COMMISSIONING OF THE FERMI@Elettra FAST TRAJECTORY FEEDBACK*

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Abstract

FERMI@Elettra is a new 4th-generation light source based on a single pass Free Electron Laser (FEL). In order to ensure the feasibility of the free electron lasing and the quality of the produced photon beam, a high degree of stability is required for the main parameters of the electron beam. For this reason a flexible real-time feedback framework integrated in the control system has been developed. The first implemented bunch-by-bunch feedback loop controls the beam trajectory. The measurements of the beam position and the corrector magnet settings are synchronized to the 50 Hz linac repetition rate by means of the real-time framework. The feedback system implementation, the control algorithms and preliminary close loop results are presented.

INTRODUCTION

Since the beginning of the FERMI@Elettra commissioning [1], a framework based on Matlab allowed the flexible implementation of slow feedback loops by arbitrarily choosing sensors and actuators from a pool of devices [2]. Based on the response matrix concept and its inversion through the Singular Value Decomposition (SVD), the framework was used to implement a slow trajectory feedback whose main goal was to steer the beam and restore a given trajectory. Since the feedback was a loop written in Matlab running with a period of a few seconds, less importance was given to its dynamic response and ability to damp noise up to a certain bandwidth.

The tight specifications in terms of stability required by a new concept machine such as a seeded FEL together with the uncertainty about the tools necessary to support a challenging commissioning, led to the implementation of a fast feedback system joining the flexibility of the Matlab framework with the capability to interact with the beam shot by shot.

To achieve such results, beam diagnostics (electron and photon Beam Position Monitors – BPMs, charge monitors, bunch length monitors, fluorescent screens, etc.) and actuators (magnet power supplies, RF plants, etc.) communicate in real-time at the linac repetition rate. A distributed shared memory (Network Reflective Memory, NRM) based on a dedicated Gigabit Ethernet network allows deterministic data exchange through the control system [3].

IMPLEMENTATION

Although a feedback loop running at 50 Hz can be easily managed by an up-to-date computer, its components must be carefully evaluated to prevent weird behaviour due to unpredictable execution time. In fact, in order to optimize the feedback performance, the whole process of collecting BPM data, performing feedback calculation and setting correctors, must be carried out in one intra-shot period of 20 ms, thus reserving just a few milliseconds for each of these operations.

CPU

The trajectory feedback relies on the control system front-end computers which interface BPMs and corrector power supplies. An additional computer, called "real-time server", is dedicated to the feedback processing. They all are VME systems with MVME7100 PowerPC CPU boards running Linux and the Adeos/Xenomai real-time extension. The availability of four Gigabit Ethernet ports onboard allows an easy and effective separation between real-time and non real-time traffic.

The adoption of the Adeos/Xenomai real-time extension reduces the latency and the jitter of critical tasks to the microsecond range. To take full advantage of the system real-time capabilities, all the software which implements data processing and communication with the hardware is executed in Adeos/Xenomai interrupt handlers or tasks. Shared memories and FIFOs allow communication between real-time tasks and Tango servers running in user space.

Sensors

55 stripline (linac) and 25 cavity (undulator region) BPMs provide beam position measurements with a measured resolution of 10 and 4 μm respectively.

The Libera Single-Pass detector, manifactured by Instrumentation Technologies, has been chosen to acquire the bunch by bunch analog signals from the stripline BPMs. The detector features two Ethernet links:

- One 100 Mbit/s port directly connected to the control system network mainly used by the Tango device server, running embedded, to configure the detector parameters (gain, offsets, …) and monitor the electronics status.
- One 1 Gbit/s port providing low latency data by transmitting, synchronously to the machine trigger,

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UDP packets containing horizontal and vertical beam positions and the four raw stripline waveforms.

The real-time acquisition is done by six VME based control system computers, each handling a group of up to 15 BPMs. A standard Gigabit switch serializes the Ethernet packets coming from a group of detectors and sends them to the CPU.

On the CPU side, a dedicated Ethernet port, which is in charge of collecting data in real-time, uses a customised driver to provide raw access to its interrupt routine. Once the packets are received, a kernel module application executed in the interrupt handler extracts and copies beam position information in the NRM and in a local circular buffer.

