EVOLUTION OF THE FERMI BEAM BASED FEEDBACKS*

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Abstract

FERMI is the first seeded Free Electron Laser (FEL) users facility. A number of shot-to-shot feedback loops running synchronously at the machine repetition rate stabilize the electron beam trajectory, energy and bunch length, as well as the trajectory of the laser beams used for the seeding and pump-probe experiments. They are based on a flexible real-time distributed framework integrated into the control system. The interdependence between feedback loops and the need to react co-ordinately to different operating conditions lead to the development of a real-time supervisor capable of controlling each loop depending on critical machine parameters not directly involved in the feedbacks. The overall system architecture, performance and user interfaces are presented.

INTRODUCTION

About four years have passed since the start of the commissioning of FERMI. After the initial phase dedicated to technical systems commissioning and understanding of the accelerator behaviour, a long time has been spent to characterize the parameters of the radiation emitted by the seeded FEL. In the meanwhile, in parallel to machine dedicated studies, an increasing number of shifts have been assigned to beamlines commissioning and users experiments [1].

The demanding users requests in terms of FEL radiation quality and the growth of the number of possible machine configurations (electron beam energy, repetition rate, photon polarization/wavelength, etc.) have dramatically increased the complexity of the operations that the control system has to manage. For this purpose, a number of software "supervisors" have been developed to coordinate and automate complex operations with the goal to reduce the workload in the control room, minimize the duration of such operations and possibly reduce errors.

In this context, a number of beam based feedbacks play a key role since they are not only used to stabilize the beams but also as servos to set and maintain the main machine parameters (beams trajectory, electron energy, bunch length, etc.).

SEEDED FEL

In the FERMI FEL, a bunched electron beam at up to 50 Hz repetition rate is first accelerated by a 1.5 GeV linac and then injected into a chain of undulators (modulators and radiators), where it interacts with an UV "seed" laser. A dispersive section transforms the electron

energy modulation produced by this interaction in bunch charge modulation thus creating a micro-bunched beam that generates ultra-short high-energy radiation pulses in the following radiator undulators.

There are two parallel chains of undulators, FEL-1 and FEL-2, working alternatively one at a time. In FEL-1, which covers the 100-20 nm radiation wavelength range, after being generated by the radiators, the photon pulses are directly sent to the beamlines for the experiments. In FEL-2, which uses a two-stage harmonic cascade configuration, the output of the first stage of modulator/radiators is used as a seed in the second stage, allowing the generation of radiation with wavelength down to 4 nm.

The key to keep the radiation output stable is to guarantee the transverse and in particular the longitudinal (temporal) stability of the interaction point between the seed laser pulses and the electron bunches along the modulators. A shot-to-shot jitter of 70 fs$_{rms}$ in the arrival time and of 10 μm$_{rms}$ in the position of the seed laser pulse with respect to the electron bunch has been achieved [2].

Besides the uncorrelated shot-to-shot noise that cannot be reduced by feedback systems, other instabilities are mainly due to slow thermal drifts which affect the RF plants and the laser systems. These instabilities have frequencies below 0.1 Hz and can be effectively damped by the beam based feedbacks.

SHOT-TO-SHOT BEAM BASED FEEDBACKS

All the shot-to-shot beam based feedbacks share the same software architecture. Sensors and actuators are interfaced to PPC VME frontend computers running Linux with real-time extension and are managed by kernel modules [3] [4]. The only sensors that are acquired by conventional user space applications are the CCD cameras used in the laser feedbacks.

The sensor values are shared among the control system computers by means of a real-time shared memory called Network Reflective Memory (NRM). The feedback loops that run on two real-time servers, one devoted to the electron beam feedbacks the other to the lasers feedbacks, collect data from the NRM, perform the feedback processing and write the new actuator settings into the NRM.

The real-time applications that manage the actuators on the frontend computers read the new settings from the NRM and set the values on the controlled devices.

Although until now FERMI has been mainly operated at 10 Hz repetition rate, a machine run has been dedicated to testing the systems at 50 Hz. During that run the feedbacks have been used smoothly and no modification

were required except some small changes of the Proportional Integral Derivative (PID) controller parameters.

Electron Beam Feedbacks

There are two classes of electron beam based feedbacks, one in charge of controlling the beam in the transverse plane (trajectory) and the other in the longitudinal plane (energy and bunch length).

