# FAST FEEDBACK STRATEGIES FOR LONGITUDINAL BEAM STABILIZATION

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*Abstract*

The key for pump-probe and seeding experiments at Free Electron Lasers such as FLASH is a femto-second precise regulation of the bunch arrival time and compression. To achieve this beam based requirements, both for a single bunch and within a bunch train, it is necessary to combine field and beam based feedback loops. We present in this paper an advancement of the currently implemented beam based feedback system at FLASH. The principle of beam based modulation of the RF set point can be superimposed by a direct feedback loop with a beam optimized controller. Recent measurements of the achieved bunch arrival time jitter reduction to 20 fs have shown the performance gain by this direct feedback method [1]. The combination of both approaches will be presented and possible advantages are discussed.

## INTRODUCTION

The Free Electron LASer at Hamburg (FLASH) is a facility for research with tunable laser light in the X-ray range. It provides its users a pulsed light with tunable wavelength down to 4.2 nm generated by SASE processes. Electron bunch trains of variable length and frequency with a repetition rate of 10 Hz are accelerated to about 1.2 GeV. Each pulse is enabled for about 2 ms meanwhile up to 2400 bunches with a maximum repetition rate of 3 MHz are injected. Providing a stable and reproducible photon pulses needs a precise acceleration field control. During the last years additional control strategies were developed and included in the LLRF controller. On the one hand the learning feedforward (LFF) minimizes repetitive amplitude and phase errors from pulse to pulse [2], whereas a second order multiple input-multiple output (MIMO) controller acts within the pulse [3]. The X-FEL requirements for field control are reached and below a relative amplitude error of 0.01 % and an absolute phase error of 0.01 degree. An optimal field control is a necessary step for optimal beam control. In presense of a beam, beam loading compensation is used to keep the field within these performance limits. Measurements of the arrival time $t_A$ and compression $C$ of each single bunch within a bunch train allows to control the beam. By beam based feedbacks the residual field errors and undesired machine fluctuations are removed to reach a bunch arrival time stability below 30 fs, which is desired by the users. Beside pump-probe experiments with optical lasers, the arrival-time jitter must be stabilized relative to experiments where the Free Electron Laser is seeded by an external seed laser. Reaching the demanded beam performance is the most challenging goal to meet.

## MODEL BASED DESIGN

An overview of a single RF station is depicted in Fig. 2 and separated into 3 main parts. This model based design is used to optimize the discrete MIMO controller $C(z)$ which is a part of the LLRF Controller by approximations, so called models of the RF field ($G_F(z)$) and the beam ($G_B(z)$). The model of the RF field is generated by system identification with special excitation signals and de-

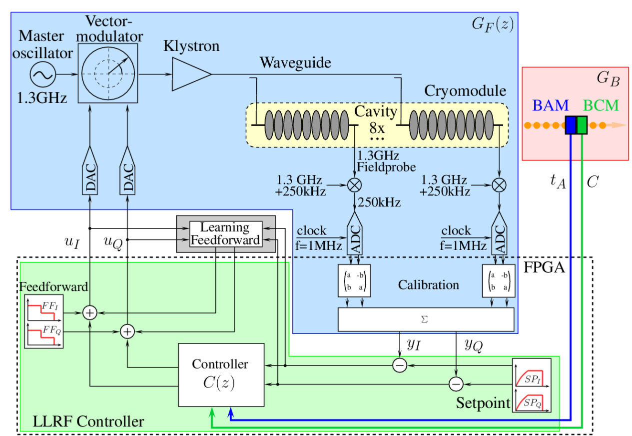


Figure 2: Overview RF station control loop

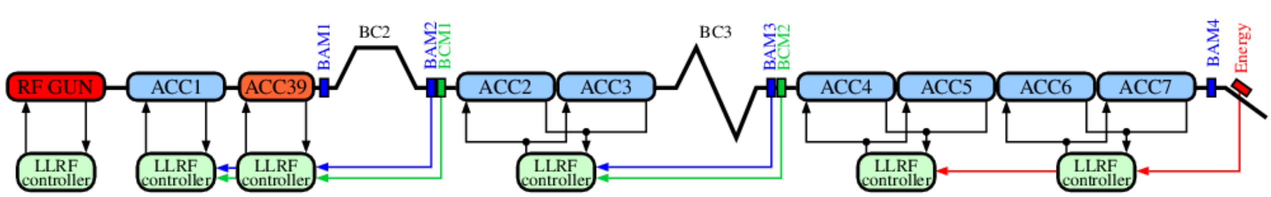


Figure 1: FLASH overview - Information flow for field and beam controller structure.