In the worst case, the whole trajectory is acquired by the front-end computers in about 140 µs.

The cavity BPM detector consists of two homemade MicroTCA cards, ADO and ADA [4]. ADO acquires analog signals directly from the cavity BPM front-end and transmits the data using a UDP packet. ADA drives the BPM calibration signal which is generated after each shot. Both boards provide a 100 Mbit/s Ethernet port that will soon be upgraded to 1 Gbit/s.

The cavity BPMs acquisition system is similar to that of the stripline BPM, except that the position calculation and the detector supervision are directly managed by the low level computers. Three control system computers are reserved for data collection through dedicated Ethernet switches.

Actuators

The trajectory correction is done by two types of magnets: air-cored, used in the low energy part of the linaca nd in the undulator region, and iron-cored, used in the rest of the machine. Two homemade magnet power supplies (model A2605 and A2620 respectively) provide 5 or 20 Amps. The external interface relies on a 100 Mbit/s Ethernet link and a simple UDP protocol allowing to drive the output current and get the status of the power supply at a maximum rate of 200Hz. Eleven low level computers, installed along the accelerator, interface the power supplies through dedicated Ethernet switches.

A kernel module application running in each computer receives synchronization and correction data from the NRM. A timer of the CPU working at 10 KHz, started every machine shot, sequentially set the power supplies connected to it. At each timer interrupt, the kernel module routine sends an UDP packet containing the current setting to one power supply; the timer is stopped immediately after the last power supply is set. The generated current is the sum of the setting provided by the Tango server and the one from the trajectory feedback. A single low level computer manage up to 40 power supplies.

Real-time Communication

The NRM plays a fundamental role interconnecting in a deterministic way all the 20 CPUs involved in the trajectory feedback. It also provides the "bunch number", a sort of "real-time timestamp" which univocally identifies each linac shot.

At present, the total amount of data exchanged on the NRM by the trajectory feedback is about 3 KB per shot. It mainly contains BPM data, corrector values and the related bunch number. The maximum propagation time across the NRM is 1 ms.

The feedback acts on the electron beam bunch by bunch, which means that the correction of a given bunch is calculated based on the measured position of the previous bunches. To maximize the dynamic performance of the feedback, the open loop total delay must be at most one shot period, thus 20 ms. The following is the time schedule of the whole feedback chain within one shot period starting from the generation of a given bunch number:

- **0 ms**: time zero, bunch number starts propagation on the NRM.
- **1 ms**: new bunch number available on the NRM.
- **1.2 ms**: linac shot, the BPMs acquire the beam position.
- **2.2 ms**: new beam positions available on the NRM.
- **3 ms**: feedback routine calculates corrector values.
- **7 ms**: new corrector values available on the NRM.
- **9 ms**: all the corrector power supplies are set with the new values.

The remaining time is sufficient for the magnet current to reach the final value and to provide the required magnetic field to the incoming bunch.

Feedback Processing

Although, for practical reasons, the trajectory feedback routines run on one dedicated CPU, the flexibility of the system allows running bunch by bunch feedbacks on every CPU which joins the NRM.

Similarly to the rest of the real-time software, the feedback code is written as a Xenomai kernel module. In particular, to take advantage of the floating point operations, which are not supported in the standard Linux kernel, the algorithm code runs in a Xenomai thread.

A Tango device server, interfaced to the kernel module by a shared memory, configures at runtime the list of sensors and actuators, sets the control parameters and loads or measures the response matrix for each of the feedback loops. Each Tango device server implements about 100 Tango commands/attributes.

The control algorithm is based on a standard PID controller which is preceded by either a configurable low pass or median filter; the latter has better performance in presence of spiky data. A series of notch filters could be configured to remove efficiently periodic noise sources. As the whole feedback chain is carried out in the time period within two shots, the closed loop dynamics is dominated by one period delay.

