RECENT LLRF MEASUREMENTS OF THE 3RD HARMONIC SYSTEM FOR FLASH*

C. Schmidt, F. Ludwig, M. Hoffmann, M. Hoffmann, P. Morozov, DESY, Hamburg, Germany

Abstract

A new 3rd Harmonic System [1] has been recently installed in FLASH facility at DESY [2]. It consists of a cryomodule with four TESLA type cavities operating at 3.9 GHz.

In order to achieve the field regulation requirements, components of the LLRF field controller electronics, namely the frequency generation hardware and the down-converters had to be modified and improved. The structure of the RF field controller is given as a combination of a multivariable feedback controller with an iterative learning control algorithm.

Field regulation performance has been measured in the cryomodule test facility in Nov 2009 and finally in FLASH during commissioning in May 2010, which is still ongoing. The results given here achieving pulse to pulse field stabilities in amplitude $< 10^{-5}$ and phase $< 0.001°$, which is significantly below the given requirements to this system.

INTRODUCTION

The 3rd harmonic system was proposed for FELs (Free-Electron-Lasers) to compensate for the non perfect bunch compression. The longitudinal phase space is rotated by the bunch compressor. Since the necessary energy chirp applied to the bunch is not linear with particles phases, but a piece of a sin curve the bunch compression cannot be optimal. The 3rd harmonic system can linearize the energy slope to the next Taylor order and such increase the SASE intensity. By linearization of the beam phase space after the first bunch compression section, more compressed and shorter bunches with higher peak currents are achieved.

Optimizing the performance parameters of the injector Linac, the 3rd harmonic system as well as all the modules before the first bunch compressor require a very precise phase control of the accelerating field of $0.01°$.

So a precisely designed field regulation and stabilization electronics is necessary, taking account for the three times higher operating frequency and the higher bandwidth of the cavities. Also because of the scaled down design of the cavities compared to the 1.3 GHz version (which is been used in all other accelerating sections of the accelerator) the nearest fundamental order (so-called $\frac{8}{9}\pi$) mode is expected to cause the feedback instable at much lower gain already.

The tests are ordered in two steps:

1. First the regular FLASH 1.3 GHz-LLRF system with a proportional controller together with a converter box was used, which converts the 3.9 GHz signals to 1.3 GHz and vice-versa. This system was tested in the cryomodule test facility.
2. For permanent FLASH operation a dedicated hardware for downconversion (and up-conversion) of the signals, as well as a more sophisticated extension to the master oscillator to generate a very pure LO-Signal was build. Also it could be confirmed, that the proportional feedback controller which was used so far was not appropriate, so we redesigned the controller concept to a combination of an adaptive (learning) pulse to pulse feedback (sometimes also called adaptive feedforward), which was able to compensate for all repetitive disturbances during the pulse in combination with a more complex model based fast feedback algorithm, not being distorted by the $\frac{8}{9}\pi$ mode.

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CONTROLLER STRUCTURE

The RF field controller algorithm is a combination of a MIMO (**M**ultiple **I**nput, **M**ultiple **O**utput) feedback controller with an Iterative Learning Controller that operates on the driving signals of both channels. It turns out that this structure is necessary due to the character of the disturbances acting on the plant. The outputs of the FPGA are the driving signals, which are converted into vector signals in the digital-analog-converter (DAC) and transmitted to the vector modulator, which is driving the klystron. An overview of the controller structure can be found in Fig. 1. Design of the controller parameters is done by model based techniques currently applied in modern control theory. The model can be found by standard subspace identification methods using input/output data of the plant only [3].

MIMO Feedback

The structure of the feedback controller currently implemented in the FPGA is fixed and given by the discrete time transfer function matrix

$$K(z) = \begin{pmatrix} K_{11}(z) & K_{21}(z) \\ K_{12}(z) & K_{22}(z) \end{pmatrix} \qquad (1)$$

with the elements

$$K_{ij}(z) = k_{ij} \frac{a_{ij} \cdot z^{-2} + b_{ij} \cdot z^{-1} + 1}{c_{ij} \cdot z^{-2} + d_{ij} \cdot z^{-1} + 1}. \qquad (2)$$

All parameters can be chosen independently and arbitrarily within the limits given by the integer arithmetics of the FPGA. Overflows of internal variables can be avoided

