Precision Regulation of RF Fields with MIMO Controllers and Cavity-based Notch Filters

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Abstract

The European XFEL requires a high precision control of the electron beam, generating a specific pulsed laser light demanded by user experiments. The low level radio frequency (LLRF) control system is certainly one of the key players for the regulation of accelerating RF fields. A uTCA standard LLRF system was developed and is currently under test at DESY. Its first experimental results showed the system performance capabilities. Investigation of regulation limiting factors evidenced the need for control over fundamental cavity modes, which is done using complex controller structures and filter techniques. The improvement in measurement accuracy and detection bandwidth increased the regulation performance and contributed to integration of further control subsystems.

INTRODUCTION

The European Free Electron Laser XFEL is a free electron laser generating X-Ray laser light of tunable wavelength by the SASE process, using an electron beam accelerated to about 17.5 GeV, in a pulsed operation mode. Providing its users stable and reproducible photons, requires a very precise control of acceleration fields. Developing and studying LLRF hardware and control strategies for the XFEL benefits from implementing and testing concepts at the Free electron LASer Hamburg FLASH. The latest renovation of the LLRF system is a change of the controller hardware to an uTCA based technology standard. One major impact for the LLRF regulation is the change of field detection, sampling frequency and precision of signal processing. Especially the higher sampling frequency allow for direct measure of further dynamics in the feedback loop.

It is well known that next to the acceleration mode, there exist further fundamental modes in a resonator effecting the closed loop system [?]. Especially the so called $8\pi/9$-mode generating a significant limitation on the maximum loop gain. In this paper a control concept is presented which has been implemented and tested at FLASH. Filtering approaches and measurements for the next fundamental mode are outlined. This allows to keep the relative amplitude and absolute phase error below the XFEL requirements of 0.01 % (rms) and 0.01 degrees (rms).

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REGULATION LIMITING FUNDAMENTAL CAVITY MODES

The Tesla type cavities used for the XFEL linear accelerator are operated in the so called π-mode. Next to the acceleration mode there exist further fundamental modes hosted by this resonator. Resonance frequencies have been measured and further theoretical background can be found in [?]. A sketch of the on axis electrical field distribution in beam direction for these modes can be found in Fig. 1.
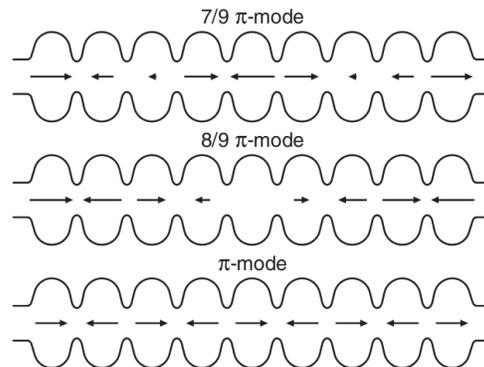

Figure 1: Sketch of electrical field $\vec{E}_z$ distribution along the axis for the acceleration and the two next fundamental modes of Tesla type cavities [?]

Exciting this resonance modes lead to a degradation of the regulation performance up to an unstable loop. Furthermore it is limiting the parameter area which can be used for the controller design. So far only aliased contributions have been measurable due to the lower sampling frequency of $f_s = 1$ MHz, and actively suppressed using a complex feedback controller. Identifying the location has been done by bandwidth sweeping techniques in iterative processes [?]. With the upgrade of the LLRF system the sampling frequency of the LLRF digital processing has been increased to 9 MHz to meet the given intra train bunch repetition frequency of XFEL. This allows to measure directly the next two fundamental modes, $8\pi/9$ and $7\pi/9$, which are located about 800 kHz and 3 MHz below the π-mode carrier frequency of 1.3 GHz. Excitation measurements have been tested at FLASH to identify there exact location.

MEASUREMENT RESULTS

Defining the necessary system control parameters requires knowledge of the particular system dynamics. Be-

side deriving the model from physical consideration there exist methods to treat the system as unknown and derive knowledge by exciting it and measuring the response. In addition, when considering a closed loop system, it is necessary to estimate its performance and stability in terms of changing system parameters. The results displayed in the following have been done at the FLASH facility with the uTCA based control system at the first acceleration module.

