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# Parameter Estimation and Tuning of a Multivariable RF Controller with FPGA technique for the Free Electron Laser FLASH

C. Schmidt, G. Lichtenberg, W. Koprek, W. Jalmuzna, H. Werner, S. Simrock

*Abstract*— **The operation of a Free Electron Laser in the X-ray wavelength range is the goal of the international XFEL project. The project critically depends on the linear accelerator component, where radio frequency fields have to be controlled with a very high amplitude and phase precision and under various sources of disturbances. This paper shows for the first time closed loop results of dynamic fixed order $H_\infty$ controllers implemented in a FPGA based control system on the FLASH facility at DESY.**

## I. Introduction

For many research activities a light source that is able to resolve objects on an atomic level would be favorable, e.g. in molecular biology. Wavelengths of X-ray radiation are in the range of the diameter of an atom ($10^{-10}$ m) such that X-ray radiation is suitable for the desired experiments. However, conventional X-ray sources can not provide X-ray pulses with a sufficiently short pulse length. This has the effect that e.g. single biomolecules are destroyed by the highly energetic radiation. Moreover, the resolution of conventionally produced X-ray radiation is limited by the broadness of its spectrum. Therefore, laser light is used for a variety of experiments because it can be better focused compared to other light sources, it is monochromatic, and very short pulses can be produced.

A current field of research in particle accelerator physics are Free Electron Lasers (FEL), which produce laser radiation with tunable wavelength. At the German Electron Synchrotron (DESY) in Hamburg the X-ray Free Electron Laser research project XFEL is conducted. The goal of the project is to build a Free Electron Laser operating in the X-ray wavelength by the year 2012 [1].

Figure 2 shows the structure of the Vacuum Ultraviolet FEL (FLASH) which is already working at DESY. On the left part, a linear accelerator is shown, which increases the energy of loaded particles, e.g. electrons by the interaction with electromagnetic radio frequency (RF) fields. The linear accelerator consists of resonators for the RF-fields housed in *cryomodules*. The RF-fields inside these superconducting resonator cavities are supplied by an actuator system for a finite time interval and then turned off again periodically.

The process requires very dense electron bunches, either longitudinal or transversal. The transverse dimensions of the electron bunches has to be in the order of the desired FEL-wavelength, while peak current after bunch compression has to exceed 50 A (infrared) or even 5 kA (X-ray), which determines the longitudinal dimension. The typical charge of a bunch is in the 1 nC-range. The requirements for the accuracy of the accelerating field can be derived from these values. In order to achieve reference tracking as well as disturbance rejection an RF-field control system is used.

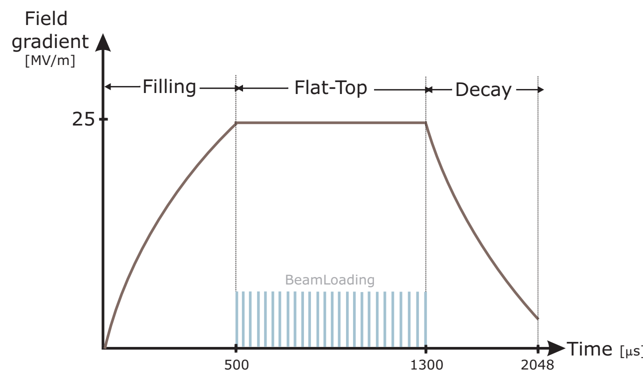


Fig. 1: One RF-pulse in Superconducting Cavities

In Figure 1 the amplitude of the desired envelope of the RF-field is displayed for one RF-pulse as a function of time. The field inside the accelerator cavities has to be kept constant once the required amplitude for the appropriate energy gain of the electrons has been reached at the end of the so called *filling phase*. During the *flat top phase* the electron beam is injected into the accelerator. When the electron beam has passed, the RF-field is turned off and the field amplitude decays. The envelope of the RF-field oscillation must be kept constant in amplitude and phase during the flat top time interval to transfer a precise amount of energy to the electrons. The control objectives regarding the necessary RF-field performance for the XFEL are specified as follows:

- The maximum of the field amplitude must be within 0.01% (rms) of the reference value.
- The field phase may not differ from the reference value by more than 0.01° (rms).

