PHASE STABILITY OF THE NEXT GENERATION RF FIELD CONTROL FOR VUV- AND X-RAY FREE ELECTRON LASER

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Abstract

For pump-probe experiments at FLASH and XFELs (free-electron lasers) the stability of the electron beam arrival time with respect to the timing reference depends critically on the phase and amplitude stability of the injector. An arrival time jitter below the longitudinal bunch duration of 60fs (rms) requires 0.01° (rms) phase and 0.01% (rms) amplitude stability. The cavity field detection critically influences the regulation of the acceleration field. In this paper we present the phase noise budget for a RF-regulation system including the noise characterization of its subcomponents, in particular downconverter, analog-to-digital converter, vector-modulator, master oscillator and klystron. We investigate the cavity field jitter induced by these noise sources within the regulation and determine the optimal controller gain.

INTRODUCTION

The SASE (Self-Amplified Stimulated-Emission) intensity of the undulator at FLASH and XFELs depends critically on the quality of the beam, respectively jitter of the arrival time of the incoming electron bunches. Due to the longitudinal dispersion introduced by the magnetic chicane for bunch compression, the amplitude and phase stability of the Low-Level-RF (LLRF) system at the injector changes the arrival time of the beam with respect to the reference clock. To reach the required stability of 0.01° (rms) in phase and 0.01% (rms) in amplitude at an operation frequency of 1.3GHz, we identify the main noise sources of a single cavity LLRF system of FLASH and investigate their influence on the cavity field timing jitter.

LLRF SYSTEM AT FLASH

A simplified schematic of a single cavity LLRF system of FLASH is shown in Fig.1. The electrical field in the cavity is measured with a probe antenna and mixed down to an intermediate frequency (IF) with an RF downconverter (DWC). The local oscillator signal (LO) for downconversion is provided by a master oscillator (MO). The IF signal is sampled with a fast analog-to-digital converter (ADC) and mixed into the baseband using IQ-detection (Inphase and Quadrature). The clock signal of the ADC must be synchronized to the LO signal for the downconverter [1]. After input calibration, set point subtraction, P-controller and feedforward algorithm, the control loop is closed via a digital-to-analog converter (DAC). The IQ-signals of the DAC are connected to the upconverter (UPC) to change the amplitude and phase of the driving signal for the cavity. A MW klystron is used to achieve a gradient of up to 30MW/m for the RF-field in the cavities for a pulsed operation mode (1ms duration).

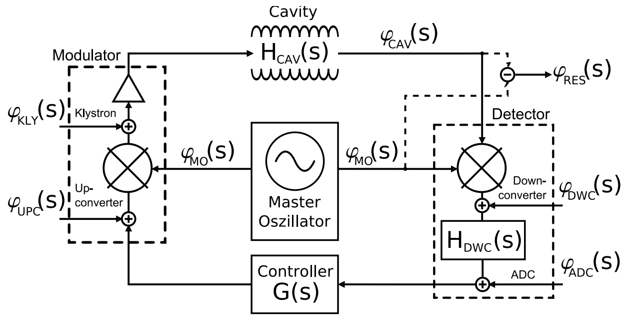

Figure 1: Simplified schematic diagram of a single cavity LLRF System at FLASH

SYSTEM PHASE NOISE SIMULATION

To extract jitter information from the LLRF system a phase noise description from linear phase-locked-loop (PLL) theory is applied. The LLRF system is solved algebraic in the Laplace-domain by transformation of all time dependent phases. The superconductive cavity is modeled by a lowpass filter $H_{\mathrm{CAV}}(s)$ with cutoff frequency ω_{12}. We assume a steady-state behavior neglecting effects of Lorentz-force detuning. The MO is the frequency reference for various subsystems of an accelerator and is characterized by its phase noise spectrum $S_{\varphi,\mathrm{MO}}(f_m)$. The output phase of the downconverter $\varphi_{\mathrm{IF}}(s)$ is given by the phase difference $\varphi_{\mathrm{CAV}}(s) - \varphi_{\mathrm{MO}}(s)$ between the cavity field phase $\varphi_{\mathrm{CAV}}(s)$ and the MO phase $\varphi_{\mathrm{MO}}(s)$. The downconverter output bandwidth is modeled by the transfer function $H_{\mathrm{DWC}}(s)$. The equivalent downconverter phase noise $\varphi_{\mathrm{DWC}}(s)$ consists of internal mixer noise and ADC noise caused by the sampling process provided by the timing system. The controller transfer function is given by $G(s)$. The behavior of the modulator is modeled by $\varphi_{\mathrm{RF}}(s) = \varphi_{\mathrm{con}}(s) + \varphi_{\mathrm{MO}}(s)$. Here, the modulator phase noise $\varphi_{\mathrm{MOD}}(s)$ contains upconverter and klystron noise contributions.