The response matrix is empirically calculated by measuring the trajectory perturbation produced by each corrector. The measurement procedure is integrated in the feedback software and is carried out with a bunch by bunch measurement. The power supplies are driven sequentially with a programmable current ramp. In the meanwhile the BPMs are acquired synchronously to the corrector excitation. At the end of the process, an algorithm calculates the response matrix correlating ramped kicks and trajectory distortions. To halve the measurement time, the process can also be performed in parallel on both planes.

The SVD algorithm is employed to calculate the correction matrix. In the "inversion" process, correctors, singular values and BPMs can be individually weighted. The correction efficiency and robustness to mesurements errors can be optimized by means of singular value reduction with the algorithm known as Tikhonov regularization.

COMMISIONING

During the FERMI@Elettra commissioning no relevant periodic noise has been measured on the beam, except for a ripple introduced by a bending magnet power supply, which has been eventually replaced. Temporary malfunctions of the timing distribution and the low level RF systems have erratically affected the beam trajectory, but also these problems have been solved by fixing the source of the disturbance. Slow drifts, which are mainly related to temperature variations and slow changes in the characteristics of the accelerating cavities, are presently the main noise sources that the feedback is supposed to counteract (Fig. 1).

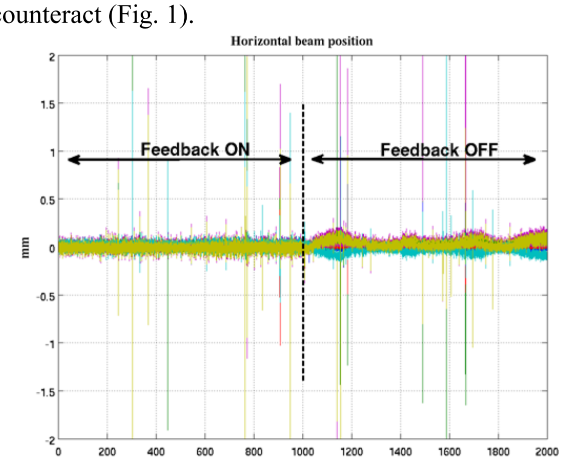

Figure 1: Feedback effect on the horizontal trajectory measured with 34 BPMs in the linac.

Micro interruptions of the electron beam due to quick trips of the RF plants and lasting a couple of linac shots, are automatically recognized by the software using simple heuristic rules and filtered out.

In order to study the closed loop behaviour, a Matlab simulation code has been developed. It allows the rapid tuning of the control parameters by manually optimizing the system response. The sensitivity function calculated with the simulation using a given set of PID parameters (kp=0.05, ki=0.2, kd=0) agrees quite well with the one measured on the real machine (Fig. 2).

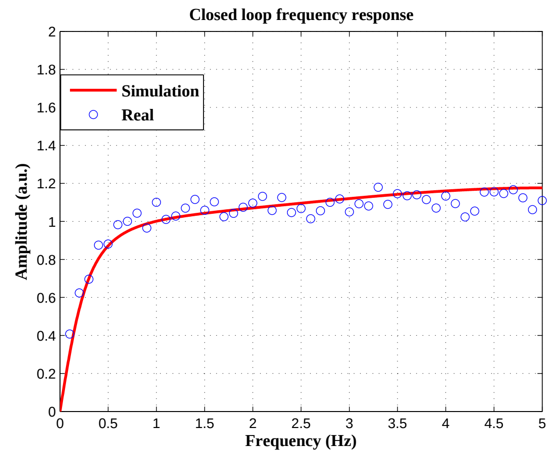

Figure 2: Simulated vs. real sensitivity functions with the linac working at 10 Hz repetition rate.

At present two fast trajectory feedback loops are used during commissioning shifts (Fig. 3). The first controls the trajectory in the linac by means of 34 BPMs and 34 correctors. The main goal is to keep stable the beam trajectory in the accelerating structures. The second makes use of 8 BPMs and 8 correctors, and act on the beam position in the undulators. With the present configuration of the control parameters no evidence of disruptive coupling between the two loops has been noticed. Nevertheless a global approach using all of the BPMs and correctors in a single loop will be pursued in the next future.