Superconductivity tends to break down above certain field gradients inside the cryomodules, leading to a significant drop of the quality factor of the resonators. The controller algorithm needs to be aware of this hard upper limit especially since the cavities need to be operated close to these limits in order to fulfill the physical goals of the machine. Thus, the

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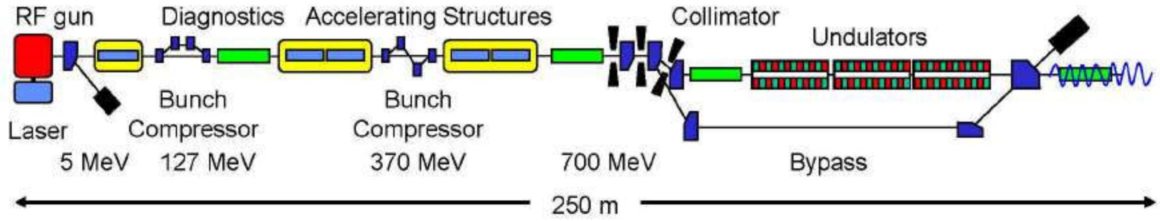


Fig. 2: A Free Electron Laser with Front End, Accelerating Structures and Undulators

open loop models should reflect the behavior of the system in a way that the precision of the closed loop dynamics given by the model is better than the desired objectives.

Until now, RF fields of FELs have been controlled by decentralized P controllers [4]. With new FPGA techniques a sampling time of $1\mu$s - that is necessary for digital control of the particle accelerators - was achieved, which was impossible before. The theoretical claim that these controllers could be parameterized by parameter identification and controller design methods have not been shown with any real FEL accelerator system before. Thus the problem was to choose appropriate identification methods and design tools that automatically find and adjust controller parameters with the help of a procedure that could be started with a single push button by the operators. Important steps to successfully realize and test the procedures proposed in this paper have been the use of black box models which are widely used in engineering instead of white box models with physical parameters that are standard in particle physics.

The paper is organized as follows: Section II gives a detailed description of the RF system of the linear accelerator with its digital control system After introducing the identification experiments in Section III, the controller design method is presented in Section IV. Finally the results of the first implemented MIMO controllers are shown in Section V.

## II. RF System of the Linear Accelerator

### A. System structure

At FLASH, eight cavities are housed in each *cryomodule*, which is a cooling structure with pipelines of liquid Helium. In total six cryomodules are assembled at FLASH but only the first accelerator cryomodule *ACC1* is considered in this paper, whereas the other modules are not structurally different. The loaded quality factor of a resonator is defined as

$$Q_{\mathrm{L}} = \frac{\omega_0}{2\omega_{1/2}} \,,$$

where $\omega_0$ denotes resonance frequency of the cavity with a half bandwidth of $\omega_{1/2}$ (HWHM[1]), and in the range of $Q_{\mathrm{L}} = 3 \cdot 10^6$. The resonance frequency is determined by the geometry which allows specific propagation of standing RF-waves.

[1]Half Width at Half Maximum

The system dynamics of the cavities can be modeled by a series of coupled LCR resonators [4]. After separation of the fast RF oscillations, a second order time variant differential equation for the envelopes of the electrical field components can be derived.

The time variance is due to the following effects: if the length of the cavity changes, the resonance frequency changes as well. Due to the relatively thin walls, the resonators become susceptible to mechanical vibrations which detune the resonance frequency. Two main disturbance sources causing this detuning are distinguished:

- Lorentz Force Detuning,
- Microphonics.

The oscillating electromagnetic fields inside the cavities induce currents in the cavity walls. These currents lead to Lorentz forces acting on the cavity walls and deforming the cavities. The magnitude of the Lorentz forces is proportional to the square of the accelerating field gradients such that Lorentz force detuning can be considered as a correlated and repetitive disturbance in frequency ranges up to 10 kHz [4]. The resonance frequency $\omega_0 = 1.3\,\mathrm{GHz}$ of the cavities with a half bandwidth of $\omega_{1/2} = 216.7\,\mathrm{Hz}$ changes by Lorentz Force Detuning in the range of $\pm 1\mathrm{Hz}/\mathrm{MV}^2$.

Mechanical vibrations caused by the accelerators environment in a typical frequency range below 1kHz are transferred by mechanical mounts to the cavities. Therefore, microphonics can be considered as uncorrelated disturbance that only weakly influences the cavity fields during the 1.3 ms long RF pulse but mainly influences the resonance frequency from one RF pulse to the next one. Other sources of disturbances like the influence of the electron beam on the RF-fields are not taken into account in this paper.

