BEAM BASED MEASUREMENTS OF THE RF AMPLITUDE STABILITY AT FLASH USING A SYNCHROTRON RADIATION MONITOR

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Abstract

To exploit the short radiation pulses in pump-probe experiments at single-pass free-electron lasers, stabilization of the longitudinal profile and arrival time of the electron bunches is an essential prerequisite. Beam energy fluctuations, induced by the cavity field regulation in the accelerating modules, transform into an arrival time jitter in subsequent magnetic chicanes used for bunch compression due to the longitudinal dispersion. The development of beam based monitors is of particular importance for the validation and optimization of the cavity field regulation. In this paper we present bunch-resolved energy jitter measurements that have been recorded with a synchrotron radiation monitor at the Free-electron LASer in Hamburg (FLASH). The (rms) beam energy jitter was determined to be $8.8\,10^{-5}$, and the cavity field detectors of the accelerating module have been identified as the main noise source within the cavity regulation system with an (rms) amplitude fluctuation of $6.5\,10^{-5}$. The reduction of deterministic cavity field imperfections by applying a feedforward learning algorithm for the cavity field regulation is demonstrated.

INTRODUCTION

Stable and reliable user operation of the Free-electron LASer in Hamburg (FLASH) requires precise control and stabilization of the RF accelerating amplitudes and phases. This is in particular true for RF accelerating fields prior to bunch compressors, as the ultra-short electron bunches with high peak currents are produced by off-crest acceleration in combination with magnetic dipole chicanes. Small fluctuations in the energy chirp rate may cause unacceptable peak current and bunch arrival time jitters. For instance at FLASH, RF amplitude and phase stabilization of about 10^{-4} and 0.01° are required to achieve peak current variations on a percent level.

A schematic of the FLASH injector is shown in Fig. 1. The RF photo-cathode gun is directly followed by the super-conducting 1.3 GHz accelerating module ACC1 which accelerates the electrons to a beam energy of typically 130 MeV. The module comprises eight 9-cell niobium cavities with a very high quality factor, i.e. very narrow bandwidth and very long response times. The maximum feedback gain g_0 that can be applied in the low-level RF (LLRF) system for the regulation of ACC1 is limited due to instabilities generated by the digital control loop, and, therefore, imperfect compensation of effects such as beam loading may occur.

A deviation of the beam energy $\Delta E/E$ transforms into a

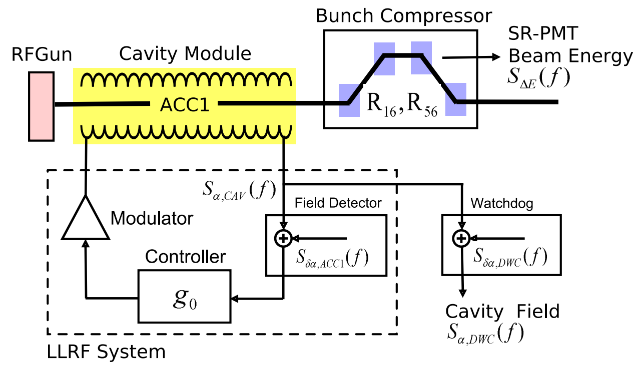

Figure 1: Schematic of FLASH injector.

horizontal beam displacement Δx in the dispersive section of the bunch compressor (BC) downstream of ACC1 and a beam arrival time difference Δt at the end of the BC given by (first order transport theory, $\beta \simeq 1$):

$$\Delta x = R_{16} \cdot \frac{\Delta E}{E} \quad \text{and} \quad \Delta t = R_{56} \cdot \frac{\Delta E}{E}, \tag{1}$$

where $R_{16} \approx 300 - 400$ mm and $R_{56} \approx 140 - 230$ mm are the the horizontal and longitudinal dispersion of the BC. The beam energy can be determined by recording the beam position Δx with a synchrotron radiation (SR) monitor.