Resonant mode excitation scans

For the following presented measurement a very simplified approach has been chosen for identifying the location of resonance modes for all cavities within one cryomodule. Since it is known that the $8\pi/9$-mode is located at about 800 kHz, a sinusoidal excitation signal, which is modulated during the RF pulse flattop, is applied on the drive signal. Within one step of this scan, a specific excitation frequency is taken and a couple of pulses are recorded for each cavity. Taking the amplitude response allows to scan through a defined frequency range and record a system frequency response plot, as shown in Fig. **??**.
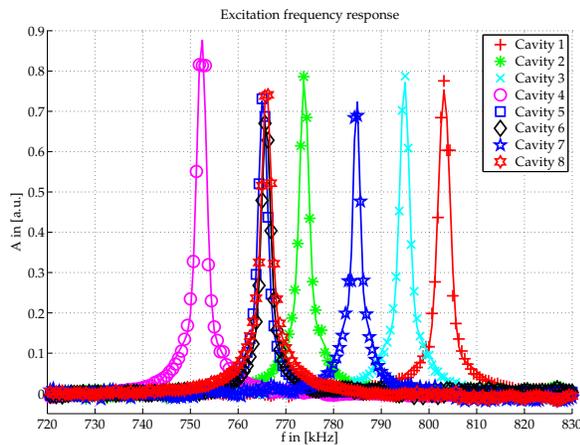

Figure 2: Individual cavity response to a sweeping sinusoidal excitation modulated to drive signal

It can be observed that there exists a spread of resonance frequencies for individual cavities of about 50 kHz, whereas 3 cavities have almost the same resonance frequency. This derives the question which distribution would be more feasible from controls perspective? Assuming all cavities within the vector sum have identical mode frequencies, suppression can be done using a narrow band notch filter. Whereas all modes are equally distributed their contribution would be suppressed by $1/N$, where N defines the number of cavities within this vector sum. Since both cases are hard to realize, individual filtering each cavity is combining both approaches.

Next also the $7\pi/9$-mode can be identified using the same approach which is presented in Fig. **??**.

One can observe comparable results in terms of spread of resonance frequencies for this scan. Identifying each cry-
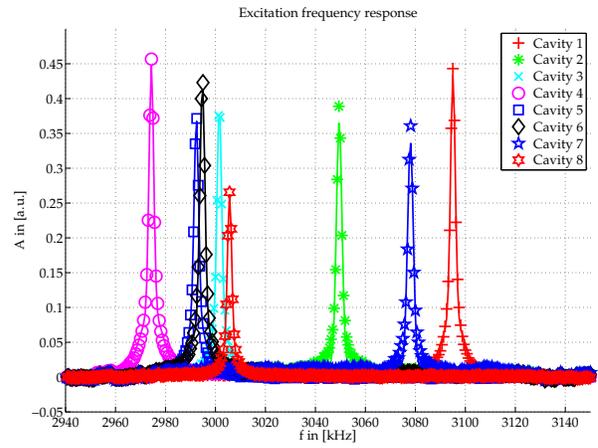

Figure 3: Individual cavity response to a sweeping sinusoidal excitation around 3 MHz, comp. Fig **??**

omodule location of resonance modes is one of the initial LLRF characterization measurement done in the module test stand before installation in the XFEL tunnel.

Characterization of feedback loop parameters

From control theory it is known that within digital control loops the processing delay introduces phase lags in the system which reduces the gain margin of the closed loop system. Having additional resonance peaks in the system this effect even leads to stability regions as function of the delay, [**?**]. To study this effect an additional loop delay has been introduced by shifting the output signal in steps of 81 MHz clock cycles. For each measurement point the proportional gain has been increased and the VS error has been recorded, this is shown in Fig. **??**.
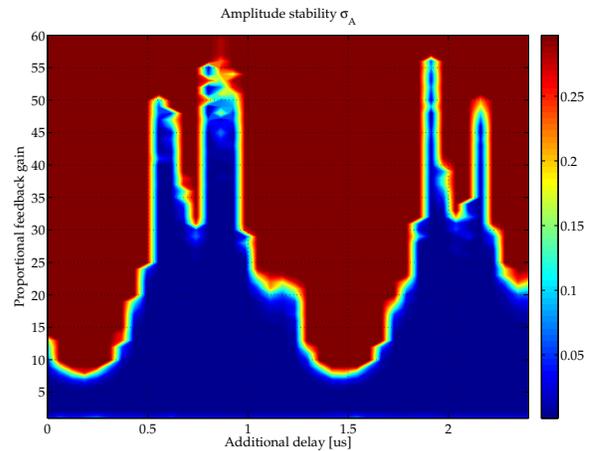

Figure 4: Stability diagram for scanning the amplitude error as function of feedback gain and additional loop delay