The actuator system receives a precise RF signal of 1.3 GHz from the master oscillator (MO). This low power sinusoidal signal can be changed by the vector modulator in amplitude and phase. The output signal of the vector modulator is amplified by a klystron, which is a radio frequency amplifier. The amplified RF waves are transferred from the klystron to the cavities inside the cryomodules via a waveguide transmission and distribution system. For economical reasons, one high power klystron supplies all $8-32$ cavities of an RF station, thus RF fields can not be influenced in each cavity individually – the system is underactuated.

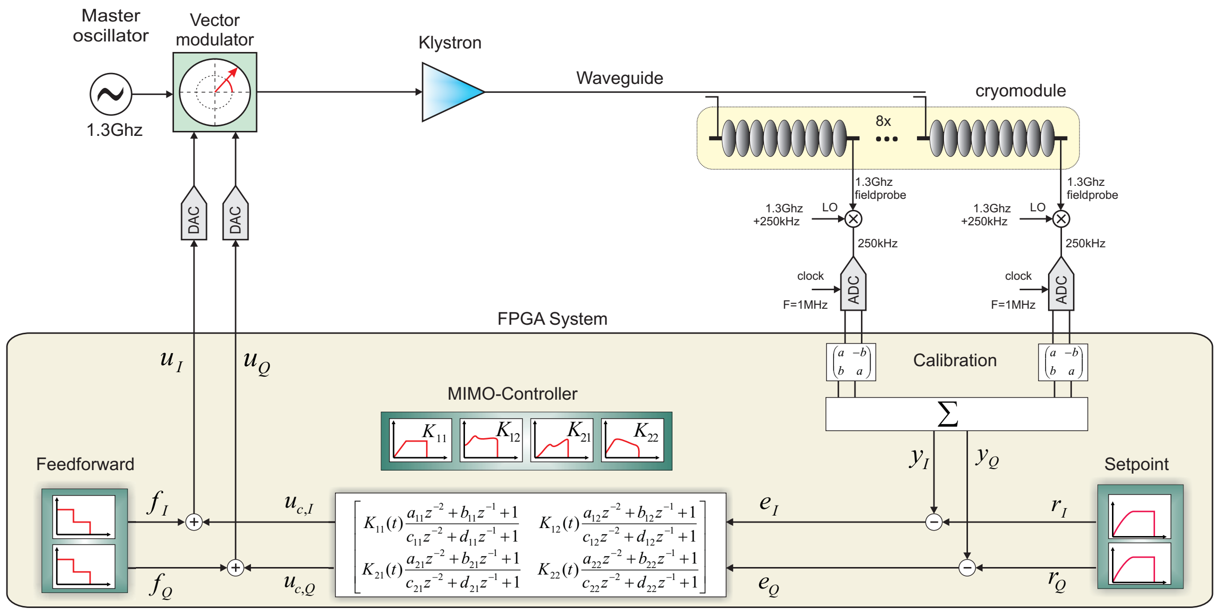


Fig. 3: Structure of the RF System with Master Oscillator, Vector Modulator, Klystron, Cryomodule, Measurement and Calibration System and the FPGA implemented Control System

## *B. Digital Control System*

The superconduction cavity simulator and Controller (SIMCON) is a project with the goal to supply reliable low latency controllers, based on field programmable gate array (FPGA) structures. The task of SIMCON is to control the vector sum of fields in superconducting cavities, but can also used as a simulator of a cavity and as test-bench for other accelerator sub-systems. It allows the practical implementation of fast algorithms. A block diagram of the Low Level Radio Frequency (LLRF) control system is presented in Fig. 3, where the lower part shows the digital FPGA controller. The LLRF control system has the task to keep the pulsed RF fields in the superconducting cavities of the RF station at the reference value during the flat top phase of one RF pulse shown in Figure 1. The main advantage compared to analog devices is that all SIMCON parameters are programmable which allows high flexibility for system upgrades and adaption.

After measuring the actual RF-field by pickup antennas, the signals are downconverted to an intermediate frequency of 250 kHz. The real (I) and imaginary (Q) field components are digitalized in analog-digital-converters (ADC) with a sampling frequency of 1 MHz. An overview of the signals shown in Fig. 3 are represented in terms of $I$ and $Q$.