SR MONITOR

The SR emitted in the third dipole of the first BC at FLASH is imaged by a SR monitor which comprises an intensified CCD camera (SR-Camera) and a multi-array photomultiplier tube (SR-PMT). By utilizing a beam splitter, both the SR-camera and SR-PMT can be used simultaneously.

The SR-camera [1] records the full x-y projection of the electron bunches. By adjusting the gate and delay of the camera timing, single bunches or any number of subsequent bunches can be chosen out of a bunch train. However, the readout of the CCD is too slow to resolve more than one electron bunch within a bunch train.

Two adjacent anodes of the SR-PMT [2] are used to measure the centre-of-gravity beam position which is given by the normalized difference signal s of both anodes:

$$s = \frac{I_1 - I_2}{I_1 + I_2}, \tag{2}$$

where I_1 and I_2 are the signal intensities of each anode.

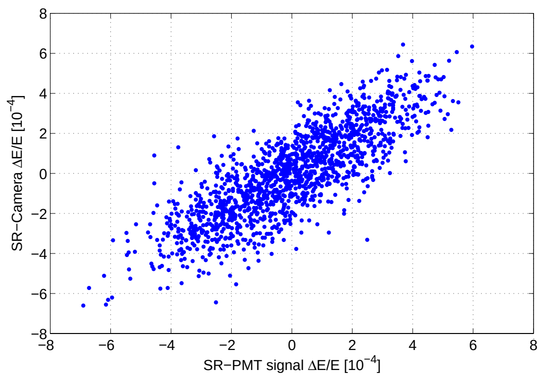

Figure 2: Correlation plot for 500 bunches recorded simultaneously with the SR-PMT and SR-camera.

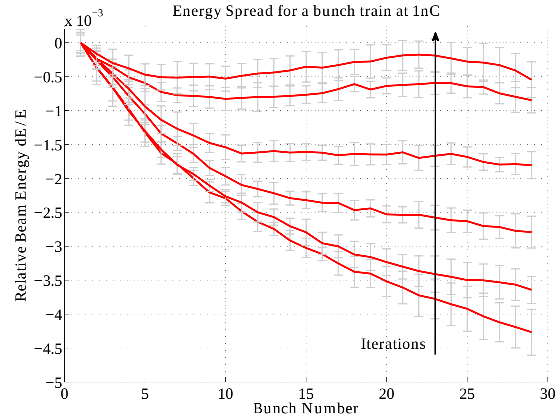

Figure 3: Removing beam induced RF field deviations along the bunch train with a learning FF algorithm.

The fast SR-PMT signals are digitized by analog-to-digital converters (ADC) which enables bunch-resolved beam energy measurement within the bunch trains. By changing the dipole current and, therewith, the beam position, both the SR-camera (in pixel) and SR-PMT (in V) can be calibrated as a relative change in the magnetic field corresponds to a relative change in beam energy.

An upper limit for the energy resolution can be estimated by recording simultaneously the relative energy jitter with the SR-camera and SR-PMT. Figure 2 shows the correlation of the energy jitter measured for 500 subsequent bunch trains. The difference of the measured energy jitter is $1.08 \pm 0.04\,10^{-4}$ which gives an upper limit for the resolution of both detectors. Assuming that both detectors have the same resolution, the resolution of each detector would be $1.08 \pm 0.04\ 10^{-4}/\sqrt(2) = 7.6 \pm 0.3\ 10^{-5}$.

LEARNING FEEDFORWARD

The RF field regulation is subject to various disturbance sources which can be distinguished into stochastic and deterministic disturbances. The effect of both disturbances can be minimized to a certain level by usage of a feedback compensator. Repetitive disturbances can also be suppressed by using the knowledge from previous regulations to adapt the system input drive for the following ones. The basic update algorithm [3] is given by:

$$u_{k+1}(t) = u_k(t) + L(t)\, e_k(t)\,, \qquad (3)$$

where u is defined as the system input and e the deviation of the measured RF output to the given setpoint. L is a linear, non-causal, time-varying filter based on the identified system model.

