FEEDBACKS AND AUTOMATION AT THE FREE ELECTRON LASER IN HAMBURG (FLASH)

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Abstract

For many years a set of historically grown Matlab scripts and tools have been used to stabilize transversal and longitudinal properties of the electron bunches at the FLASH.

Though this Matlab-based approach comes in handy when commissioning or developing tools for certain operational procedures, it turns out to be quite tedious to maintain on the long run as it often lacks stability and performance e.g. in feedback procedures. To overcome these shortcomings of the Matlab-based approach, a server-based C++ solution in the DOOCS (Distributed Object Oriented Control System) [1] framework has been realized at FLASH. Using the graphical UI designer jddd [2] a generic version of the longitudinal feedback has been implemented and put very fast into standard operation. The design uses sets of monitors and actuators plus their coupling which can easily be adapted to operation requirements.

The daily routine operation of this server-based FB implementation has proven to offer a robust, well maintainable and flexible solution to the common problem of automation and control for such complex machines as FLASH and will be well suited for the European XFEL purposes.

INTRODUCTION
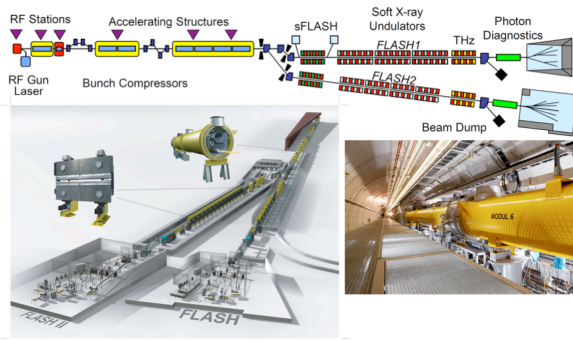
The FLASH Facility

Figure 1: The Free Electron Laser in Hamburg (FLASH) with the extension FLASH 2 which is being constructed at the moment.

The Free electron Laser in Hamburg (FLASH) has been the world's first soft X-ray free-electron laser (FEL). It is available to the photon science user community for experiments since 2005. The main Linac is driven by seven superconducting accelerator modules. Many of the technologies in use have been further developed to adopt it at the European XFEL project. At the moment FLASH is extended by a second undulator line (FLASH 2) providing multiple photon users with beam at the same time.

Control System Infrastructure at FLASH

The prominent control system used at FLASH is DOOCS. A key concept of the here shown feedback loops is to use the central data acquisition service (DAQ) [3] for synchronizing all data of a single machine shot. This synchronized data can be used within so called middle layer servers to compute higher level monitoring data like e.g. beam energy (derived from beam position monitors plus optics data) or be used for feedback within the machine. As can be seen in figure 2 can these middle layer servers (e.g. the energy server) itself provide data to servers further downstream (in this case the slow RF feedback).
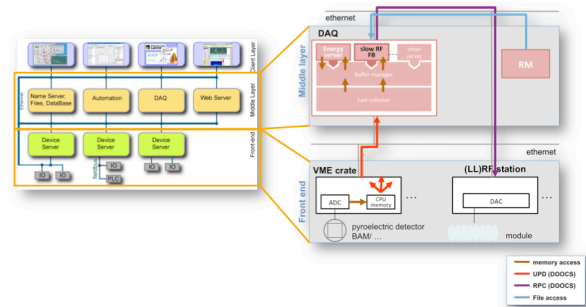

Figure 2: Data flow for a typical DAQ based middle layer server – here for the slow longitudinal feedback.

EVOLUTION OF FEEDBACKS AT FLASH

In the beginning most of the automation got its origin in simple processing scripts to ease operation "put together during a shift". At FLASH these where mostly Matlab scripts with rudimentary GUIs without or only poor exception handling.

If such a tool has proven to be needed for standard operation it is good practice to turn it into a *server* properly integrated into the control system infrastructure.

As an example (and since it is an essential tool for standard operation of a FEL) the *slow longitudinal feedback* (also called *slow RF feedback*) will be discussed here in more detail.
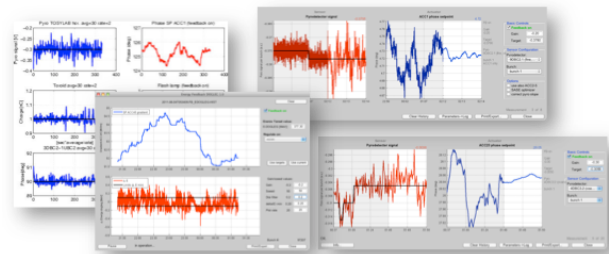

Figure 3: Some examples of Matlab based feedback programs.