- *Input signals* $u_{\mathrm{I}}, u_{\mathrm{Q}}$: Control signals of the actuator system which are acting on the vector modulator.
- *Output signals* $y_{\mathrm{I}}, y_{\mathrm{Q}}$: The real and imaginary part of the sum of the RF-field voltage vectors of eight cavities.
- *Reference signals* $r_{\mathrm{I}}, r_{\mathrm{Q}}$: Reference signals of the real and imaginary part of the vector sum of the RF-field's voltage vectors given by look-up tables for the specified field gradient.
- *Feedforward signals* $f_{\mathrm{I}}, f_{\mathrm{Q}}$: Open loop control Signals.
- *Control signals* $u_{\mathrm{c,I}}, u_{\mathrm{c,Q}}$: The feedback controller's output signals which are superimposed on the feedforward signals.
- *Control error signals* $e_{\mathrm{I}}, e_{\mathrm{Q}}$: Deviations in real and imaginary part of the output signals from the reference signals.

Calibration of the measurement signals is done for compensation of effects resulting e.g. from different cable lengths. The control algorithm usually uses the vector sums of all calibrated measurement signals of the individual cavities as signals to be controlled, because of the lack of individual actors for each cavity. The new control algorithm at the FLASH LLRF system presented in this paper is a combination of 2 nd order multiple input multiple output (MIMO) feedback with feedforward components for both channels. The outputs of the FPGA are the driving signals, which are converted to complex vector signals in the digital-analog-converter (DAC) and transmitted to the vector modulator.

The stability margin of the control loop depends on the overall gain and latency of the loop. The FPGA controller aims at the values of $1\,\mu$s for the latency and 100 for the gain. Experiments show an estimated loop latency without controller of approximately 500 ns. The remaining 500 ns may be attributed to the controller. The controller is implemented with VHDL programming code and synthesized by Xilinx XST. With respect to the operating frequency $f_{\mathrm{res}} = 1.3\,$GHz the vector modulator can be modeled as a first order low pass with a corner frequency of 10 MHz. The klystron is a high power RF amplifier that can be considered as well as a first order lowpass filter with a corner frequency of 8 MHz. The bandwidths of both actuator elements are very large compared to the narrow cavity bandwidth $\omega_{1/2}$, and the dynamical behavior of the actuator system is negligible in the frequency range up to 1 MHz considered for control.

## III. Parameter Identification

Although additional external disturbances and a number of nonlinearities in the actuator system are known to be relevant for a broad range of operation setpoints, standard identification procedures for linear time invariant (LTI) models could be chosen to estimate black box models that can be validated at specific setpoints [3]. In the following the subspace identification method `N4SID`, provided by Matlab's System Identification Toolbox [5] is used to estimate the parameters $A,B,C,D$ of a black box state space model

$$x(k+1) = Ax(k) + Bu(k)\ , \tag{1}$$

$$y(k) = Cx(k) + Du(k) \tag{2}$$

where u(k) and y(k) denote the system input and output respectively and x(k) is the state vector of the system at time $k$.

The flat top phase of the pulse is of main interest for control and is at the same time marking the operation point. Only measurements from this period are used for system identification. Persistent excitation signals can be injected in the accelerator system by superimposing random signals on standard feedforward tables with defined setpoints. A typical input sequence for the feedforward table is shown in Fig. 4.

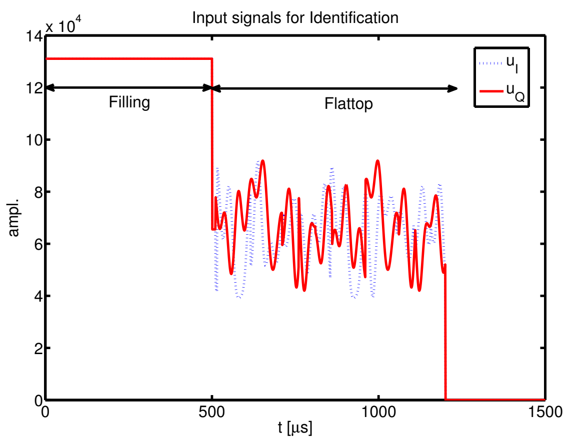


Fig. 4: Input Disturbances on both Channels at Flat Top

In the first $500\mu s$ (filling phase), the actuator system is operated with maximum power, i.e. maximum feedforward signal. As soon as the flat top phase begins, the feedforward signal is reduced by a factor of 0.5 in normal operation. In this flat top phase, an excitation signal is added to the feedforward signal as shown in Fig. 4. Thus open loop input-output data is generated, which shows worse performance than closed loop data, but which can be used later for parameter identification. The disturbances are exciting both channels of the input signals at the same time, which has turned out to be advantageous for good parameter identification results. High amplitudes of the excitation signals leads to a good signal to noise ratios.