Applying standard PLL system theory to the regulation loop of Fig.1, the cavity field phase in dependence of each subsystem phase results to

$$\begin{aligned} \varphi_{\mathrm{CAV}}(s) \quad = \quad & K_{\mathrm{MO}}(s)\,\varphi_{\mathrm{MO}}(s) \\ & + K_{\mathrm{DWC}}(s)\,\varphi_{\mathrm{DWC}}(s) \\ & + K_{\mathrm{MOD}}(s)\,\varphi_{\mathrm{MOD}}(s) \end{aligned} \qquad (1)$$

with

$$K_{\mathrm{MO}}(s) = H_{\mathrm{CAV}}(s)\,\frac{1+G(s)\,H_{\mathrm{DWC}}(s)}{1+H_{\mathrm{CAV}}(s)\,G(s)\,H_{\mathrm{DWC}}(s)} \quad (2)$$

$$K_{\mathrm{DWC}}(s) = \frac{H_{\mathrm{CAV}}(s)\,G(s)\,H_{\mathrm{DWC}}(s)}{1+H_{\mathrm{cav}}(s)\,G(s)\,H_{\mathrm{DWC}}(s)} \quad (3)$$

$$K_{\mathrm{MOD}}(s) = \frac{H_{\mathrm{CAV}}(s)}{1+H_{\mathrm{cav}}(s)\,G(s)\,H_{\mathrm{DWC}}(s)}. \quad (4)$$

As long as all noise contributions are uncorrelated, the cavity field phase noise spectrum is given with Eqn. 1, $s = j\omega_m = j\,2\pi f_m$ and the definition of the phase noise spectral density

$$S_\varphi(f_m) = \lim_{T\to\infty}\frac{1}{T}\left|\mathcal{F}_T\left[\varphi(t)\right]\right|^2 = |\varphi(s)|^2 \quad (5)$$

$$\mathcal{F}_T\left[\varphi(t)\right] = \int_{-T}^{+T}\varphi(t)e^{-j2\pi f_m t}dt \quad (6)$$

by

$$\begin{aligned} S_{\varphi,\mathrm{CAV}}(f_m) = {} & |K_{\mathrm{MO}}(f_m)|^2\,S_{\varphi,\mathrm{MO}}(f_m) \\ & + |K_{\mathrm{DWC}}(f_m)|^2\,S_{\varphi,\mathrm{DWC}}(f_m) \\ & + |K_{\mathrm{MOD}}(f_m)|^2\,S_{\varphi,\mathrm{MOD}}(f_m), \end{aligned} \quad (7)$$

whereas f_m is the offset frequency related to the carrier frequency f_c. Once having Eqn.7, the phase noise spectrum of each node of the LLRF system can be calculated. Each subsystem of an accelerator should be synchronized to the MO and only relative fluctuations between the cavity field and the MO have to be considered. For this, we determine similarly by analyzing the residual phases

$$\varphi_{\mathrm{RES}}(s) = \varphi_{\mathrm{CAV}}(s) - \varphi_{\mathrm{MO}}(s) \quad (8)$$

the residual phase noise spectra $S_{\varphi,\mathrm{RES}}(f)$. For pump-probe experiments the arrival time of the beam relative to the master oscillator is important, which can be decribed by the residual integrated timing jitter for a given bandwidth ΔB and carrier frequency f_c

$$\Delta t_{j,\mathrm{rms}} = \frac{1}{2\pi f_c}\sqrt{\int_{\Delta B} 2S_{\varphi,\mathrm{RES}}(f_m)\,df_m}. \quad (9)$$

PHASE NOISE CHARACTERIZATION

In this section we present simulated phase noise spectra and residual timing jitter for the FLASH LLRF system based on noise measurements of each subsystem. Fig.2 shows the noise characterization of relevant subsystems.

Master oscillator: The master oscillator phase noise spectrum $S_{\varphi,\mathrm{MO}}(f_m)$ is measured. Its integrated timing jitter is 85 fs within a bandwidth of ΔB=[10 Hz,20 MHz].