THE SLOW LONGITUDINAL FEEDBACK

The longitudinal phase space of the electron bunch is the most important parameter determining the gain and stability of the lasing process. To meet the requirements of stable user operation, the preservation of the established longitudinal properties is the key to reliable operation.

There are in general three parameters that need to be taken care of: **charge**, **compression** and **energy**. We will not further discuss any details about the interplay between these parameters and the lasing process (this has been discussed in e.g. [4]). Instead, we will show the layout and architecture of the feedback and the connected operator GUIs.

The Longitudinal Feedback Loops at FLASH

In the current layout (Fig. 4) there are up to **six feedbacks loops** active along the electron beam-line to preserve the longitudinal phase space properties.
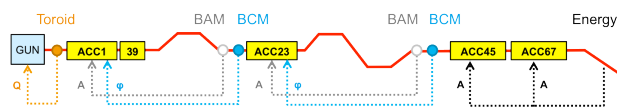

Figure 4: Schematic diagram showing the monitor and actuator positions of the six longitudinal feedback loops.

These feedback loops are:

Charge FB
  • Monitor: Toroid directly behind the laser driven photo injector (GUN)
  • Actuator: rotatable $\lambda/2$ plate in laser beam line

Compression FBs
  • Monitor: pyro-electric detector (BCM)
  • Actuator: RF phase of nearby module

Beam arrival FBs
  • Monitor: beam arrival time monitor (BAM)
  • Actuator: RF amplitude of nearby module

Energy FB
  • Monitor: Energy measurement in dispersive section
  • Actuator: RF amplitude of last modules

Monitors, Actuators and the Reality

While the charge can easily be measured using a standard toroid, the beam energy is determined by a middle layer server using a spectrometric orbit measurement in a dispersive section [5]. Technical details of the beam arrival time and bunch compression monitors have also been discussed in [4].

The wide operation range of FLASH (bunch charges from 0.06 nC up to nC level, energies from $0.37 - 1.25$ GeV corresponding to $45 - 4$ nm) can causes the monitors to show nonlinear response. To get proper response of the FB loops for this wide range of operation, one can a) choose between different monitors and b) needs to measure the response matrix for each (strongly) differing operation point. Switching between different monitors is nicely integrated into the standard operation panels. Measuring of a response matrix is done using a Matlab GUI.

The Feedback Algorithm

The feedback algorithm assumes that for a small change of the actuators ($\delta\mathbf{a}$) one can expect a linear response on the monitors ($\delta\mathbf{m}$). This very common and robust approach has been covered extensively in literature. Thus one can use the inverse of the response of all monitors ($\mathbf{R}$) to evaluate a global correction in one step as follows:

$$\delta\mathbf{a} = \mathbf{R}^{-1} \cdot \delta\mathbf{m}$$

Using all relevant monitors and actuators, the full equation for a global correction becomes:

$$\begin{pmatrix} \delta ampl_{ACC1} \\ \delta phase_{ACC1} \\ \delta ampl_{ACC39} \\ \delta phase_{ACC39} \\ \delta ampl_{ACC23} \\ \delta phase_{ACC23} \\ \delta ampl_{ACC45} \\ \delta phase_{ACC45} \\ \delta ampl_{ACC67} \\ \delta phase_{ACC67} \end{pmatrix} = \begin{bmatrix} R_{11} & R_{12} & \dots & \dots & R_{91} \\ & \ddots & & & \\ & & \ddots & & \\ & & & \ddots & \\ 0 & & & & \vdots \\ & & & & R_{99} \\ & & & & R_{910} \end{bmatrix} \begin{pmatrix} \delta BAM_{1UBC2} \\ \delta BAM_{BC2} \\ \delta BCM_{BC2}(fine) \\ \delta BCM_{BC2}(coarse) \\ \delta BAM_{BC3} \\ \delta BCM_{BC3}(fine) \\ \delta BCM_{BC3}(coarse) \\ \delta BAM_{18ACC7} \\ \delta Energy_{Dogleg} \end{pmatrix}$$

Since here both, the monitor and the actuator vectors, include redundant entries one needs to do the proper wiping of columns and rows to select between the monitors/actuators of choice.