Studying the measured signals, oscillations in the 250 kHz spectra can be observed, which can be referred to the intermediate frequency of the down converters described in Section II-B. In Fig. 5, measured vs. simulated signals are shown for an identified model of 3rd order. The slow systems dynamics are sufficiently modeled.

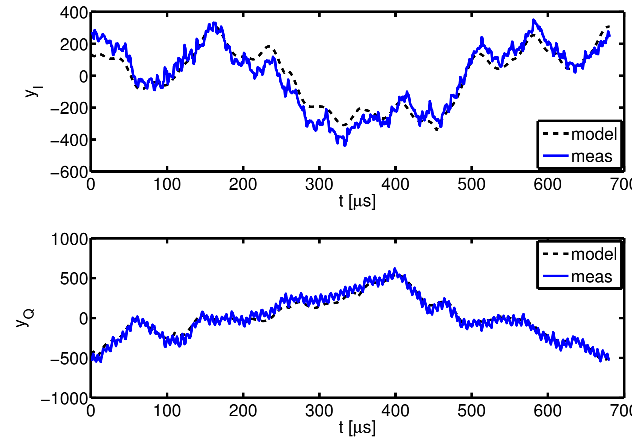


Fig. 5: Measured vs. simulated Vector Sum Signals

An example for identified matrices of a discrete time state space model (1)-(2) is

$$A = \begin{pmatrix} 0.99747 & -0.00098 & 0.00391 \\ 0.00749 & 0.99935 & -0.00141 \\ -0.01025 & -0.00611 & -0.34314 \end{pmatrix},$$

$$B = 10^{-4}\begin{pmatrix} 0.0001 & 0.0004 \\ 0.0023 & 0.0048 \\ 0.1289 & -0.2077 \end{pmatrix},$$

$$C = 10^{4}\begin{pmatrix} 3.7756 & 0.2514 & 0.0006 \\ -2.6351 & 0.4001 & 0.0036 \end{pmatrix},$$

$$D = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}.$$

The discrete time model is transformed to continuous time by MATLABs `d2c` algorithm, because the controller design procedure described in the following section is based on continuous time LTI models.

## IV. Controller Design

The fixed structure of the Controller implemented in the FPGA is given by

$$K(z) = \begin{pmatrix} K_{11}(z) & K_{21}(z) \\ K_{12}(z) & K_{22}(z) \end{pmatrix} \tag{3}$$

with the elements

$$K_{ij}(z) = k_{ij}\frac{a_{ij}\cdot z^{-2} + b_{ij}\cdot z^{-1} + 1}{c_{ij}\cdot z^{-2} + d_{ij}\cdot z^{-1} + 1}\,. \tag{4}$$

All parameters can be chosen independent and arbitrary within the limits given by the integer arithmetics of the FPGA. Overflows of internal variables are prevented by adjustable bit shift operators at the controller input and output registers. From the operators perspective, the number of tuning parameters increased from 1 (gain adjustment) to 20, which would be not possible to adjust manually. An automated update algorithm needs to be found in case of changing system parameters to guarantee longtime performance and stability.

### A. *Design objectives*

The design goal is to obtain high RF field flatness in amplitude and phase during the flat top phase, which gives best performance of the electron beam that is responsible for the quality of the laser beam. The vector sums of the probe signals are subtracted from the setpoint signals and given to the controller inputs. All measured probe signals show disturbances and noise from system specific as well as environmental sources. Attenuating all these disturbances by the controller might show an improvement for the observed RF signals, but no influence on the beam quality. Knowing that the cavity itself has lowpass filter characteristics, a useful control loop bandwidth can be estimated as it is shown next.

### B. *$H_\infty$ loop shaping*

The design objectives are disturbance rejection as well as reference tracking in the closed loop system. Both objectives are in contradiction over all frequencies, but a balanced trade-off between both can be found with the following standard design method.

