FEEDBACK STRATEGIES FOR BUNCH ARRIVAL TIME STABILIZATION AT FLASH TOWARDS 10 fs

C. Schmidt*, M.K. Bock, S. Pfeiffer, H. Schlarb, DESY, Hamburg, Germany
W. Koprek, PSI, Villigen, Switzerland
W. Jałmużna, TUL-DMCS, Łódź, Poland

Abstract

Highly precise regulation of accelerator RF fields is a prerequisite for a stable and reproducible photon generation at Free Electron Lasers such as FLASH. Due to major improvements of the RF field controls during 2010 and 2011 the FEL performance and the beam stability was significantly improved. In order to facilitate femtosecond precision pump-probe and seeding experiments at FLASH a combination of RF and beam based feedback loops are used. In this paper, we present the achieved stabilization of the arrival time and the pulse compression at FLASH using intra-pulse train feedbacks. Current limitations and future steps toward sub-10 fs rms jitter are discussed.

INTRODUCTION

The Free Electron LASer at Hamburg (FLASH) provides its users a pulsed soft X-Ray laser with tunable wavelength below 5 nm by SASE processes. Therefore electron bunch trains of variable length and frequency are accelerated to about 1.2 GeV with a repetition rate of 10 Hz. Precise acceleration field control is essential to provide a stable and reproducible photon generation. A major upgrade of hardware, firmware and software has been completed during 2010, providing:

- improved RF field stability by new cascaded feedback, feed-forward controller structures
- higher reproducibility of the operator selected phase and amplitudes values
- limitations of internal controller tables and parameters to prevent exceptions
- higher degree of automation leading to faster recovery after trips and operation changes
- beam-based feedbacks to remove residual field errors and undesired machine fluctuations

The about 30 fs pulse arrival-time stability desired by the users is the most challenging goal to meet. The arrival-time jitter must be stabilized relative to pump-probe experiments with optical lasers and to experiments where the Free Electron Laser is seeded by an external seed lasers. Thus, the electron bunch arrival-time must be stabilized relative to an external optical source which synchronizes these laser system which delivers fine corrections to the RF field.

* christian.schmidt@desy.de

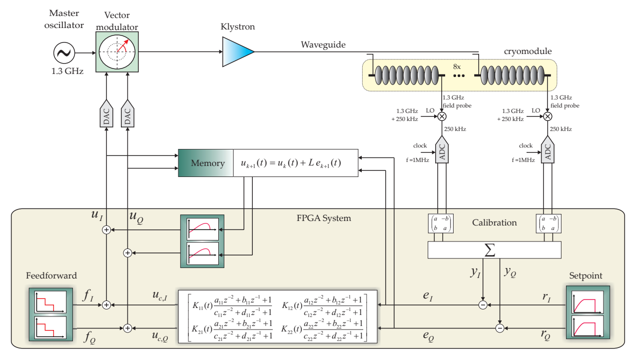

Figure 1: Block diagram of the digital LLRF control system

The RF feedback control system has been modified such that the combined controller concept keeps the relative amplitude and absolute phase error below 0.01 % (rms) and 0.01 degrees (rms). To further improve the electron beam stability, beam based measurements are processed in real-time in the RF control system. In order to avoid conflicts with the RF probe based regulation, the beam induced correction changes the set-point tables used for the RF feedback system with a microsecond intra-bunch train response-time. This reduces the arrival time jitter from about 60 fs to 20 fs for bunches in regulation.

Recent measurements have shown that this beam feedback implementation can be optimized by additional feedback loops on different time scales to have a comparable cascaded feedback structure as for the field controller by itself. In this paper current limitations of the feedback structure and future steps towards the sub-10 fs (rms) jitter are discussed.

LLRF CONTROL SYSTEM

An overview of the digital LLRF field control system currently implemented at FLASH is sketched in Figure 1.

The accelerating fields of up to 16 cavities are measured by I-Q type down-converters operated at a 250 kHz switching frequency. The signals at the mixer output are sampled by 14 bit high speed ADCs. The In-phase (I) and quadrature (Q) voltages are summed together and compared to the set-point table and fed to the digital controller. The digital control is comprised of a feed-forward drive and the feedback correction for the removal of pulse-to-pulse variations. The output of the digital controller is converted to analog signals (DAC) connected to a vector modulator which varies the amplitude and phase of the 1.3 GHz mas-

ISBN 978-3-95450-117-5

ter oscillator RF reference signal. This signal is used to drive a 10 MW multi-beam klystron.

