undulator gaps and the seed laser energy according to the user request in terms of FEL polarization and wavelength.

Other two key variables, the dispersive magnet strength and the seed laser power, are optimized by performing scans versus the FEL spectrum. Whereas the mentioned variables are changed according to the requested FEL parameters (power, wavelength and bandwidth), other variables have to be kept constant during this process. In particular, controlling the overlap of the seed laser and the electron beam in the undulators is one of the most important and challenging tasks due to the high number of variables involved.

Seed Laser Alignment

The alignment procedure consists in measuring the electron beam position before and after the modulator by means of two YAG screens. After inhibiting the electron beam, the position of the seed laser beam is acquired by the same couple of screens and moved in order to overlap the electron beam. The procedure, which is carried out manually, has the drawback of being destructive (a screen has to be inserted) and complex because the seed laser has to be steered on the two screens one at a time. At the end of the procedure, which could take several cycles of screen insertion/extraction, the screens are removed and a shot-to-shot feedback loop is activated to keep the seed laser trajectory stable on two CCDs. The first CCD is located about 8 m upstream the modulator. The second should have been located inside the modulator but unfortunately the laser beam is measurable only intercepting both the seed laser and the electron beam. In order to have an estimation of the laser beam size and transverse position, the seed laser beam is split before the modulator. A small portion of the beam follows an equivalent optical path inside a closed box and its transverse profile, the so called "virtual undulator", is acquired by a CCD.

Although this solution gives a good estimation of the seed laser position and shape in the modulator, the virtual modulator is very sensitive to thermal drifts due to the multiple beam reflections in the box. Moreover, a mirror installed just in front the modulator, used to steer the laser beam into the modulator, increases the dependence of the whole system on thermal stability since its movement is not compensated by the feedback.

Another critical point is the dependence of the seed laser optical transport on wavelength change. Peaks of absorption of the mirrors at 250 nm cause an intensity drop of the profile acquired by the CCD, which can only in part be compensated by the automatic gain control of the CCD itself. As a result the estimation of the centroid of the laser profile at this wavelength becomes inaccurate thus reducing the benefit of running a trajectory feedback based on these CCDs.

Electron Beam Alignment

The mechanical misalignments of undulators and magnets have been fixed during the initial FEL commissioning. Instead, the electron beam steering based on the photon beam emitted by each radiator is carried out before each machine run. In case the radiator emissions are not well superimposed, the electron beam trajectory is adjusted inside the undulators by changing the trajectory feedback set-points.

Although the optimal electron beam trajectory is then maintained constant by a feedback loop, offsets of a few tens of microns are often empirically applied to maximize the intensity of the FEL emission.

The alignment of the first stage of FEL-2 is one the most challenging task because no available diagnostics is able to discriminate the emission of the first and the second stage [5]. In this case the insertion of a screen acquired in single shot (to avoid high radiation doses) is the only available option. Once the screen is extracted, the FEL-2 first stage is virtually a black box leaving to the operator just the possibility to optimize blindly the electron beam trajectory.

AUTOMATIC TRAJECTORY OPTIMIZATION

Optimizing a multidimensional system is a difficult task when the relations between the system inputs and the objective function are uncertain. Humans tend to explore all the inputs in order to create a model. Random scans are essential to find the inputs that are most correlated with the objective function; these are then scanned one at a time to find best values and the optimization process is iterated until the objective function reaches a satisfying value.

A similar approach is also adopted by stochastic optimization (SO) algorithms. Contrary to deterministic optimization where the relation between the objective function and the input values is well defined, stochastic optimization is based on the random exploration of the system input space. Stochastic approximation, simultaneous perturbation, simulated annealing, random search and evolutionary algorithms are the most promising optimization methods. Their strategies slightly differ one from the other on how they introduce randomness in the search process and on how they define the climbing step to reach the optimum. Formally it has been demonstrated that the best search algorithm does not exists (see No Free Lunch theorems [6]) and the success of an optimization algorithm depends on how it fits its problem.

The search of the optimal seed laser and electron beam trajectories (array of horizontal/vertical beam positions) presents all the characteristics of an optimization problem that could be solved by this kind of algorithms. The system is multidimensional, non-linear and uncertain. In FERMI the objective function used so far is the FEL radiation intensity measured by a gas monitor or by a CCD camera. A more complex objective function to be used in the future could be a combination of FEL parameters (power, bandwidth and spectral purity) opportunely weighted.