We create the *pseudo inverse* using a singular value decomposition (SVD) to create the inverse response matrix $\mathbf{R}^+$. Since this method fills in general all elements with non-zero values, a binary matrix $\mathbf{B}$ ($b_{ij} \in \{0,1\}$) holding the selection of the monitors and actuators to be used, is constructed from the monitor/actuator selection by the operator. Using a *Hadamard product* (element wise multiplication) of this matrix $\mathbf{B}$ with the inverse response matrix one can finally create the requested matrix $\mathbf{C}$ to be used in the equation given above.

$$\mathbf{B} \circ \mathbf{R}^+ = \begin{bmatrix} b_{11}k_{11} & b_{12}k_{12} & \dots & b_{1i}k_{1i} \\ & \ddots & & \vdots \\ & & & b_{ji}k_{ji} \end{bmatrix} = \mathbf{C}$$

The final structure of the matrix $\mathbf{C}$ in e.g. the case of selecting the *fine BCM* monitors, and acting on *ACC1* for the compression loop and *ACC45* for the energy loop, would have the following structure:

$$\mathbf{C} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & c_{15} & c_{16} & 0 & 0 & c_{19} \\ c_{21} & c_{22} & c_{23} & 0 & c_{25} & c_{26} & 0 & 0 & c_{29} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ c_{51} & c_{52} & c_{53} & 0 & c_{55} & c_{56} & 0 & 0 & c_{59} \\ c_{61} & c_{62} & c_{63} & 0 & c_{65} & c_{66} & 0 & 0 & c_{69} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ c_{91} & c_{92} & c_{93} & 0 & c_{95} & c_{96} & 0 & 0 & c_{99} \\ c_{101} & c_{102} & c_{103} & 0 & c_{105} & c_{106} & 0 & 0 & c_{109} \end{bmatrix}$$

The implementation of these matrix operations can be seen in figure 5 in the GUI showing the colored table (*Expert/configuration panel*).

Operators' View

The operation of the slow longitudinal feedback is monitored and controlled using a set of panels created with the graphical control system editor *jddd* [2].

There are three levels/scopes of operation offering different complexity (Fig. 5):

- **Operator panel: basic operation** e.g. to open/close individual loops (charge, BCMs, BAM, energy), overall FB status
- **Monitor/actuator overview: show FB performance** to monitor/actuator traces, set targets, monitor/actuator status
- **Expert/configuration panel: full expert view** which offers full access to response matrix, monitor/actuator details/configuration and much more
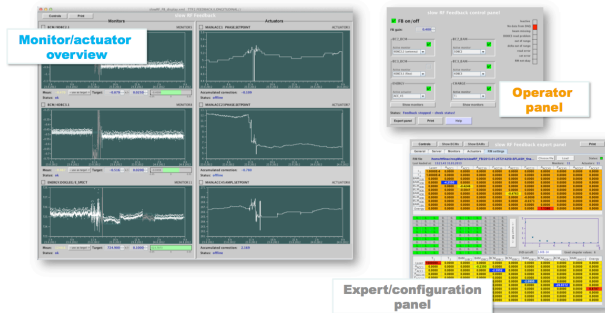

Figure 5: The three main GUIs used for operation of the slow longitudinal feedback.

Much effort has been put into keeping the pure operation of the FB as easy as possible while still offering the maximum flexibility in terms of configuration (e.g. SVD *cut-offs*) or choice of monitor to actuator loops. So is e.g. the *operator panel* hiding all complexity of the involved matrix operations and "simply lets the operator choose the monitors and actuators he wants".

OTHER FEEDBACKS

Orbit Feedback

The orbit FB designed for standard operation at FLASH has been discussed on the PCaPAC 2010 [6] already. The schematic diagram below shows the locations where the orbit FB has been running successfully along the machine.
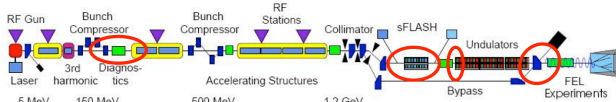

Figure 6: Sections where the orbit FB is used at FLASH.

RF Feedback for the Transverse Deflecting Structure

By simple cloning the slow longitudinal FB and proper configuration, a slow FB loop controlling the RF phase for a transverse deflecting cavity, which is being used for bunch length measurements, could be set up "within hours" [7] (Fig. 7).
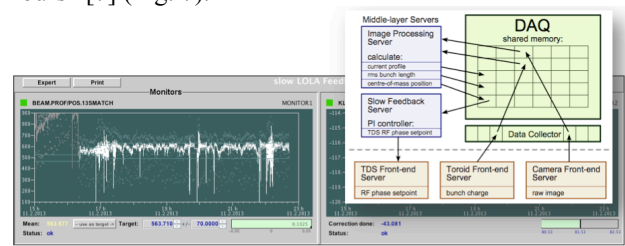

Figure 7: A clone of the slow longitudinal FB used for stabilizing the streaked beam on an off axis screen.

SUMMARY AND CONCLUSIONS

Preserving the longitudinal properties of the electron bunches is essential for a FEL running as a user facility.

The daily routine operation of the shown server-based FB implementation has proven to offer a robust, well maintainable and flexible solution to this common problem of automation and control for such complex machines as the FLASH and will be well suited for the European XFEL purposes.

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