Due to the very low-bandwidth of the super conducting cavities and delays in the closed loop system, it is not possible to either suppress high-frequency distortions or achieve zero steady-state errors with the feedback only [1]. With knowledge about field imperfections in previous pulses, the residual control errors can be minimized by a model based learning feed-forward optimization. The performance criteria are distinguished between intra-pulse and pulse-to-pulse variations. Fluctuations for consecutive pulses are not predictable and must be compensated by the feedback controller. This controller used to be a proportional feedback, which has been updated now to a multi-variable, second-order controller, whose coefficients are automatically tuned by model based controller methods. With such controllers one primarily achieves a higher closed-loop system bandwidth without amplifying high-frequency noise. This cascaded control strategy keeps the relative amplitude and absolute phase error below 0.01 % (rms) and 0.01 degrees (rms) as it is shown in Figure 2 and Figure 3.

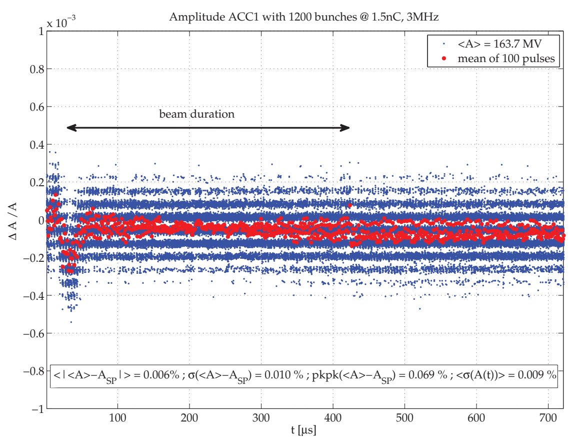

Figure 2: Amplitude control performance of the first acceleration module ACC1 for high beam loading conditions

It can be seen that with the current hardware almost the resolution of digital sampling points can be reached. Further even for high beam loading conditions the RF field can be kept at the desired set-point trajectory. To cope with different beam charges and frequencies a nominal beam loading compensation table is scaled by actual charge measurements. This allows instantaneous reactions of missing beam loading due to exceptions from the machine protection system, preventing that cavity gradient limits are suddenly reached. The residual errors due to imperfect compensation tables are minimized by learning feed-forward control to the given level in Figure 2. This self-adapting processes also leads to a higher machine reproducibility. Without learning feed-forward, the residual control errors must be minimized by a variety of expert manual tuning whenever the beam-loading changes.

All individual control tables are designed such that the

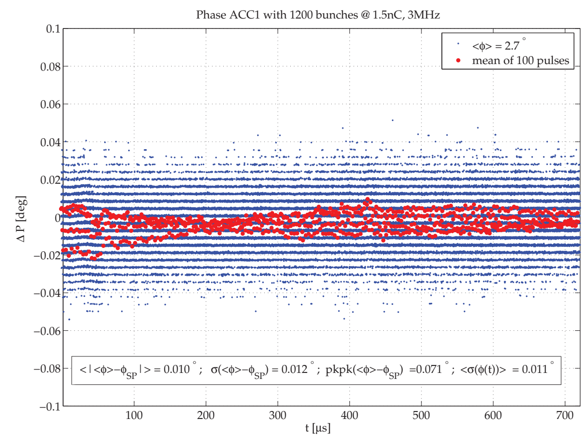

Figure 3: Phase control performance of the first acceleration module ACC1 for high beam loading conditions

maximum output signal contribution is limited by individual thresholds to prevent unforseen events like miscalculation. Depending on the system impact different algorithms are cascaded to keep the inner loop always in boundaries. In this case long term drifts in the system do not lead fast algorithms to run out of there dynamic range.

BEAM BASED FEEDBACK SYSTEM

Because of small field detection errors, [2], systematic errors due to the calibration of the cavity field probes, common mode errors caused by jitter and drifts of the RF reference [3], long range wakefields, variations of the photo-injector drive laser pulses and small current fluctuations of the magnetic chicane power supplies, measurements of the electron beam do not necessarily precisely match the vector sum calculated from cavity field probes.

The electron beam time structure is well suited for fast intra-train feedbacks using beam based measurements incorporated to the Low Level Radio Frequency (LLRF) control system. The feedback allows further improving the bunch compressions, bunch arrival and bunch energy stability which directly impact the quality of the FEL photon beam. An overview of the currently installed beam based feedback system at FLASH is given in Figure 4.

Currently there are four based feedback system the BAM and BCM after BC2 and BC3 are used to modify the RF set-point during the pulse, depending on an arrival time or compression variation to a given set-point. The RF feedback controller has to follow this adapted trajectory. This finally stabilizes the beam arrival time and compression jitter within a pulse and for consecutive pulses. The last BAM, 18ACC7 can be used as out of loop measurement of the arrival time [4], beside its function as a user based timing reference signal.