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The algorithm implementation takes advantage of a software communication protocol developed in house, called NRM (Network Reflective Memory) [7] that is used to distribute across the control system a shot-to-shot timestamp, the so called "bunch number". Moreover, the NRM transmits all the variables involved in the feedback loops and the photon beam transport diagnostic values. This real-time network, which was mainly developed for the shot-to-shot feedbacks, replicates snapshot of all FERMI important parameters in all the computers of the control system, allowing shot by shot data analysis that go beyond the feedback system purposes.

The optimization process is strictly integrated into the trajectory feedback loops; it changes at each shot the feedback set points, acquires sensors and actuators and couples them with the objective function.

The algorithm consists of six steps:

- Collects N trajectories and the corresponding objective function values (ex. FEL output intensity);
- Sorts the trajectories according to the objective function value in descending order;
- Calculates a "**golden**" trajectory by averaging the first M trajectories (M is usually 10% of N);
- Calculates a "**reference**" trajectory by averaging the remaining N-M-P trajectories where P is the number of the "**worst**" trajectories (P usually 10% of N);
- Sums the difference between the golden and the reference trajectory to the feedback set point;
- Go back to the first step until a reasonable result is obtained.

The optimization algorithm can run in active or passive mode. In the active mode the trajectory feedback injects a perturbation in the system by changing the set-point of a selection of sensors. In order to speed up the scan accordingly to the feedback system response, the perturbation applied to each horizontal/vertical position usually resembles a 2D square spiral. The spiral scans have to be opportunely desynchronized between different positions in order to maximize the number of trajectory combinations. The maximum spiral dimension is normally determined a priori according to the physical magnitudes of the underlying process. It can be constant during the whole optimization process or decrease in time according to simulated annealing principles. In case the initial spiral dimension cannot be determined, a warming-up process adjusts the spiral size until the absolute value of the Pearson correlation between the horizontal or vertical position and the objective function reaches a predetermined value.

The reduction of the convergence time is the main advantage of injecting a controlled perturbation. The drawback is an additional perturbation of the beam trajectory that could affect user experiments.

In passive mode the exploration is allowed by the shot-to-shot noise present on the beam, making this optimization process virtually transparent to the experiments. A trick for increasing the noise magnitude when it is not sufficient to improve the objective function consists in increasing the trajectory feedback gain.

In FERMI the alignment of the seed laser with the electron beam is based on the active optimization mode. The trajectory feedback starts rotating the seed laser spot on two CCDs and four iterations of 130 shots are sufficient to maximize the FEL intensity (see Fig. 1).

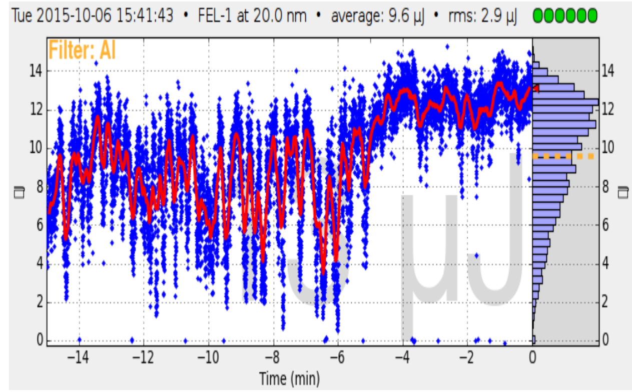

Figure 1: Increase of the FEL output intensity and stability achieved by running the seed laser alignment optimizer.

Usually the optimal electron beam trajectory in the undulator is found manually and then the optimization algorithm in passive mode is launched to see whether there is room for further FEL improvements. At least five iterations of 600 shots are necessary to get significant results. In order to avoid the optimization statistics been biased by residual dispersive trajectories, the matching between the electron energy beam and undulators configuration has to be verified in advance.

Alternatively to the gas monitor, a CCD in the experimental station can also be used to measure the FEL intensity. The advantage is that the optimized parameter is closer to the experiment, thus taking into account also effects occurring downstream the gas monitor (Fig. 2).

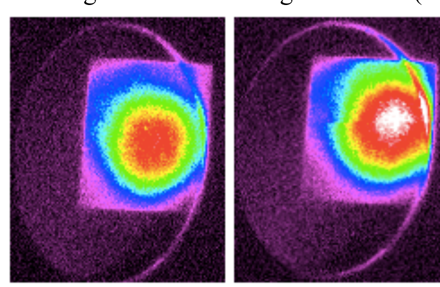

Figure 2: Profile of the FEL radiation on a YAG screen in the experimental chamber before (left) and after (right) the optimization of the electron beam trajectory in the undulators (15% of intensity increase).

CORRELATOR

The automatic detection of the machine parameters that most affect the noise of the FEL beam and the launch of the optimization procedure on those parameters allow a faster achievement of the optimal working point.

