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PROGRESS ON THE MULTI BUNCH FEL PERFORMANCE AT FLASH

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Abstract

At the SASE-FEL user facility FLASH, superconducting TESLA-type cavities are used for acceleration. The high achievable duty cycle allows for operating with long bunch-trains, hence considerably increasing the efficiency of the machine. However, RF induced intra-bunch-train trajectory variations were found to be responsible for significant variations of the SASE intensity within one bunch train. This work presents the latest achievements in improving the multi-bunch FEL performance by reducing the intra-bunch-train variation of RF parameters. Particular attention is given to the static and dynamic detuning of the cavities. It will be shown that the current level of LLRF control is suitable to limit the variation of RF parameters considerably.

INTRODUCTION

The Free-Electron Laser in Hamburg (FLASH) is a high-gain FEL user facility operating in the soft X-ray regime [1, 2]. The current layout of FLASH is shown in Figure 1. Acceleration of the electron bunches is achieved by using 56 superconducting TESLA-type [4] cavities in seven modules (ACC1-7). Due to the high achievable duty cycle, a long radio frequency (RF) pulse structure can be provided, which allows to operate the machine with long bunch trains.

The principles of RF induced intra-bunch-train trajectory variations have been described in Detail in Ref. [5]. At FLASH, several cavities with individual operational limits [6] are supplied by one RF power source. The low-level-RF system (LLRF) [7] is able to restrict the variation of the vector sum of the amplitude and phase of the accelerating field within one RF station below 0.01 % and 0.01°, respectively [8]. However, caused by the effects of beam loading and Lorentz force detuning, individual cavities have an intrinsic variation of RF parameters within one bunch train. Misaligned cavities in combination with variable RF parameters induce intra-bunch-train trajectory variations.

At high beam energy the FEL saturation length at FLASH is close to the total length of the undulator. Small perturbations, for example betatron oscillations or energy variations, will limit the output power of the amplification process. It has been shown [5] that RF induced intra-bunch-train trajectory variations are substantially decreasing the multi bunch FEL performance and must be considered as the dominant source of intra-bunch-train variations of the SASE intensity.

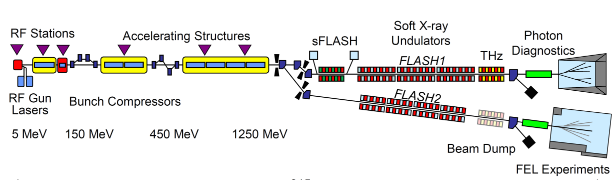

Figure 1: Schematic layout of the FLASH facility [3].

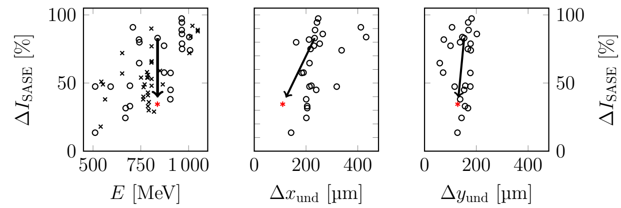

Figure 2: Analysis of the intra-bunch-train variation of the SASE intensity ΔI_{SASE}, recorded at FLASH during user runs with 400 bunches. The mid and right plot shows ΔI_{SASE} as a function of the horizontal and vertical RMS intra-bunch-train offset variation in the undulator, Δx_{und} and Δy_{und}, respectively. In the left graph, ΔI_{SASE} is plotted as a function of beam energy E.

Figure 2 supports these findings, showing analyzed data from 28 user runs with 400 bunches between July 2015 and January 2018. Plotted is the variation of the SASE intensity within one bunch-train, ΔI_{SASE}, as a function of the beam energy E (left). The dots represent data available in the data acquisition system [9], the crosses correspond to evaluated logbook [10] entries. The center and right graph relates ΔI_{SASE} to the horizontal and vertical RMS intra-bunch-train offset variation in the undulators, Δx_{und} and Δy_{und}, respectively. The red asterisks reflect data after significantly reducing RF variations, as will be explained later. Each set of data is averaged over about 100 consecutive bunch trains.

Regarding regular machine operation, the trajectory variation is significantly larger in the horizontal plane. Since misalignments are considered to be equally distributed in both planes, detuning related coupler kick variations [11] are the only reasonable explanation for the increased horizontal trajectory variation. Furthermore, the SASE intensity variation tends to increase with larger horizontal trajectory variation, whereas the vertical plane seems uninfluential [5].

FLASH has been upgraded consistently within the last decade which is accompanied by the fact that it consists of different types of sub-systems, such as accelerating modules. The cavities in ACC1, ACC6 and ACC7 are equipped with a remote-controlled stepper motor for the power coupler antenna. This allows to change the loaded quality factor Q_L, hence the amount of power coupled from the waveguide into the cavity. Additionally, these cavities are equipped with double piezoelectric elements [12] which allows for fast fine tuning of each cavity. Due to technical issues, however, the piezo tuners are regularly switched off since 2015. At ACC2-5, only the coarse tuning of the cavities can be adjusted remotely during regular machine operation.