Figure 3 shows the energy slope along bunch trains with 29 bunches measured with the SR-PMT for several iterations of a learning feedforward (FF) algorithm. Note that stochastic effects were eliminated by normalising the energy of the first bunch for each bunch train to zero. As can be seen, the energy slope over the bunch train is about $4\ 10^{-3}$ (lowest curve) even with the feedback controller turned on. Only a few iterations of the leaning FF algorithm were necessary to reduce the energy slope caused by beam loading.

The standard deviation of the beam energy of all bunches in the bunch train relative to the corresponding mean value is shown in Fig. 4. The convergence speed of the learning FF algorithm is high enough to achieve a rms beam energy stability of below 10^{-4} within a bunch train after several iterations. Each iteration step corresponds to a measurement over 10 bunch trains.

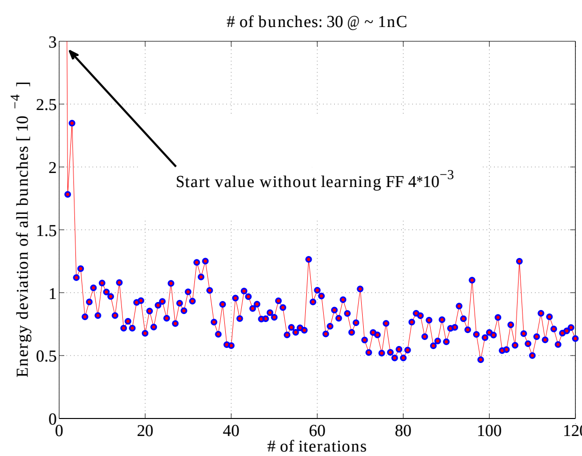

Figure 4: Minimization of the rms energy deviation of all bunches within a bunch train by applying the learning FF algorithm.

BEAM STABILITY

The cavity field amplitude and phase fluctuations within the LLRF regulation system depend mainly on the controller loop gain and amplitude and phase noise of each subsystem: cavity, master reference, field detectors, modulator and klystron [4]. To clarify how the LLRF system contributes to the beam energy and bunch arrival time fluctuations, we have determined its correlation to the cavity vector sum field of ACC1. For minimum noise contribution and closed loop operation of the regulation system, the measured closed-loop cavity vector-sum-field noise decreases with increasing loop gain and is not suitable for correlation measurements. Nevertheless, the cavity field noise in correlation to the beam energy jitter can be detected by using a second noise 'watchdog' system which is operated simultaneously in open loop mode as depicted in Fig. 1. Solving both LLRF systems using algebraic methods presented in [4] and neglecting phase noise contributions, both the beam energy noise $S_{\Delta E}(f)$ and cavity field noise $S_{\alpha,DEV}(f)$ detected by the watchdog system are given by

$$S_{\Delta E}(f) = S_{\alpha,CAV}(f) \quad (4)$$

$$S_{\alpha,DEV}(f) = S_{\delta\alpha,DEV}(f) + S_{\alpha,CAV}(f)\,, \quad (5)$$

where $S_{\alpha,CAV}(f)$ is the vector sum amplitude noise of the cavity field and $S_{\delta\alpha,DEV}(f)$ the field detector noise. Using a perfect controller with a gain of $\mathrm{g}_0 \gg 1$, which eliminates most of the regulation noise, indicated by a nearly noiseless cavity vector sum signal, shifts the field detector noise directly onto the beam in closed loop operation. Using $S_{\alpha,CAV}(f) = S_{\delta\alpha,ACC1}(f)$ and Eq. (5), the correlation between the beam energy fluctuations and the detected cavity field noise is given by

$$\gamma_{\delta E,\alpha}(f) = \left(1 + \frac{S_{\delta\alpha,DEV}(f)}{S_{\delta\alpha,ACC1}(f)}\right)^{-\frac{1}{2}}. \quad (6)$$

