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LONG TERM STABILITY AND SLOW FEEDBACK PERFORMANCE AT THE EUROPEAN XFEL

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Abstract

The European XFEL is now routinely running in user operation since more than two years. Up to 8 longitudinal and 9 transversal slow feedback loops are routinely used to keep the accelerators chosen operation conditions. First tests of comparing the machine 'free-floating' state versus fully fixing all relevant monitoring signals have been carried out and show interesting results.

Here we will review the feedback systems in terms of software architecture and conceptual layout but also in respect to feedback and FEL performance.

SOME HISTORY: SLOW FEEDBACKS AT FLASH

Both the transversal and longitudinal feedbacks (FBs) used at the European XFEL have first been introduced at the Free Electron Laser in Hamburg FLASH [1]. The first implementations of a transversal feedback as it is used at the European XFEL [2], date back to 2011. While prior implementations at FLASH where Matlab graphical user interface (GUI) based ‘stand-alone’ applications, the nowadays used implementation is a DOOCS [3] server based centrally managed application.

While round trip time and also interfacing to monitors and actuators for the stand-alone implementations where acceptable, these architectures hold risk of having multiple instances running at the same time, to name just one of the drawbacks of such an implementation.

THE SLOW TRANSVERSAL FEEDBACK

The server based slow transversal feedback (also called ‘orbit feedback’) [4] is running on a central server machine hosting the data acquisition system (DAQ) [5]. This system synchronizes all incoming data streams on the level of macro-pulses (this is the repetition rate the machine is triggered with – typically 10 Hz. For details on the structure of beam delivery at the European XFEL see [6]). This ensures that all beam position data served to upstream clients is originating from the same macro-pulse. The general architecture in terms of involved infrastructure and dataflow is shown in Figure 1.

The orbit feedback is using a simple PI controller to correct orbit deviations at the currently active beam position monitors (BPMs). The needed amount of correction is calculated using the theoretically calculated orbit response matrix which is read from the online optics model [7] and doing a singular-value-decomposition (SVD).

All parameters like active actuators (up till now we just use corrector magnets), active monitors (BPMs) as well as SVD parameters etc. can be re-configured on-the-fly. Thereby the orbit feedback offers a lot of flexibility, while the underlying control algorithm is kept very simple and thereby robust! This has proven to be exactly the combination which was needed to allow for a fast and reliable commissioning of the European XFEL accelerator.

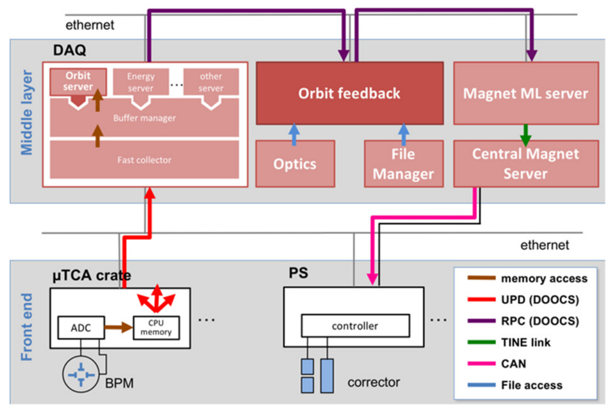

Figure 1: Implementation of the slow transversal feedback within the overall control software architecture.

Layout of Orbit Feedback Along the Linac

First idea has been to run the orbit stabilization as a global feedback. While the software architecture and overall concepts behind the feedback also allow for this, it has shown to be much more practical to use several decoupled instances of the feedback. One global feedback would impose a much more complex architecture in terms of sensitivity and exception handling. Further allows the operation of decoupled feedbacks for more flexibility in terms of the various operation modes of the facility (e.g. only injector operation versus full beam transport to main dumps).

The nowadays used distribution of all orbit feedback instances along the accelerator is shown in Figure 2.

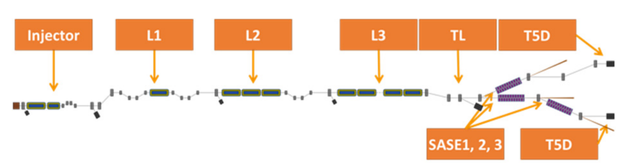

Figure 2: Distribution of orbit feedback instances along the accelerator.