The number of the variables that have to be monitored and correlated with the FEL parameters is very large and

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inhomogeneous, so at the moment the search is restricted to those involved in the FERMI beam based feedbacks.

In order to evaluate the best noise detecting strategies a software application written in Matlab, acquires every second the last N shots (N between 100 and 2000) of 214 sensors/actuators, correlates them with the FEL output intensity and finally sort them in descending order according to the correspondent correlation value.

In an ideal world the correlation between feedback variables and FEL should be as low as possible. Sensors with high correlation values indicate a displacement from the optimal values, whereas high correlation in the actuators could suggest a feedback malfunction (too high feedback gain, feedback loops crosstalk, sensor malfunction, etc.).

It has been empirically noticed that a gap of more than 20% between the top shots of the list and the rest is a clear indication of malfunction. For example, this tool can identify with a very good reliability the temporal and transversal misalignment of the seed laser with respect to the electron beam (see Fig. 3), glitches on the RF plants and in general a misconfiguration of any feedback system.

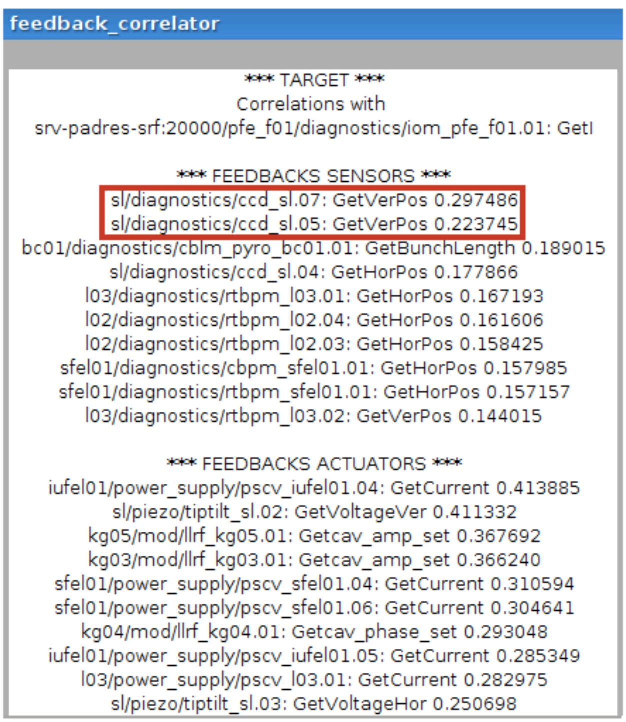

Figure 3: List of sensors/actuators most correlated with the FEL intensity; seed laser vertical positions on the two CCDs on top of the ranking indicate a seed laser transverse misalignment.

CONCLUSION

In order to cope with system uncertainties a procedure based on stochastic optimization principles has been developed and integrated in the seed laser and electron beam feedbacks. Beam nonlinearities and thermal drifts affecting the feedbacks systems could be well recovered by automatic optimization procedures based on stochastic algorithms. In order to proactively detect the arising of system drifts that affect FEL radiation, a tool that correlates all the feedback sensors/actuators with the FEL output power has been developed. Recurrent patterns in correlation values are useful to detect noise sources and implement the appropriate countermeasures.

Being able to easily optimize the accelerator and the FEL will be a great value for the future FERMI experiments.

REFERENCES

[1] G. Gaio et al., “Evolution of the FERMI beam based feedbacks”, THPPC129, ICALEPCS2013, San Francisco CA, USA.

[2] S. Di Mitri et al., “Electron beam optics and trajectory control in the Fermi free electron laser delivery system”, Phys. Rev. ST Accel. Beams 15, 012802.

[3] G. De Ninno et al., “Start-to-end time-dependent study of FEL output sensitivity to electron-beam jitters for the first stage of the FERMI@Elettra project”, MOPPH058, FEL 2006, Berlin, Germany.

[4] C. Scafuri, B. Diviacco, “Automation of the Wavelength Change for the FERMI Free Electron Laser”, TUPPC052, ICALEPCS2013, San Francisco CA, USA.

[5] L. Giannessi, “First lasing of FERMI FEL-2 (1°stage) and FERMI FEL-1 recent results”, MOOB06, FEL2012, Nara, Japan.

[6] D. H. Wolpert and W. G. Macready, “No Free Lunch Theorems for Optimization”, IEEE Transaction on Evolutionary Computation, Vol. 1, No. 1, April 1997

[7] L. Pivetta et al., “The FERMI@Elettra distributed real-time framework”, THDAUST03, ICALEPCS2011, Grenoble, France.

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