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This work aims to explore the possibilities of limiting trajectory variations by reducing the variation of RF parameters within one bunch train with the current level of LLRF control at FLASH. Special consideration will be given to the role of the static and dynamic detuning of the cavities.

PRINCIPLES OF RF VARIATIONS

The variation of the amplitude of the accelerating field within one bunch train, ΔV, is key in the creation of trajectory variations. For typical machine operation at FLASH with low beam currents, the amplitude variation is determined mainly by the detuning of the cavities [5].

The required RF power for providing a certain accelerating gradient increases if the cavity is detuned with respect to the power source. The coarse detuning, which is defined as the mean cavity detuning within the RF flattop, should therefore be zero for optimal operation. It is affected by microphonic noise of the cavities and, more importantly, by Lorentz forces induced by the accelerating fields.

High electromagnetic fields in resonators lead to strong Lorentz forces on the walls of these structures. As a consequence in pulsed operation mode, the cavities are deformed dynamically in the range of some µm [7]. This results in a dynamic variation of the resonance frequency, a Lorentz force detuning (LFD). It scales quadratically with the accelerating field [13] and due to the high quality factor Q_L, the LFD within one bunch train is in the order of the bandwidth of the cavity of for example 300 Hz [14].

As mentioned before, the RF power is distributed to the individual cavities according to their operational limits. The gradients, thus the LFD therefore differs between individual cavities. If the detuning changes, the amount of power coupled into or reflected from the cavity changes. The dynamic behavior of the power reflection cannot be compensated for individual cavities by a vector sum RF control. As a result, the accelerating fields of individual cavities have a slope during the RF flattop [7]. The particular time dependence of the RF parameters depends considerably on the amount of LFD and on the coarse detuning of the cavities.

The effect will be shown for typical operational conditions of the sixth accelerating module (ACC6) at FLASH using a cavity simulator [15]. In the simulation feedback is on, the vector sum is constant in all cases, $Q_L = 3 \cdot 10^6$, and there is no beam loading considered. The RF parameters are calculated for different coarse detuning and for different coupling factors for the simulated Lorenz force, thus different amounts of cavity detuning within the flattop.

The results are shown in Figure 3. Plotted are the accelerating gradients (top) and detuning (bottom) of eight cavities for three scenarios: 1) detuned cavities with LFD, 2) tuned cavities with LFD and 3) tuned cavities with decreased LFD. The latter reflects the operation of fast piezo tuners which are able to limit the detuning below 20 Hz [16]. The dashed lines indicate the beam duration of long bunch trains.

Shown are furthermore the intra-bunch-train variation of the accelerating gradient ΔV, the mean cavity detuning

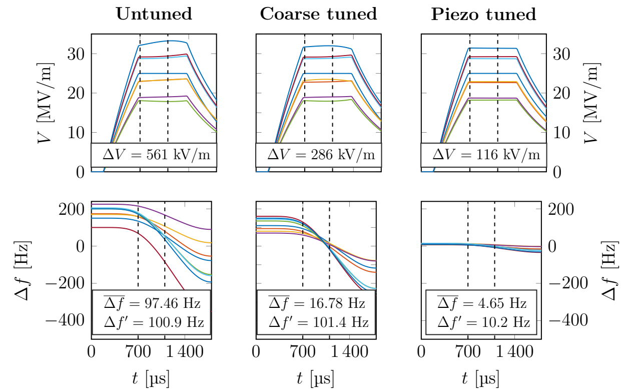

Figure 3: Simulated accelerating gradients V (top) and detuning Δf (bottom) of eight cavities at ACC6 at FLASH for different scenarios regarding the coarse tuning and the coupling factors for the simulated Lorentz force. The dashed lines indicate the beam timing for long bunch trains. Shown are also the mean cavity detuning within the RF flattop $\overline{\Delta f}$, and the intra-bunch-train variation of the gradient ΔV and detuning $\Delta f'$ (each parameter RMS over all cavities).

within the RF flattop $\overline{\Delta f}$ and the range of detuning within the bunch-train $\Delta f'$ (each parameter RMS over all cavities).

Comparison between the left and center column reveals that by decreasing the coarse detuning of the cavities from 97 Hz to 17 Hz, the variation of the accelerating gradient gets reduced by a factor of two. Additional limitation of the LFD from 101 Hz to 10 Hz decreases the gradient variation to a fifth of the initial range.

MITIGATION OF RF VARIATIONS

In this section we present a detailed evaluation of the RF setup at multi-bunch operation at FLASH. A total amount of 28 user runs with 400 bunches between July 2015 and January 2018 have been investigated (cf, Fig. 2) and are compared to dedicated measurements. We will show that the current level of LLRF control is capable of significantly reducing intra-bunch-train RF variations, if the machine is set up accurately.

The upper row of Figure 4 shows the intra-bunch-train variation the accelerating gradient ΔV and the detuning $\Delta f'$, and the coarse detuning $\overline{\Delta f}$ of each 1.3 GHz cavity (RMS over all user runs). The lower row shows the absolute value of each parameter after a dedicated setup procedure, at which the piezo tuners (module 1,6,7) were switched on and after coarse tuning of remaining cavities.