While the single feedback instances are all derived from the same software (and just get configured differently), the demands and targets for the individual instances differ a lot. One can roughly divide the feedbacks into three classes:

- Orbit keeper
    - Here the feedback is aiming for maintaining the orbit over larger sections. Examples are: L2, L3
- Launch stabilization

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- The orbit feedback is aiming to fix position and angle in front of a critical section. Examples are here the undulators (SASE 1, 2, 3) or the collimation section (TL).

- Multi-purpose
  - At these locations the orbit feedback might either be used to keep the launch or in contrast do e.g. larger orbit manipulations. This is the case e.g. for the undulator launch feedbacks (more on this in the following).

In X-ray beam delivery mode, we are typically running 9 instances of the feedback, distributed as shown in Figure 2.

The performance of the feedbacks in terms of targeted maximal allowed orbit deviation depend heavily on the section of the accelerator. Typically, the seen orbit variations in the low energy regions of the linac are much higher compared to the ones in the high energy regions. Table 1 shows a typical set of thresholds of the orbit feedback within it is not reacting – the so-called 'deadband'.

Table 1: Typical Set of Deadband Settings for All Instances of the Orbit Feedback

Location	FB category	Deadband
Injector	Rarely used	-
Linac 1	Launch	10-20 µm
Linac 2	Orbit keeper	10-20 µm
Linac 3	Orbit keeper	10-20 µm
TL	Launch	5-10 µm
SASE1	Launch/multi-purpose	2-4 µm
SASE2	Launch/multi-purpose	2-4 µm
SASE3	Launch/multi-purpose	2-4 µm
T4D	Launch	40-80 µm
T5D	Launch	40-80 µm

Orbit Feedback Performance and Lessons Learned

The deadbands given in Table 1 present the outcome of the experience made by operating the orbit feedback over the last two years. Excluding the dump lines (where the BPM resolution is the worst one due to e.g. large beam pipe) the empirically chosen deadbands very well reflect the expected beam stability along the machine.

The seen feedback performance and also overall functionality thus very well fits to the current machine operation modes.

While the instances along the linac are usually kept running all the time, the undulator feedbacks are just used in launch configuration if the machine is running in smooth user run. If the machine needs to be tuned to a different setup (e.g. larger wavelength changes), often a so-called adaptive orbit feedback is used. The details of the concept behind his feedback are described in [8]. Thus, the tuning for optimal SASE performance usually is an iterative process switching back and forth between these different orbit feedbacks. A typical scenario would look like shown in Figure 3.

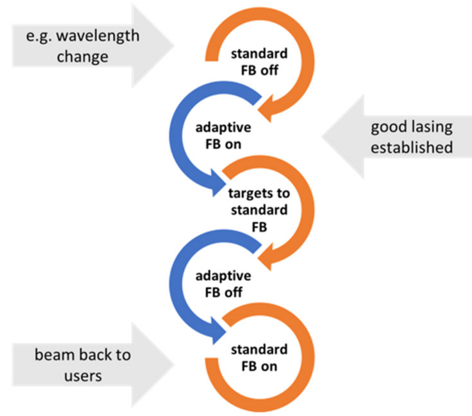

Figure 3: Typical sequence of orbit feedback usage for e.g. wavelength change.

Using the feedbacks in this sequence we are a) able to have an easy way for finding the optimal launch and b) also can rapidly switch to a save state and thereby hand back the beam to the users.

Beside maintaining the launch conditions into the undulators, the SASE orbit feedbacks have also been used to steer the photon beam. The idea arose from the experience that we used 'some' correctors within the undulator section to modify the pointing of the photon beam on request of the users. Here we usually just used some few (2-4) correctors per plane. To not apply any drastic kicks to the beam trajectory, the idea was to allow the undulator feedback to use all correctors and just apply a linear slope to the targets along the undulator line.

Figure 4 shows the outcome of applying a linear slope of 200 µm to the vertical plane. Using this approach, we could a) keep the lasing power at the same level, while b) moving the photon beam by roughly 400 µm (as requested by the photon users) and c) did not need to touch any settings of the undulators (which can at least be time consuming).