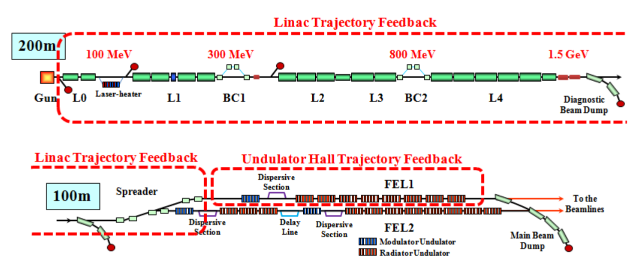

Figure 3: The machine sectors where the two feedback loops are currently operating.

The fast response matrix measurement procedure demonstrated to be very efficient. By using a four-shot ramp per corrector, the measurement of the linac response matrix in both planes takes less then 20 seconds (10 Hz repetition rate).

Small variations of the beam energy, changes of the beam transport optics, uncorrelated noise coming from the electronics and non linearity of the BPMs can lead to discrepancies between the response matrix and the real machine, and produce an increase of the beam position *rms* when the feedback is on. The amplification of the noise is concentrated in the higher part of the spectrum. In order to mitigate this problem, the Tikhonov regularization method has been adopted. It allows a good correction at the lower frequencies while the higher part of the spectrum is not amplified significantly. This method has the additional advantage of avoiding the correction of unreal trajectories that often brings to useless high corrector strengths.

Although the fast feedbacks have been successfully used during the first experiments on the beamlines, the most frequent usage is during the machine commissioning with the following purposes:

- Perform trajectory scans inside the accelerator cavities to find a condition that minimizes the beam emittance.
- Restore a given golden trajectory.
- Keep stable the trajectory when changing the phases of the RF plants.

Each feedback loop can be easily operated and monitored from the control room using a QTango [5] graphical panel (Fig. 4).

The general configuration of the feedback including correction and control parameters can be changed also by non-expert people. In addition to the standard ON/STANDBY/OFF buttons and trajectory plots, a *SlowMode* checkbox reduces automatically the feedback gain by a factor of ten. When the feedback is run just once to restore or steer a trajectory, the *SteerMode* checkbox controlling the Tikhonov regularization factor is enabled, and the singular value reduction is not applied.

A useful graphical feature using slide bars allows selecting just a part of the machine and to close the loop on it. This is accomplished on the fly by setting to zero the weights of BPMs and correctors that must be excluded.

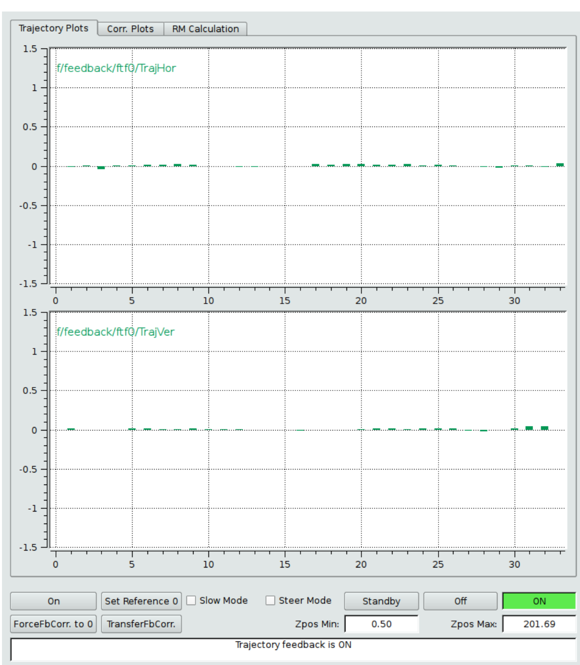

Figure 4: Fast trajectory feedback control panel.

CONCLUSION

The experience gained in developing fast feedback systems for the Elettra storage ring [6] together with the availability of a powerful and well integrated real-time framework, helped the development and commissioning of the fast trajectory feedback, which is now regularly used during machine operations.

Additional features are planned to facilitate its operation and increase the robustness in case of disruptive events such as unexpected changes of the beam energy due to trips of the linac accelerating sections.

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