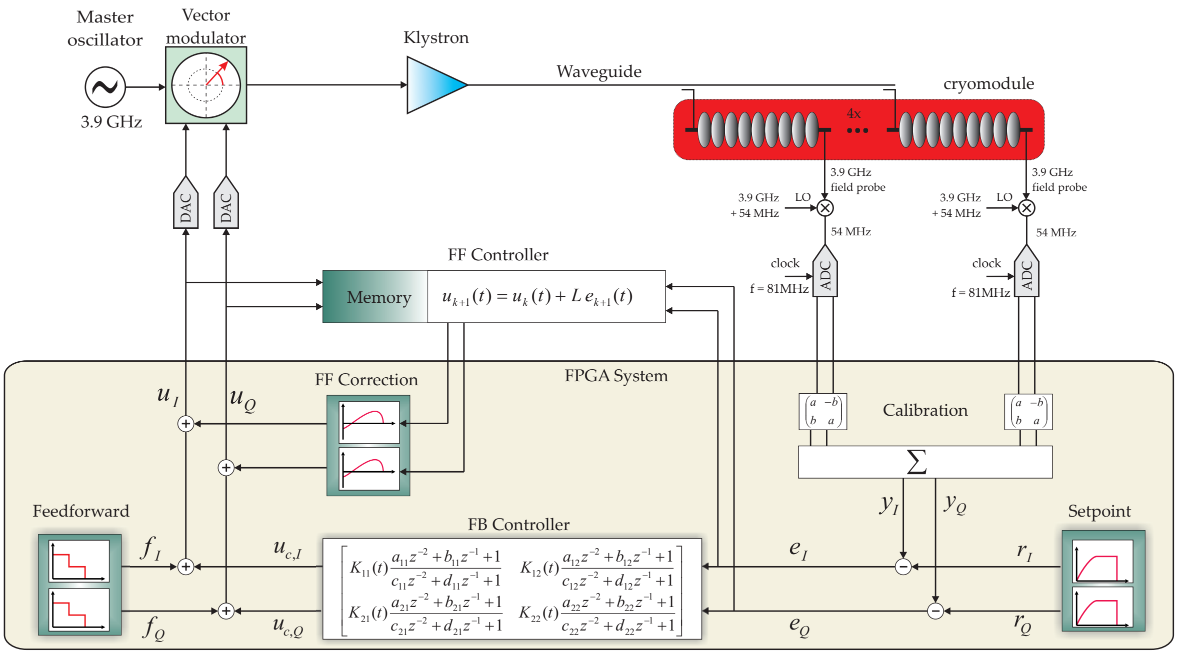

Figure 1: Overview of the digital RF field controller for the 3.9 GHz third harmonic module at FLASH.

by adjustable bit shift operators at the controller input and output registers [3].

In general the gain of dynamic controllers are frequency depended which does not allow to compare the static gains with proportional controllers. In order to sweep the static gains, the p-controller is implemented in series scaling the controller output.

Iterative Learning Control

The RF field regulation is subject to various, random and deterministic disturbance sources. The effect of both classes of disturbances can be minimized using 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 reference for the RF field is in general not changed very frequently, so the control task can be seen as a repetitive process for the pulsed operation mode of this accelerator. The basic update algorithm [4] is given by:

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

where u_k is defined as the system input and e_k the deviation of the measured RF output to the given setpoint for the pulse number k. L is a linear, non-causal, time-varying filter based on the identified system model. The current implementation of the system allows to change all tables inside the FPGA between two consecutive pulses. With the minimum computation of the underlying algorithm, as well as fast data transfer is fast enough, the adaptation can be performed synchronized to the repetition rate of the plant. Three steps have to be performed between two pulses: Read previous error and feedforward signals e and u, compute feedforward signal of next pulse by iterative learning control, and write feedforward signals to FPGA tables.

MEASUREMENTS

In Fig. 2 the behavior of the MIMO controller in comparison with the proportional controller used so far is shown. While the proportional controller excites the loop at frequencies of several 10 kHz already at very low gain, all though it can suppress pulse to pulse fluctuations well at much higher gain, the MIMO controller combines both features and can contain the loop stable performing at least as well as the p controller during the pulse as well as pulse to pulse.

Defining a pseudo-gain for the MIMO controller (transfer function interpolated to zero frequency) the performance can be expressed in terms of this pseudo-gain (see Fig. 3, this time measured at FLASH). Now, a much higher gain can be achieved.

Beside the feedback controller further an learning control algorithm has been discussed which is used to optimize the feedforward drive to the system in order to reduce repetitive controller errors, like beam loading. Further slopes caused by insufficient feedforward tables are removed within minor iteration steps. In Fig. 4 the iteration steps are given for such a case. The open loop feedforward signals have been debased for demonstration. After the algorithm has converged the rms error during the adapted flattop region can be found as $4.2 \cdot 10^{-5}$ in amplitude and $0.0037°$ in phase.