For regular machine operation the RMS value of all cavities of the gradient variation is $\Delta V_{\text{rms}} = 462$ kV/m, cavity detuning $\overline{\Delta f}_{\text{rms}} = 331$ Hz and detuning variation $\Delta f'_{\text{rms}} = 122$ Hz. The values for the tuned setup are $\Delta V_{\text{rms}} = 129$ kV/m, $\overline{\Delta f}_{\text{rms}} = 53$ Hz and $\Delta f'_{\text{rms}} = 72$ Hz.

The impact of piezo tuner (ACC1/6/7) on limiting both, the gradient and the detuning variation is evident. However, careful tuning can significantly decrease the variation of RF

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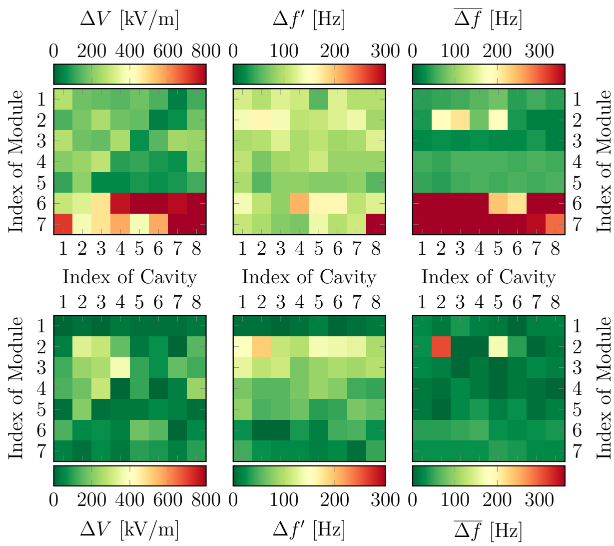

Figure 4: Intra-bunch-train variation of the accelerating gradient ΔV (left column) and detuning $\Delta f'$ (mid), and coarse detuning $\overline{\Delta f}$ (right) of 56 cavities at FLASH. The upper row shows the RMS values from 28 different user runs with 400 bunches, the lower row shows the absolute values after a dedicated setup procedure.

parameters even without piezo tuners, as shown exemplarily for ACC4/5 in Figure 5.

The coarse detuning of the cavities is determined mainly by the Lorenz forces. If the accelerating gradient of one RF station is changed, the coarse tuning of the cavities has to be adjusted. Figure 4 points out that especially for ACC6/7, where the gradient has to be changed frequently to reach different beam energies, the coarse detuning is poorly adjusted in regular operation (RMS value in ACC6/7: $\overline{\Delta f}$ = 590 Hz). Consequentially, the gradient variation is particularly large in these cavities (RMS in ACC6/7: ΔV = 805 kV/m).

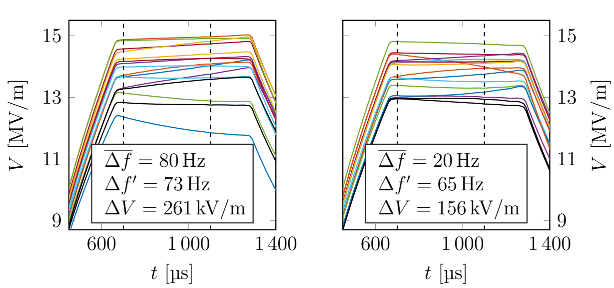

Figure 5: Measured accelerating gradients V of 16 cavities at ACC4/5 before (left) and after coarse tuning (right). The dashed lines indicate the beam duration. Shown are also the intra-bunch-train variation of the accelerating gradient ΔV and detuning $\Delta f'$, and the mean cavity detuning within the RF flattop $\overline{\Delta f}$ (RMS of all cavities, cf. Fig. 3).

IMPACT ON TRAJECTORIES AND SASE

The red plot marks in Figure 2 show the impact of the previously described tuning procedure on the RMS offset variation in the undulator and the variation of SASE intensity within one bunch train. For the highlighted example (arrow), the reduction in the horizontal and vertical plane is 124 µm and 25 µm, respectively, while the SASE intensity variation gets reduced by 49 %. The mean SASE intensity within the bunch train is thereby increased from 74 % to 91 % with respect to the bunch with maximum intensity.

Results indicate that the multi-bunch FEL performance at FLASH can be improved significantly if the RF setup receives more attention during the machine setup. Besides, the piezo tuners are important for limiting crucial horizontal trajectory variations in the undulator and their reliable operation should be of priority.

Furthermore the reproducibility of machine settings can be positively influenced by permanently maintaining the tuning setup. This requires automated processes which monitor and adjust the detuning, which is foreseen and already tested using automated piezo tuners. For higher Q_L machines like European XFEL [17] these comments are even more important.

CONCLUSION

RF induced intra-bunch-train trajectory variations predominantly limit the multi-bunch FEL performance at FLASH. We have demonstrated that the current level of LLRF control is suitable to limit the variation of RF parameters within one bunch train significantly and quantified its impact on the FEL performance, showing a considerable decrease of SASE intensity variation. It must be concluded that the current level of RF control is underutilized in regular multi-bunch operation.

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