First the so called generalized plant as shown in Fig. 6 is given, with the two dimensional vector signals:

| | |
|---|---|
| $r$ | reference input signal, |
| $u$ | plant input / controller output, |
| $y$ | plant output, |
| $e$ | controller input / tracking error, |
| $z_s$ | filtered sensitivity output, |
| $z_t$ | filtered complementary sensitivity output. |

To describe the behavior of a closed loop system we introduce two transfer function matrices, the sensitivity $S(s)$ and complementary sensitivity $T(s)$. The transfer function $S(s)$ and $T(s)$ giving the behavior from the reference inputs $r$ to the controller inputs $e$, and to the plant outputs $y$ respectively. It is well known that both functions are related as follows $S(s)+T(s)=I$. For good tracking we need $T(s)\approx I$, which implies that $S(s)\approx 0$. This should be achieved at the closed loop bandwidth of the system.

For arbitrary high frequencies, perfect tracking is impossible due to physical restrictions. High frequencies in the system are mostly related to disturbances which need to be rejected in the closed loop system $S(s)\approx 0$. An $H_\infty$ design is performed to find an optimal controller while shaping the transfer functions by the weighting filters $W_S(s)$ and $W_T(s)$ as shown in Fig. 6. For these filters the following constraints have to hold

$$\left\| \begin{array}{c} W_S(s)\,S(s) \\ W_T(s)\,T(s) \end{array} \right\|_\infty < 1\,, \tag{5}$$

where a controller has to be found which minimizes the $H_\infty$ norm of (5). The controller estimation is done by using the HIFOO algorithm [6]. The filters can be tuned to find an appropriate fixed order controller for the accelerator system, where $W_S(s)$ and $W_T(s)$ act as upper bounds for the maximum singular values of $T(s)$ and $S(s)$.

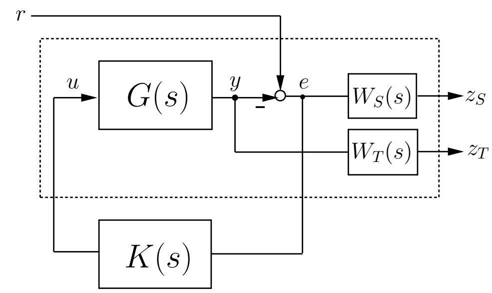


Fig. 6: Generalized Plant with Weighting Filters $W_S$ and $W_T$

In the following section we are presenting the results of the controller design and the used shaping filters. The estimated controller parameters have to be converted back to a discrete time model which then can be implemented. Therefore stability limits caused by latencies in the control algorithm have to be taken into account [7].

## V. Results

In this section the first results of the procedure outlined before are presented. It needs to be mentioned that the whole accelerator and control system is a high precise machine with a large number of uncertainties. Therefore implementation of any control or data acquisition algorithm has to be done carefully. Matlab is used as a script language to communicate directly with the FPGA, which implies that the machine is not protected against failures due to these processes. All controller parameters have to be checked before downloading to the FPGA. Nevertheless stability problems regularly occur close to the maximum gain values for a stable loop. A smooth step by step increase to high power operation points has to be done for investigation of the performance limits without so called interlocks, i.e. shutdowns of the accelerator power due to instabilities of the loop.

The weighting filters are chosen to be second order transfer functions, which allows at least 10 tuning parameters to shape the closed loop behavior, more precisely to adjust the 20 controller parameters.

$$W_S(s) = \frac{1}{M_S}\frac{(s+\omega_{S1})(s+\omega_{S2})}{(s+\omega_{S3})(s+\omega_{S4})}\,, \tag{6}$$

and

$$W_T(s) = \frac{1}{M_T}\frac{(s+\omega_{T1})(s+\omega_{T2})}{(s+\omega_{T3})(s+\omega_{T4})}\,. \tag{7}$$

In Fig. 7 examples of singular value plots of $T(s)$ and $S(s)$ are shown including controller designed by HIFOO with shaping filters as given above. With this shaping filters controller parameters are calculated and implemented in the FPGA after transforming the coefficients to discrete-time.