Note that the given results are in-loop signals, which cover long term drifts caused by the measurement equip-

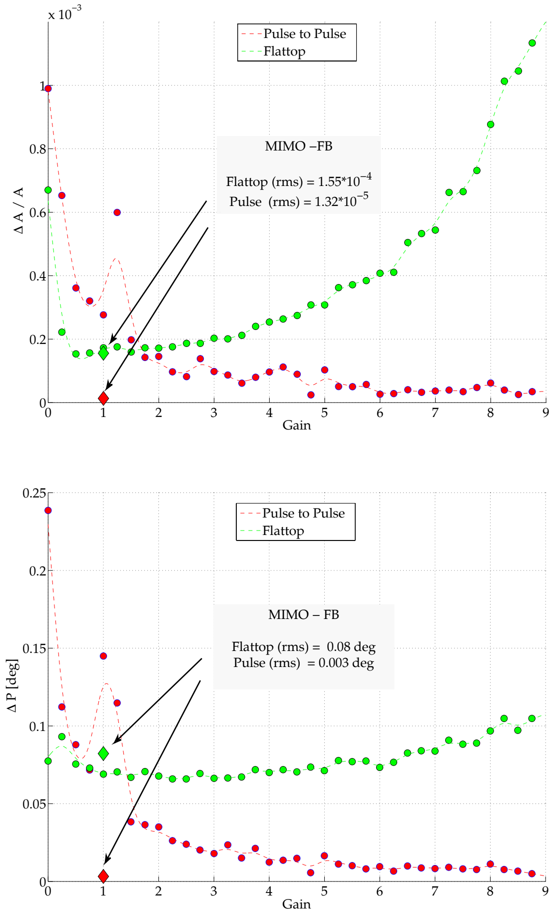

Figure 2: Amplitude (top) and phase stability achieved in the cryomodule test facility using the proportional controller and the MIMO controller (noted at gain = 1). The useful gain interval for the proportional controller is very limited.

ment [5]. To verify the achieved results beam based measurements have to be performed, which is currently under investigation.

SUMMARY

The measurements showed a promising in loop vector-sum amplitude stability of about $2 \cdot 10^{-5}$ for pulse-to-pulse operation in the test facility and at best $< 10^{-5}$ in FLASH. Corresponding phase stabilities are $0.003°$ and at best $< 0.001°$. The fast fluctuations on the signals during the flattop of the pulse is about $1.5 \cdot 10^{-4}$. Residual field imperfections are dedicated to measurement noise, which is assumed not influencing the beam energy spread. From RF field controls perspective the given limits could be reached by this combined controller concept. Further the system gains robustness due to the usage of the feedforward adaptation, which always minimizes the residual control, even when strong setpoint changes occur, e.g. machine tuning processes.

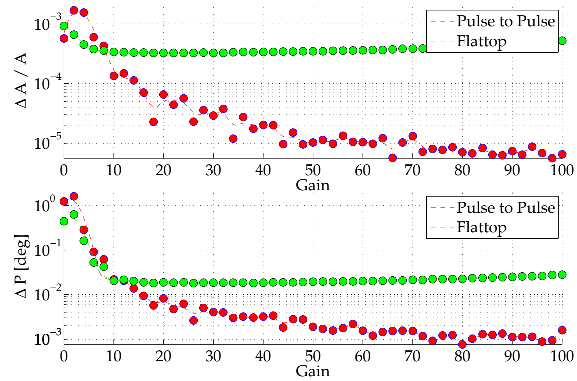

Figure 3: Amplitude (top) and phase stability achieved at FLASH using the MIMO controller.

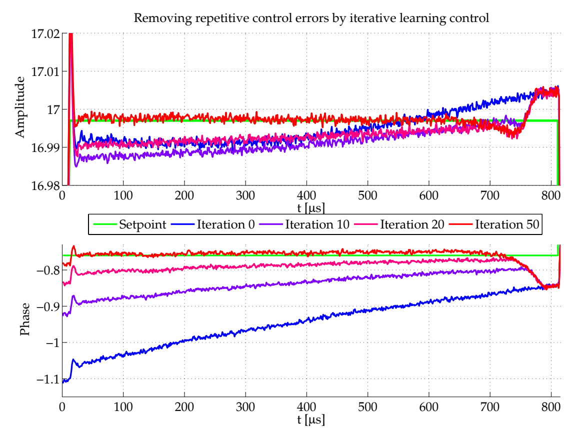

Figure 4: Within 50 iterations, nearly all repetitive errors are removed during the flattop phase.

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