Downconverter: The downconverter frontend phase noise is -147dBc/Hz determined by $S_{\varphi,\mathrm{DWC}}(f_m) = S_{V,\mathrm{DWC}}(f_m)/k_\varphi^2$, whereas the measured downconverter voltage-to-phase conversion factor is k_φ = 30 mV/° and its spectral density of voltage noise is 70 nV/$\sqrt{\mathrm{Hz}}$. The ADC phase noise contribution is -135dBc/Hz determined by measuring the short circuit noise of 160μV (rms) at a sampling rate of 1MHz, respectively 0.5MHz noise bandwidth including aliasing effects.

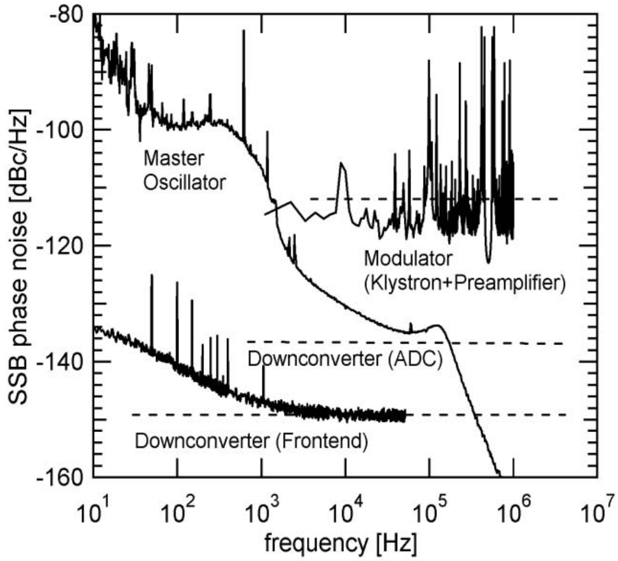

Figure 2: Measured phase noise of relevant LLRF subsystems.

Modulator: The modulator (MOD) white noise contribution is -110dBc/Hz. It includes the upconverter, high power preamplifiers and the klystron. It is measured during the klystrons pulsed operation time. The upconverter noise of -153dBc/Hz was negelected.

Cavity: The cavity transfer function is modeled by a 1st order lowpass $H_{\mathrm{CAV}}(s) = \omega_{12}/(s+\omega_{12})$ with cutoff frequency $\omega_{12} = 2\pi f_{12}$ of f_{12} = 200 Hz. Similar to modulator noise, cavity microphonics is reduced by the controller gain. Here cavity microphonics is not considered.

The downconverter and modulator transferfunction is modeled by a 1st order lowpass with a cutoff frequency of f_{DWC} = 10 MHz, respectively f_{MOD} = 10 MHz. The controller has a constant gain with $G(s) = g_0 \approx$100. Putting altogether the residual phase noise reduces to

$$\begin{aligned} S_{\varphi,\mathrm{RES}}(f_m) = {} & \left|\frac{s}{s+\omega'_{12}}\right|^2 S_{\varphi,\mathrm{MO}}(f_m) \\ & + \left|\frac{\omega'_{12}}{s+\omega'_{12}}\right|^2 \left[S_{\varphi,\mathrm{DWC}}(f_m) + \frac{1}{g_0^2}S_{\varphi,\mathrm{MOD}}(f_m)\right] \end{aligned} \quad (10)$$

with the loop bandwidth $\omega'_{12} = g_0\omega_{12}$ or effective noise bandwidth. According to Eqn.10 the MO, respectively downconverter and modulator phase noise is highpass, respectively lowpass filtered. Fig.3 shows the phase noise spectrum of each node. The cavity field follows the MO within the loop bandwidth ω'_{12}. Outside the loop bandwidth the MO and downconverter noise is filtered by the cavity. For microphonics or low frequency phase fluctuations below ω'_{12}, e.g. drifts from the downconverter, this noise reduction is inefficient and self calibration techniques must be used. According to Fig.3, the noise measured from