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fined from the vector modulator input to the vector sum signal. The controlled and measured signals are given as real part I (in-phase) and imaginary part Q (quadrature). The master oscillator supplies a RF reference signal with a frequency of 1.3 GHz which can be changed by the vector modulator in amplitude and phase. This signal is used to drive a 10 MW multi-beam klystron. At the end of each cavity a field probe is taken by I-Q type down-converters operated at a switching frequency of 250 kHz. The mixer output signals are sampled by 14 bit high speed ADCs and calibrated, e.g. due to different cable length. All field probe signals of up to 16 cavities are summed up to the vector sum. To cope with the short excitation time of maximum 800 $\mu s$ it is necessary to split the identification procedure for the field into two steps. For symmetry reasons of the system a grey-box model structure is used which is similar to the standard cavity equations. First the static gain and bandwidth, which is due to superconducting cavities 3 decades of frequency below the passband modes, is identified by using a pseudo random binary (PRB) signal. The resulting model is fixed and within a second step the passband modes are included to the model by exciting the system with a chirp sine signal [4]. Therefore the discrete field model $G_F(z)$ is given by Eqn. (1).

$$\underbrace{\begin{pmatrix} y_I(k) \\ y_Q(k) \end{pmatrix}}_{y_F(k)} = \begin{bmatrix} G_{II}(z) & G_{IQ}(z) \\ G_{QI}(z) & G_{QQ}(z) \end{bmatrix} \cdot \underbrace{\begin{pmatrix} u_I(k) \\ u_Q(k) \end{pmatrix}}_{u(k)} \qquad (1)$$

This field model is used to calculate an optimal and robust MIMO controller $C(z)$ by using modern optimal controller design methods like HIFOOd [5]. The LFF update matrices are also calculated with the field model $G_F(z)$ and the controller $C(z)$. The colored boxes of the field model and LLRF controller can also be found in the FLASH overview depicted in Fig. 1. Beside the 1.3 GHz driven cavities (ACC1 to ACC7), a 3.9 GHz driven RF station, namely ACC39 is used to linearize the longitudinal phase space. After each bunch compressor (BC2 and BC3) the beam is measured by a bunch arrival time monitor (BAM) [6] and a bunch compression monitor (BCM). Both beam related signals are connected to the previous LLRF controller which allows to control the beam directly.

Similar to the field system, an approximation of the behavior of the beam properties can be found by system identification, see Fig. 3. However, the transient behavior is described by the field model and includes the bandwidth and other passband modes, like the $8/9\pi$ mode. After converting $y_F$ to amplitude and phase coordinates and subtracting the reference signal the absolute amplitude error is mapped by a matrix operation which is a part of $\widetilde{G}_B$ to a relative amplitude error, see Eqn. 2.

Since the dynamics are part of the field model $G_F(z)$, it is sufficient to identify a static gain of $G_B$ which maps relative amplitude and absolute phase changes to arrival time

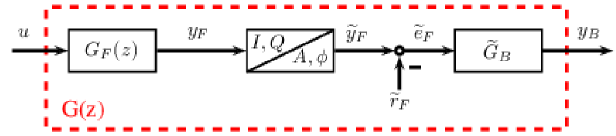


Figure 3: Model based plant design.

and compression changes, Eqn. (2).

$$\underbrace{\begin{pmatrix} \Delta t_A(k) \\ \Delta C(k) \end{pmatrix}}_{y_B} = \overbrace{[G_B] \cdot \begin{bmatrix} \frac{1}{A} & 0 \\ 0 & 1 \end{bmatrix}}^{\widetilde{G}_B} \underbrace{\begin{pmatrix} \Delta A(k) \\ \Delta \phi(k) \end{pmatrix}}_{\widetilde{e}_F} \qquad (2)$$