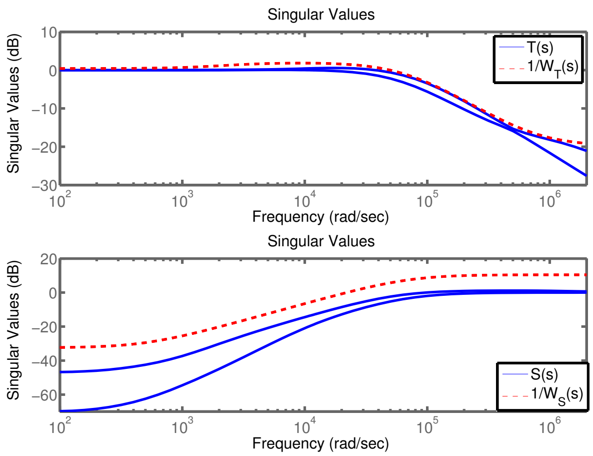


Fig. 7: Shaped Functions $S(s)$, $T(s)$ with weighting filters

The performance of the designed controller was tested in real time experiments at the FLASH facility in October 2007. One of the resulting trajectories for the case of a first order MIMO controller is shown in Fig. 8. It can be seen that there is a large overshoot at the beginning which is caused by the use of standard feedforward tables, which show maximum values until the end of the filling phase.

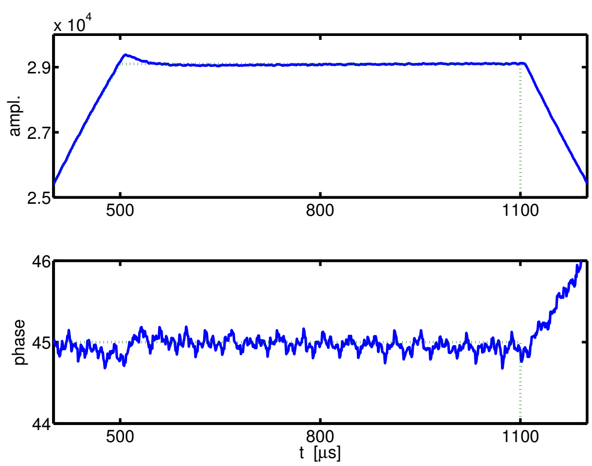


Fig. 8: Reference Tracking: Amplitude and Phase

For the second part of the flat top, the obtained RMS values are 0.14% (amplitude) and 0.07° (phase) – which is still an order of magnitude worse than the desired accuracies, but an improvement compared to previously used decentralized controllers.

Fig. 9 shows a detail of the final filling and the beginning of the flattop phase for a different operating point. Here also, the first overshoot is crucial for the overall performance. Methods for adaptation of the feedforward tables can improve this behaviour significantly, [8].

## VI. CONCLUSIONS AND FUTURE WORK

A procedure for low order MIMO LTI controller design was described and implemented on an FPGA based digital control system of a particle accelerator. It was shown that the fixed order controller can be found by using the $H_\infty$ controller design algorithm HIFOO. The procedure was applied online and the achieved controller parameters have been tested in the FPGA based LLRF control system of the FLASH facility at DESY, Hamburg. Tests of control loop stability and controller performance give promising results.

To achieve the goal of a user friendly solution of automated controller tuning, further studies have to be done. Critical controller parameters have to be tested and interception routines need to be defined to guarantee on the one hand a stable system and on the other hand a high performance. Operating points close to the physical machine limits and also long flat top intervals have to be tested. Next, closed loop behavior in presence of beam disturbances needs to be studied. Iterative Learning Control algorithms could be used to adapt the feedforward signals which will further improve the machine performance.

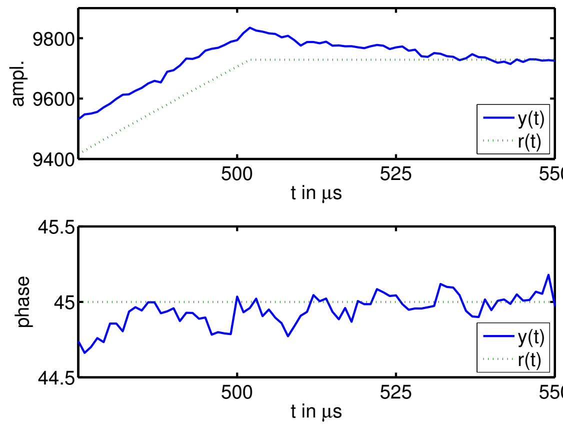


Fig. 9: Reference Tracking: Details of Amplitude and Phase

## VII. ACKNOWLEDGMENTS


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