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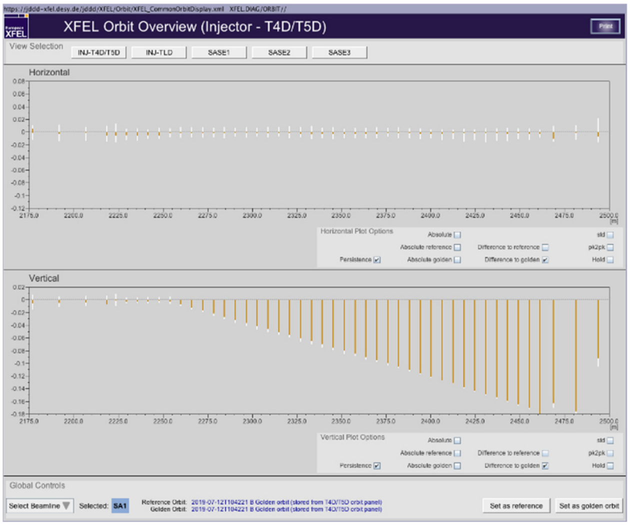

Figure 4: Graphical user interface showing the application of a linear slope of 200 µm in the vertical plane at the SASE1 beam-line. Shown is the difference orbit in respect to the situation before the orbit feedback targets have been modified.

THE SLOW LONGITUDINAL FEEDBACK

Similar as the trajectory feedbacks did the first implementations of the longitudinal feedbacks date back to the early days of the FLASH facility. Also, here first implementations have been realized using stand-alone GUI programs. With the development of the underlying software landscape the implementation as centrally managed server instance has been straight forward.

The architecture and integration into the DAQ system is similar to the one of the orbit feedbacks. The feedback algorithm again uses a simple PI-controller to maintain the desired target for various parameters related to the longitudinal phase space. This feedback has also been designed to run in fully coupled manner, thus allowing to consistently keep machine at a chosen point in the longitudinal phase space.

Table 2: Overview of the Types of Monitors and Corresponding Actuators for the Longitudinal FB

Monitor	Monitor Type	#	Actuator
Toroid		1	Laser attenuator
BCM	Beam compression monitor	3 (6)	RF phase
BAM	Beam arrival time monitor	4 (6)	RF gradient
Energy	Spectrometric energy measurement	4	RF gradient or phase

Table 2 shows an overview of the types of monitors available in the longitudinal feedback. All monitors and actuators can be dis-/enabled on-the-fly. The underlying architecture does further allow to either run coupled or uncoupled response matrices.

Experience Made with Maintaining the Longitudinal Phase Space

The inherent stability of the European XFEL is already very good due to careful design and engineering providing a stable and contained environment for the electronics and beam-lines. The amount of regulation to keep a certain operation point in longitudinal phase space thus is strongly reduced compared to FLASH. Nonetheless are the visible drifts of the various subsystems having a clearly visible impact on the SASE performance, as shown in Figure 5.

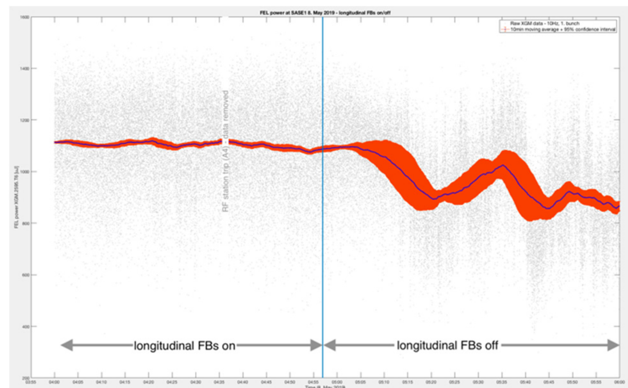

Figure 5: FEL power at SASE2 beam-line over ~2 hours. The vertical line marks the time where the longitudinal feedbacks went off. Blue line: 10 minute moving average, red area: 95 % confidence interval.

CONCLUSIONS

The standard orbit feedback has proven to be very appropriate in terms of versatility and robustness. This not only holds true for the commissioning but also for the experience made within the first years of user operation. Even more complex orbit manipulations, like shown for the shifting of the photon beam pointing could easily be accomplished with the feedback as it is.

Even though the longitudinal stability of the European XFEL is inherently very good, did we observe large excursions and degraded FEL performance if run without any feedbacks. The longitudinal feedbacks are very well able to counter fight these drifts and instabilities. So also this feedback provides all needed functionality and performance needed for these days operation modes.

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