## BEAM BASED FEEDBACK SYSTEM

The measured beam related signals, namely the arrival time $t_A$ and compression $C$ are used to optimize the beam stability. Since the field is controlled by in-phase and quadrature signals, a modulation optimizes the reference trajectory which is converted from amplitude and phase corrections to I-Q signals by a matrix multiplication. This linearized modulation holds around the field reference for small phase changes and is separated in a scaling and rotation part and given as

$$\underbrace{\begin{pmatrix} Y_{M,I} \\ Y_{M,Q} \end{pmatrix}}_{Y_M} = \overbrace{\underbrace{\left(1 + \frac{\Delta A}{A}\right)}_{Scaling} \cdot \underbrace{\begin{pmatrix} 1 & -\Delta\phi \\ \Delta\phi & 1 \end{pmatrix}}_{Rotation}}^{MOD(\frac{\Delta A}{A}, \Delta\phi)} \cdot \underbrace{\begin{pmatrix} U_{M,I} \\ U_{M,Q} \end{pmatrix}}_{U_M}.$$

The inverse of $G_B$ leads to the optimal amplitude and phase reference correction based on arrival time and compression errors and is called beam based feedback matrix (BBF), see Fig. 4. It is shown that beam based feedback by a set point modulation improves the beam performance. First tests in 2011 showed that a direct feedforward correction still improves the beam properties, see [1]. But this method uses a second MIMO controller which is activated if the beam is present and uses more programmable space on the FPGA. The new controller structure is based on a cascaded feedback loop where the beam measurements with a loop delay of $t_{D,B} = 2\ \mu s$ are used as inner loop and the field measurements with $t_{D,F} = 4\ \mu s$ as outer loop, see Fig. 4. The plant model $G(z)$ is the same as in Fig. 3. Two additional gains one for the field (FW) and one for the beam (BW) measurements are implemented to weight both signals independently. For example, if FW is 1 and BW is zero then only field control is active. To minimize the arrival time jitter a gain scan is presented in Fig. 5. The color code represents the improvements of the arrival time compared to only field control. If the field gain is kept constant and the beam gain is increased the arrival time stability gets better and after a maximum it is worse again. This is explainable by the different loop delays of the field and beam feedback such that both feedback loops fight against each




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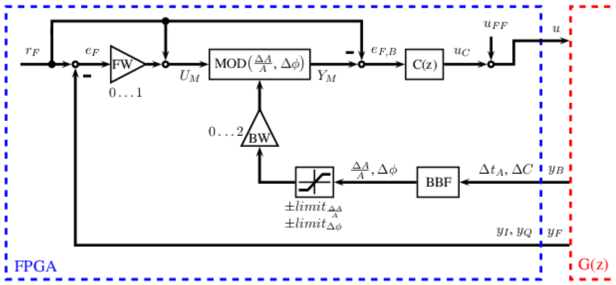


Figure 4: Cascaded feedback structure for controller design.

other. The lowest arrival time jitter for ACC1 is found at a field gain factor of zero and a beam gain factor of about 0.6. Hereby without field control the minimal arrival time jitter can be found. But in case of beam cuts, the field is driven in open loop since the field weighting factor is zero which causes problems for the LFF algorithm, like oscillations.

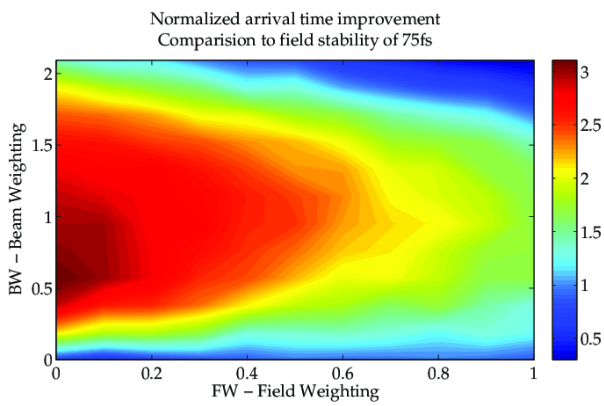


Figure 5: Arrival time scan with cascaded beam based feedback.