The correlation between the beam energy jitter measured with the SR-PMT and the cavity field measured with the watchdog system is shown in Fig. 5 for 6000 bunch trains at 6 degree off-crest operation of ACC1. Long-term drifts were eliminated in the data. Except for some occasional deviations, the measurements are in accordance with Eq. (6) for $\gamma_{\delta E,\alpha}(f) = 1/\sqrt{2} \approx 0.707$, only assuming that the field detectors have the same noise spectral density.

The upper part of Fig. 5 shows the rms amplitude field detector noise measured with the watchdog system, The value of $9.2\ 10^{-5}/\sqrt{2} = 6.5\ 10^{-5}$ is in agreement with an independent characterization of the field detectors at FLASH of $6.5\ 10^{-5}$ amplitude and $5.0\ 10^{-5}$ phase stability using the master reference. The expected noise reduction factor of $\sqrt{8}$ using the vector sum principle of 8 single field detectors, each characterized to be $1.5\ 10^{-4}$, has been demonstrated in machine operation. Using Eq. (1), the rms arrival time jitter caused by the LLRF system, dominated by the field detector noise, amounts to about 40 fs.

A slightly higher beam energy jitter of $8.8\ 10^{-5}$ measured with the SR-PMT (Fig. 5 (middle)) indicates either the presence of additional uncorrelated beam charge or bunch arrival time fluctuations entering the accelerating module of the same order or resolution limitations by the SR-PMT. These limitations might decrease the correlation (Fig. 5 (bottom)). Other effects increasing the correlation, e.g. phase noise fluctuations, controller imperfections and

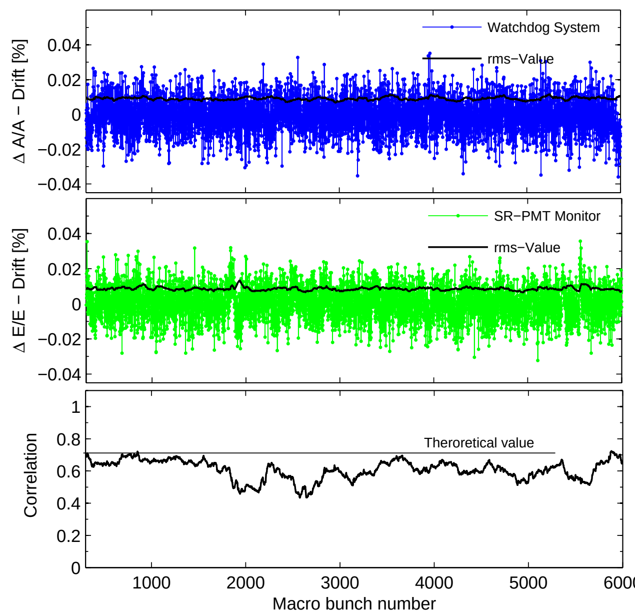

Figure 5: (top) Cavity vector-sum field amplitude fluctuations measured with the watchdog system, (middle) beam energy fluctuations measured with the SR-PMT, (bottom) correlation between watchdog system and SR-PMT.

higher order cavity passband modes, will be investigated in the future.

CONCLUSIONS

A SR monitor based on a multi-anode photomultiplier tube, installed in the first bunch compressor at FLASH, has been used to measure the beam energy jitter compared to the field regulation in the first accelerating module. We have demonstrated that deterministic disturbances, e.g. beam loading, can be suppressed to a rms value below 10^{-4} over a bunch train by applying a learning feedforward algorithm. Using a noise watchdog system, the cavity field detectors have been identified as the main noise source within the cavity regulation system with an amplitude fluctuation of $6.5\ 10^{-5}$. The beam energy jitter measured with the SR-PMT was determined to be $8.8\ 10^{-5}$.

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