Beside the intra train feedback, same monitors are used as a slow feedback device which tracks the RF set-point, compensating for slow drifts in the system. In addition the

ISBN 978-3-95450-117-5

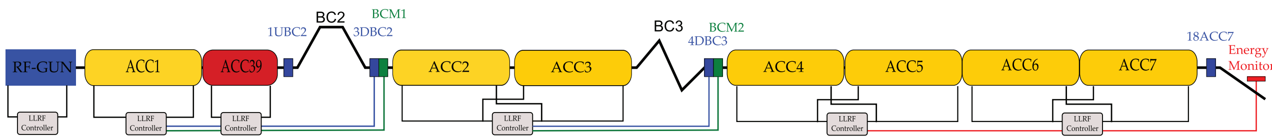

Figure 4: Sketch of beam based feedback implementation structure implying RF feedback control loops

final beam energy is measured by information from beam position monitors in the last dispersive section and feed-backed to the amplitude set-point of either one of the last acceleration modules. The incorporation of this individual feedback systems is currently under investigation.

Due to the large longitudinal dispersion of the first magnetic chicane, an arrival-time of 7 ps per percent voltage modulation of the first cryomodule is induced, dominating the electron-beam arrival-time jitter at FLASH. Since RF phase variations change both the compression of the electron bunch as well as its arrival-time the control algorithm has to always act on amplitude and phase simultaneously. From the experimentally determined response, a feedback matrix is calculated and applied to the field programmable gate array (FPGA) of the controller. For compression monitoring, a newly installed 140 GHz photo detector was used with a significantly improved signal-to-noise ratio compared to pyro-electric detectors [5]. The improved SNR allowed for stabilizing the bunch compression, without compromising the arrival-time jitter.

ARRIVAL TIME STABILIZATION MEASUREMENTS

In Figure 5 the rms arrival time jitter of each bunch in a macro pulse over a period of 8 min is shown, when intra-bunch train feedbacks are activated on each accelerator station upstream of each chicane.

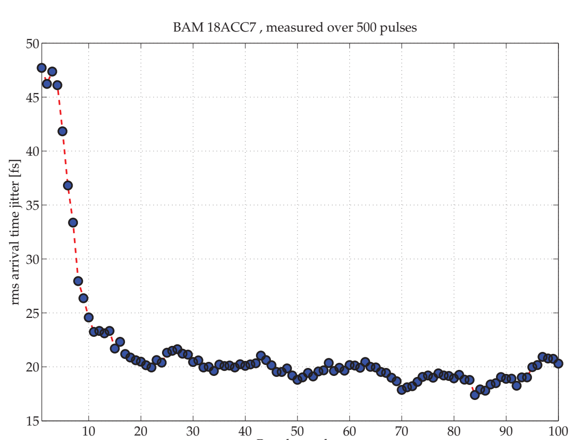

Figure 5: Out of loop measurement of achieved arrival time jitter, stabilization is done by the intra-train feedback system applied in BC2 and BC3

Due to causality and the system delay, the first four bunches are not affected by the intra-train feedback system. The arrival-time jitter of 48 fs (rms) reflects the stability of the RF regulation without beam-based feedback, [6]. After about 15 microseconds, the arrival-time jitter approaches steady state and is reduced to below 22 fs (rms) for the remaining 85 electron bunches. The transient time of the feedback is caused by the narrow bandwidth of the cavities (300Hz) and limitations upon the applicable feedback gain of the RF controls. The first bunches in this case can be detained from lasing process by using fast kickers in front of the undulator, allowing specific user requirements.

STRATEGIES FOR INTEGRATED BEAM BASED FEEDBACK CONTROLLER

It has been shown that the arrival time jitter can be significantly reduced by using beam based feedbacks. Real-time set-point adaptation prevents conflicts with the regular RF feedback system. Nevertheless residual arrival time variations within a bunch train might be observed. This is mainly determined by the RF feedback controller, acting on the stepwise reference changes. This effect increases when the RF measurement and arrival time measurement drift against each other. Similar to the RF learning feed-forward algorithm, this repetitive arrival time error is used to optimize the RF set-point trajectory such that the beam based feedback system has to control pulse to pulse fluctuation only. This reduces the overall arrival time variation in a macro-pulse by factor of 5 to less that 100 fs within 300 bunches, as it shown in Fig. 6.

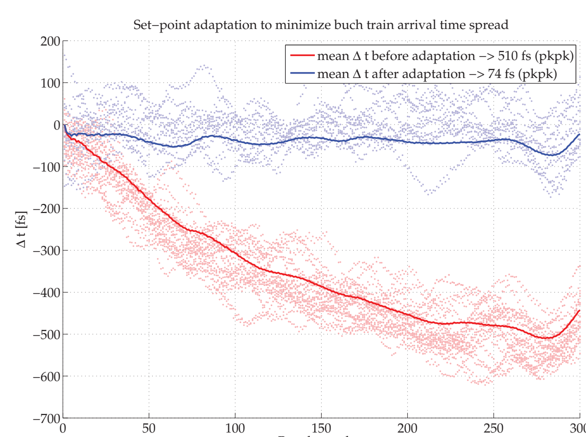

Figure 6: Pulse to pulse set-point correction using the bunch arrival time monitor 3DBC2

This concept fulfills the cascaded strategy which has

ISBN 978-3-95450-117-5

been applied for the RF feedback, to keep inner fast regulation loops in range by learning from previous pulses.