The main goal of the transverse feedbacks is to stabilize the trajectory in the linac in order to control the wake-fields, and inside the undulators to preserve the overlap with the seed laser. There are presently four feedback loops (Fig. 1), two dedicated to FEL-1 and two to FEL2 operations, controlling a total of 62 Beam Position Monitors (BPM) and 62 correctors [5].
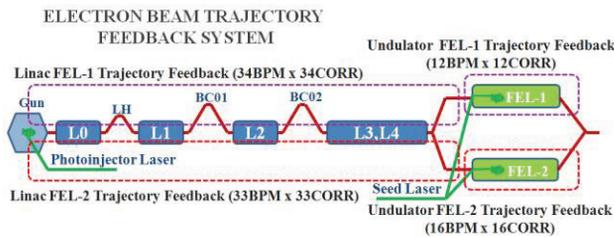

Figure 1: Layout of the trajectory feedback loops.

The longitudinal feedbacks keep the beam energy constant to guarantee the correct electron energy in the undulators and a precise arrival time of the electron bunches with respect to seed laser pulses in the modulators. Moreover, the longitudinal feedbacks stabilize the bunch length which directly affects the distribution of charge in the electron bunches.

At present we operate three separate longitudinal feedback loops (Fig. 2). One controls the energy in the Laser Heater (LH) and energy and bunch length in the first Bunch Compressor (BC01). A second loop controls energy and bunch length in the second Bunch Compressor (BC02). At the end of the linac a third loop stabilizes the final beam energy. Energy and bunch length are measured by BPMs in dispersive regions and pyro detectors respectively. The actuators are amplitudes and phases of the RF plants.
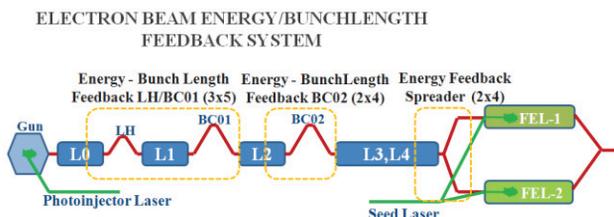

Figure 2: Layout of the longitudinal feedback loops.

In order to avoid correcting the beam during Radio Frequency (RF) trips, which normally last one or two shots, the application which interfaces the Low-Level RF (LLRF) systems analyzes shot-by-shot the LLRF parameters, detects any spike and notifies it through the NRM to all the feedbacks, which eventually discard those shots in their calculation.

The feedbacks configuration, including sensors, actuators, PID parameters, etc., can be changed on-the-fly during the feedback operation.

Laser Beam Feedbacks

Two pulsed laser systems are currently installed in FERMI: the seed laser and the photo-injector laser, which is used to extract and shape the electron bunch from the cathode and also for the Laser Heater. The seed laser is one of the most sensitive systems of FERMI: a variation of 0.01° C of the seed laser room temperature determines a time shift between the electron bunch and the seed laser pulse of 50 fs with a consequent drop of the FEL output intensity.

Two different types of shot-to-shot feedbacks guarantee temporal and trajectory stability of the seed laser. Both of them make use of CCD cameras and mirrors moved by piezoelectric devices.

The position of the beam in a given point is measured by acquiring an image of its transverse profile. This is done in a non-destructive way by using a "beam sampler", namely a semi-reflective mirror, and eventually converting the radiation to visible light in order to be detected by a CCD. The images are acquired by Intel based dual-CPU servers through Gigabit Ethernet links from Basler CCD cameras [6]. The calculation of the beam position using one of the possible algorithms (Raw RMS, Gaussian, Asymmetric Gaussian, etc.) is performed by a Tango device server. An optimized code, which makes use of the GNU Scientific Library (GSL) for non-linear fitting and of the OpenMP GCC extension for parallel computing, allows calculating an Asymmetric Gaussian fitting of the laser spot on a 782x582-pixel image in less than 4 ms, a time sufficient to perform a 50 Hz feedback loop [7].

For the actuators, an in-house developed controller based on a BeagleBone board with Ethernet interface [8] is able to control shot-by-shot two piezo drivers used to steer the beam in the horizontal and vertical plane [9].

One of the most important sources of temporal and transverse beam instabilities in the seed laser system is the thermal drift of the amplifier. Two different feedback loops, one controlling the temporal drifts and the other the trajectory in the resonant cavity, have been deployed.