It is clearly visible that for the initial system delay this leads to instabilities already for small feedback gains. In addition one can see that the distance between two unstable regions is about 1.25 us which corresponds to 800 kHz

resonance frequency. Once applying a notch filter for this particular mode, further instability regions are visible in Fig. **??**.
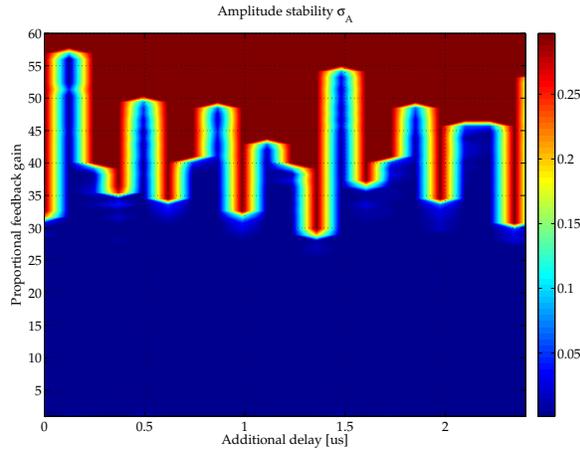

Figure 5: Stability diagram compare Fig. **??** with applied band-stop filters

Comparable to the previous plot one can observe stability regions, which are separated by about 300 ns, fitting to the $7\pi/9$-mode location.

REGULATION STRATEGY

The spread of resonance frequencies within one cryomodule requires a broad band notch filter to sufficiently suppress all individual cavity contributions. First only the $8\pi/9$-mode is considered. With the change of the LLRF system and increased hardware capabilities it turned out to be preferable to introduce individual filters in a preprocessing stage before computing the vector sum. This allows to reduce the bandwidth of the notch filter and individual tuning. Realization is done by a second order IIR filter:

$$\begin{pmatrix} \widetilde{u}_I(k) \\ \widetilde{u}_Q(k) \end{pmatrix} = \begin{bmatrix} F(z) & 0 \\ 0 & F(z) \end{bmatrix} \cdot \begin{pmatrix} u_I(k) \\ u_Q(k) \end{pmatrix},$$

where each controller transfer function is implemented as

$$F(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}.$$

The filter is designed such that data processing is done internally with a higher clock frequency, allowing usage of the same filter stage for multiple channels, minimizing the implementation costs in terms of FPGA space. Keeping the system most generic, this filter can be used for other applications, by application of a different set of coefficients computed by the control system server.

A comparison of the closed loop regulation with and without applied filters for equal feedback parameters is shown in Fig. **??**.

It can be easily observed how the $8\pi/9$-mode oscillations on the signals are filtered such that only pulse to pulse
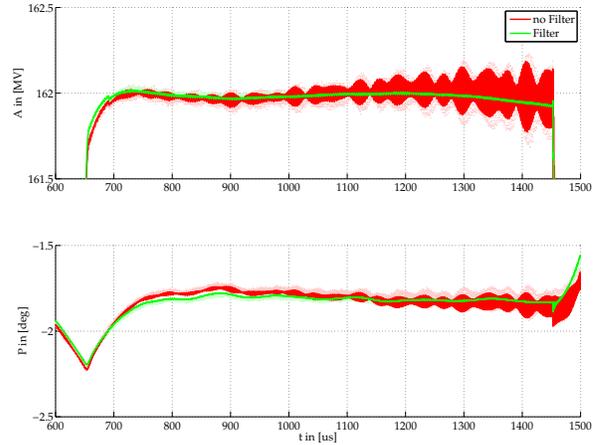

Figure 6: Zoomed flattop region of regulation with proportional feedback, with and without $8\pi/9$-mode filter

fluctuations are visible. A higher feedback gain can be achieved without adjusting the loop delay of the system.

CONCLUSION AND OUTLOOK

With the change of the LLRF control system a strategy for regulation of fundamental modes had to be developed. Recent measurements show the distribution of resonance modes within one cryomodule demanding active suppression strategies to fulfill performance specifications of the XFEL. Implementation of individual narrow band notch filters in the preprocessing stage for each cavity allows to improve the regulation performance of the closed loop system. Suppression of the $7\pi/9$-mode is intended to be done using a complex multiple input/output (MIMO) controller. Since the mode location, measured at about 3 MHz, is far outside the closed loop bandwidth allows to use a broad band notch filter at the output stage of the controller. Further measurements are planned to study the interaction of these modes with the electron beam.

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