One important advantage is the corrected set point $Y_M$ which is now directly the reference for LFF, see Fig. 4. This allows to reduce possible repetitive arrival time spreads within a bunch train without using a second LFF to correct the set point. But the first and last 15 bunches are not optimized due to the backwards adaptation of the correction signal which is added to the feedforward signal $u_{FF}$, see Fig. 6. Such an algorithm has problems especially at edges like switching on and off the beam. For the first 15 Bunches this is not critical because those are used to stabilize the beam and can be kicked out to use only the bunches with stabilized arrival time and compression. Fig. 7 gives an example how the arrival time jitter is minimized at FLASH. Starting with the arrival time jitter coming from the GUN (BAM1) the second subplot shows the improvements of the arrival time jitter by a factor of 3 where ACC1 is controlled by the cascaded beam based feedback structure.

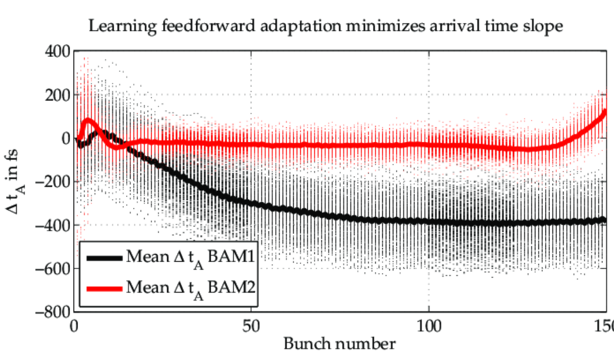


Figure 6: Arrival time correction by LFF.

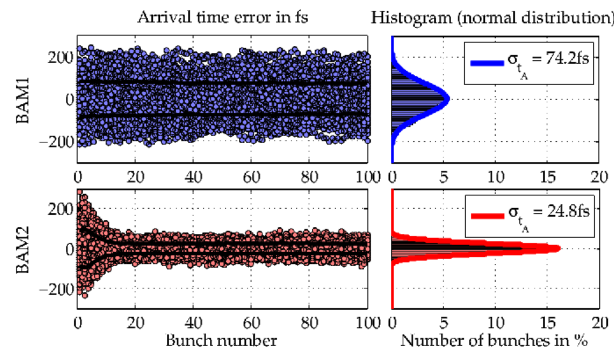


Figure 7: Usual bunch arrival time jitter and standard deviation with beam based feedback.

## CONCLUSION AND OUTLOOK

The first test of the currently installed new beam based feedback structure on ACC1 reduces the arrival time jitter by an additional factor of about 2 compared to the beam based set point modulation. Two additional gains are used to weight the field and beam independently where a global optimum of the arrival time performance can be found. The structure is designed such that learning feedforward for the field reduces repetitive arrival time errors. Including the same controller structure at ACC23 will further reduce the arrival time jitter. A set point modification for the last bunches will lead to a flat arrival time over the whole bunch train.

## REFERENCES

[1] C. Schmidt et al., "Feedback Strategies for Bunch Arrival Time Stabilization at FLASH Towards 10 fs," FEL'2011, Shanghai, August 2011, THPA26, http://www.JACoW.org

[2] S. Kirchhoff et al., "An Iterative Learning Algorithm for Control of an Accelerator based Free Electron Laser," 47th IEEE Conference on Decision and Control, Cancun, Mexico, 2008

[3] C. Schmidt et al., "Parameter estimation and tuning of a multivariable RF controller with FPGA technique for the Free Electron Laser FLASH," American Control Conference, Seattle, Washington, USA, 2008

[4] S. Pfeiffer et al., "Grey Box Identification for the Free Electron Laser FLASH exploiting Symmetries of the RF-System," 18th IFAC World Conference, Milano, Italy, August 2011

[5] A. Popov et al., "Fixed-structure discrete-time $H_\infty$ controller synthesis with HIFOO," 49th IEEE Conference on Decision and Control, Atlanta, Georgia, USA, December 2010

[6] M.K. Bock et al., "Benchmarking the performance of the present bunch arrival time monitors at FLASH," DIPAC2011, Hamburg, Germany, May 2011