The seed laser system generates an UV beam to seed alternatively either FEL-1 or FEL-2, and a second IR beam called Seed Laser for Users (SLU), which is used for pump-probe experiments in the beamlines [10].

Position and angle of the seed laser inside the modulators of FEL-1 or FEL-2, called pointing, must be kept constant to assure the overlap with the electron beam. This is accomplished by a feedback loop relying on two CCDs and two mirrors mounted on piezo movers placed in the laser path before the modulators.

The most challenging path in terms of trajectory and temporal stability is the SLU one. A 150 m long transport line takes the laser to the experimental hall where the

beam can be forwarded to one of the experimental stations by means of a switching mirror.

The shot-to-shot jitter of the arrival time between the FEL and the SLU pulses measured in the experimental stations is 15 fs_{rms} [10]. Slow drifts are mainly due to variation of the path length in the transport; for this reason three feedback loops have been deployed to keep constant the trajectory. The first stabilizes the beam trajectory from the source to the switching mirror, the second is dedicated to the breadboard of each experimental station, while the third controls the pointing of the laser on the sample inside the experimental chamber (Fig. 3).
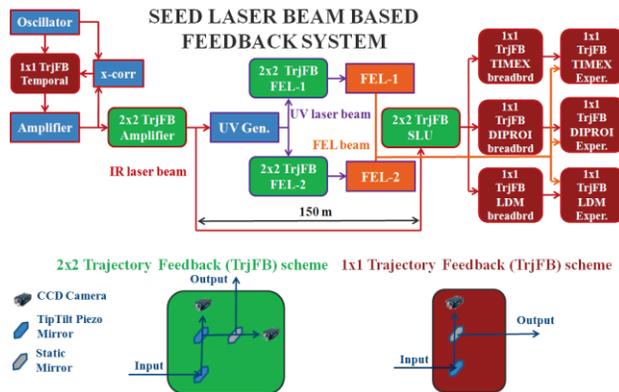

Figure 3: Block diagram of the seed laser system with representation of all the feedback loops.

FEEDBACKS SUPERVISOR

In order to cope with the complexity of setting up all the feedback loops depending on the FERMI configuration, a feedbacks supervisor has been developed.

When running in FEL-2 mode, the electron beam feedbacks of FEL-1 must be inhibited because they partially share sensors and actuators with the FEL-2 feedbacks. The correct response matrices, which are determined empirically, have to be loaded in the proper feedback. Moreover, the correct calibration parameters of those BPMs of FEL-1 and FEL-2 which share the same detectors must be loaded in the corresponding Tango device server.

In some cases the various feedback loops functionally depend one on the other and must be run simultaneously. For example in order to correctly measure the energy (used by the longitudinal feedback) by means of a dispersive BPM inside a bunch compressor, another feedback must stabilize the launching trajectory upstream the bunch compressor itself. In another case the last BPMs must be excluded from the linac trajectory feedback when they are used by the energy feedback loop. The supervisor must assure that the feedback loops are activated in the required configuration and sequence.

A specific module of the supervisor works in real-time to reconfigure on-the-fly the feedback loops in some particular cases. An example is related to a "software interlock" working in real-time that automatically reduces the electron bunch generation frequency when the

radiation doses in the undulator area exceed a threshold value. It is based on shot-to-shot measurements provided by Cherenkov fibers detectors via the NRM. The frequency reduction is obtained by synchronously shifting shot-by-shot the timing of the RF pulse in the gun with respect to the photo-injector laser pulse. In this event, the supervisor alerts the feedback loops that inhibit the processing of the missing bunches and adjust the PID parameters according to the new repetition frequency.