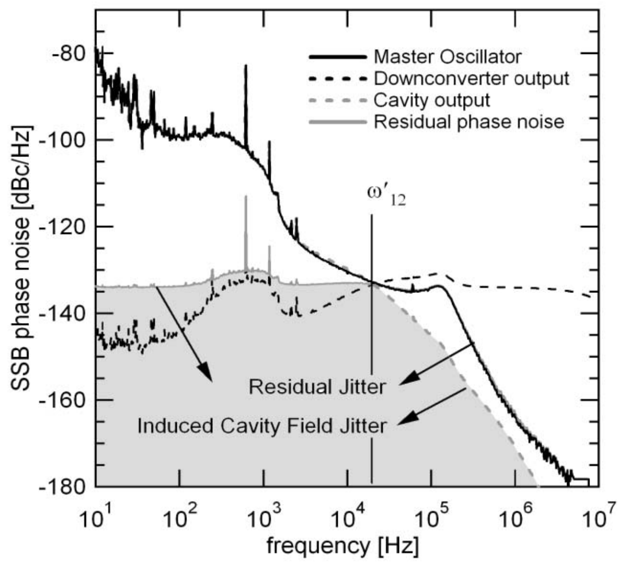

Figure 3: Phase noise spectra of a single cavity LLRF system based on a noise characterization of each subsystem.

downconverter output (93 fs, 0.044° (rms)) is much larger than the actual residual or induced cavity field (shaded area) noise, which directly effects the electron beam jitter. Therefore reducing the downconverter bandwidth effects its output signal but not significantly the induced cavity field jitter.

INDUCED CAVITY FIELD JITTER

The induced cavity field timing jitter in dependence of the controller gain, downconverter noise and modulator noise for the actual FLASH MO is shown in Fig.4. With increasing gain the downconverter contributions to the jitter increases while the MO and modulator contributions decrease, respectively vice versa for decreasing gain. However, experimentally the gain is limited by the loop stability due to the loop lantency. Tab.1 summarizes the jitter budget.

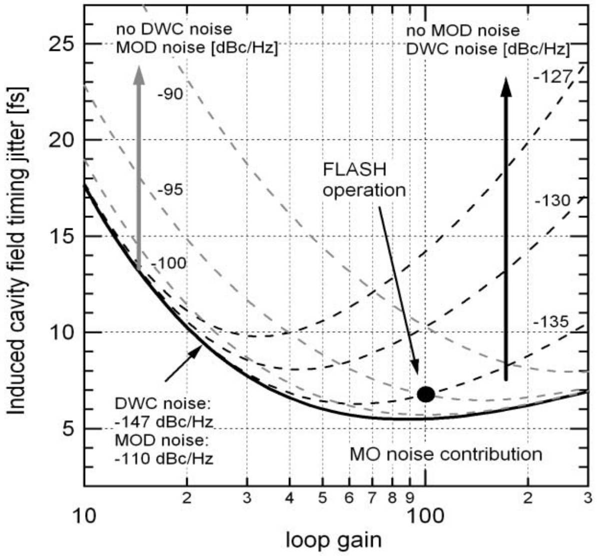

Figure 4: Induced cavity field jitter in dependence of loop gain and phase noise from master oscillator (MO), downconverter (DWC) and modulator (MOD).

Subsystem	Phase noise [dBc/Hz]	Residual jitter [fs]	Induced jitter [fs]
MO	see Fig.3	14.1	5.5
DWC (Frontend)	-147	1.8	1.8
DWC (ADC)	-135	5.8	5.8
MOD	-110	1.2	1.2

Table 1: Residual and induced cavity field jitter budget for FLASH with f_{12} = 200 Hz, g_0 = 100. Timing jitter values are rms values.

Except low frequency noise from microphonics, disturbancies from klystron and electromagnetic accelerator environment, the induced cavity field jitter of 8.2 fs (operating point marked by a dot) is limited mainly by the MO performance (5.5 fs, 14.1 fs residual jitter) and the actual ADC sampling scheme (5.8 fs) caused by aliasing effects.

SUMMARY AND OUTLOOK

A phase noise budget for a single cavity LLRF regulation system for XFELs based on a noise characterization of its subsystems has been presented. High frequency phase noise above the loop bandwidth is filtered efficiently by the cavity. The induced cavity field jitter and residual jitter between the cavity field and the master oscillator (MO) are significantly lower than the measured jitter from the detector, respectively downconverter. Direct beam based phase measurement techniques or fast bunch arrival time monitors have to be applied to characterize the induced cavity field jitter [2]. For the actual FLASH LLRF parameters, we predict an induced cavity field jitter of 8.2 fs (3.8m°) for optimal operation, respectively 15.3 fs (7.1m°) residual noise, which is mainly caused by MO noise and the actual ADC sampling scheme. The difference phase jitter between two LLRF systems is expected to be smaller, because both LLRF systems are driven by the same MO, which should be verified experimentally using correlation readout techniques. Furthermore noise contributions from microphonics, klystron and electromagnetic disturbancies within the accelerator environment and the drift budget of the LLRF system should be investigated.

REFERENCES

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