The real-time adaptation of the beam based feedback has the main advantage to influence the RF regulation only by reference changes. But this also implies that the response time of this system is only determined by the RF controller, which is designed for the RF feedback loop only. This controller is not necessarily optimized for the beam feedback as well, e.g. the tradeoff between reference tracking and noise suppression is different. Therefore tests have been made in order to extend the RF drive to the system by an additional direct beam feedback. In addition one can observe that the latency in this loop is lower then in the regular RF loop. As a first test, the RF feedback has been turned off during beam duration and the beam signal has been used instead. One can see in Figure 7, that this reduces the arrival time jitter in 3DBC2 as well as compression variations.

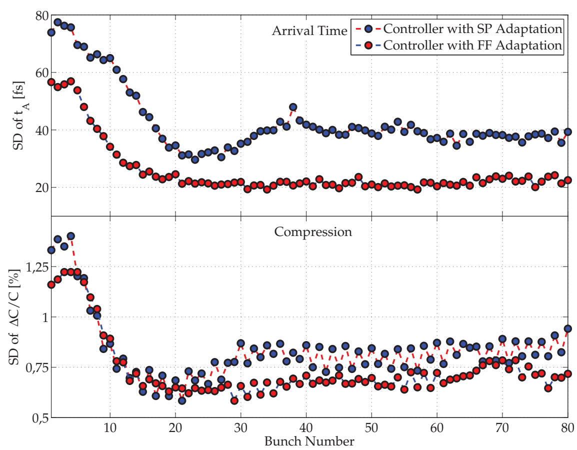

Figure 7: Comparison between adaptation of feed-forward drive and intra-pulse set-point variation

In addition it can be seen that the arrival time jitter for the first bunches is lower then for the set-point adaptation feedback. The reason in expected to be the learning feed-forward algorithm which has to compensate for large varying control errors exciting broadband controller inputs. For the feed-forward adaptation only, this effect is suppressed due to the small bandwidth of the RF system.

It is assumed the combination of both beam based feedback loops, set-point and feed-forward adaption working together with a model based controller design will further reduce the jitter. Integration of all slow, intermediate and fast feedback loops in one unique structure is a challenging task towards a stable a highly precise light source.

CONCLUSION AND OUTLOOK

The combination of pulse-to-pulse learning feed-forward drive correction, a multi-variable, second order feedback controller and the fast beam-based set-point adaptation has significantly improved the performance of the LLRF control system and allows for femtosecond precision pump-probe and seeding experiments at FLASH. Additional integrated slow feedback adaptations as well as beam-based optimized set-point trajectory's will support intra-train feedback. Integrated beam-based feed-forward drive can further reduce arrival-time jitter due to faster response time and higher control bandwidth. Further improvements of the arrival-time stability from $dE/E = 0.003\%$, towards $dE/E \leq 10^{-5}$ or $<$ 7 fs (rms) most likely requires a fast e. g. normal conducting cavity with 15 kV acceleration voltage but sufficient bandwidth installed upstream of the BC2 chicane.

REFERENCES

[1] W. Koprek et al.,"Intra-train longitudinal feedback for beam stabilization at FLASH", FEL'2010, Malmoe, May 2009, THOAI2, http://www.JACoW.org

[2] Ch. Gerth, F. Ludwig and C. Schmidt, "Beam based measurements of the rf amplitude stability at FLASH using a synchrotron radiation monitor", DIPAC'09, Basel, May 2009, TUPD22, http://www.JACoW.org

[3] F. Ludwig et al.,"Drift calibration techniques for future FELs", IPAC'10, Kyoto, May 2010, TUPEA041, http://www.JACoW.org

[4] M.K. Bock et al., "Benchmarking the performance of the present bunch arrival time monitors at FLASH", DIPAC'2011, Hamburg, May 2011, TUPD28, http://www.JACoW.org

[5] C. Behrens, B. Schmidt and S. Wesch, "Upgrade and evaluation of the bunch compression monitor at the free-electron laser in Hamburg (FLASH)", IPAC'10, Kyoto, May 2010, MOPD090, http://www.JACoW.org

[6] Ch. Gerth, M. Hoffmann, F. Ludwig, H. Schlarb, C. Schmidt, "Beam energy measurements in the injector at FLASH using a synchrotron radiation monitor and bunch arrival Monitors", FEL'2011, Shaghai, August 2011, THPA12, http://www.JACoW.org

ISBN 978-3-95450-117-5