GRAPHICAL USER INTERFACES

The various feedback applications don't share the same code, but control algorithms and functionalities are similar. All of them have multiple input/outputs, rely on Singular Value Decomposition (SVD) for the response matrix inversion and use a PID controller. Instead, a substantial difference consists in the way the response matrix is empirically determined by measuring it on the real machine.
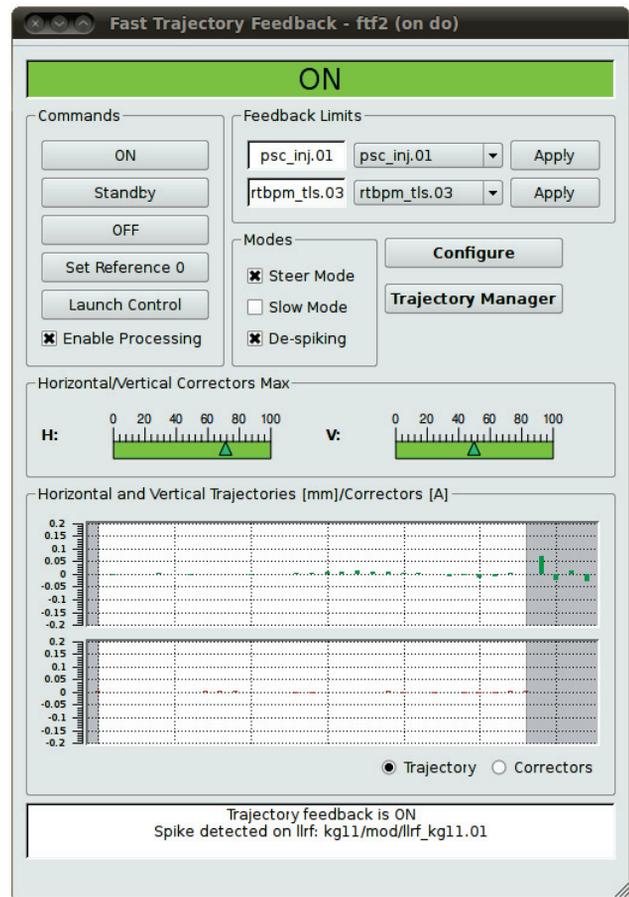

Figure 4: Trajectory feedback control panel.

A lot of effort has been spent to uniform all the feedback interfaces to client application in order to simplify the development of supervision applications and the operation from control room using graphical user interfaces. The feedbacks that control electron and laser beam trajectories have the same type of control panel (Fig. 4), while the longitudinal feedbacks panel is slightly different.

The machine setup and FEL performance optimization is carried out by physicists and normally involve a lot of tuning procedures. Apart from a few exceptions where the optimization is automatic, these operations are still done manually. Two of the most important parameters that have to be tuned are the electron beam trajectory in the undulator region and the seed laser pointing. The optimization procedure is often performed by scanning the position of the beam on single sensors. This can be easily done by changing the corresponding set-point value when the feedback loop is closed, thus using the feedback as a servo. In FERMI this operation is simplified by a graphical application that displays the transverse position of the beam measured by the selected sensor using a 2-D plot (Fig. 5). The panel draws in real-time the current position as well as the past positions using persistency and circles with variable size and colour. Using the mouse, the "current position" circle can be dragged in a new position in the 2-D plot, and the new value of the set-point is automatically communicated to the feedback loop.
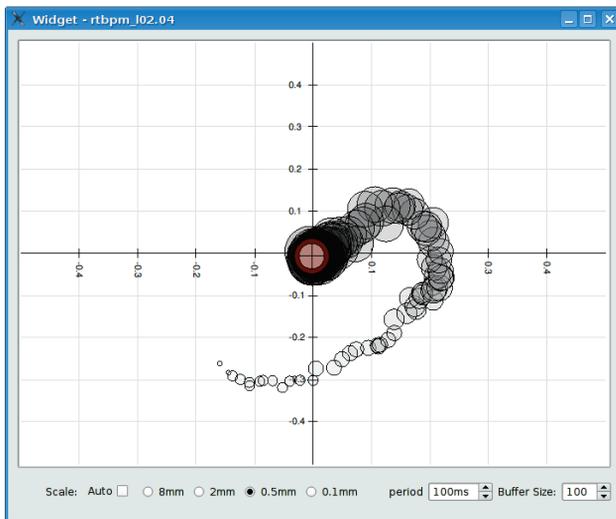

Figure 5: Trajectory feedback set-point panel.

CONCLUSIONS

Relying on a real-time feedback infrastructure, a number of feedback loops have been implemented, which guarantee stability and reproducibility of the machine performance. Moreover, the use of the feedbacks during the machine commissioning significantly facilitates and speeds up the optimization of the machine performance.

A supervisor application dynamically manages the configuration of the feedbacks adapting them to different machine setups and operating modes.

The number of operating beam feedback loops is continuously growing following the increasing demand of stability from the experiments and the need to further ease and automate the machine tuning.

In the near future, new control techniques and algorithms will be investigated to increase the feedback overall performance and robustness.

ACKNOWLEDGEMENTS

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