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REAL-TIME ESTIMATION OF SUPERCONDUCTING CAVITIES PARAMETERS

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Abstract

Performance of accelerators based on the superconducting cavities including FLASH and XFEL facilities at DESY is affected by cavity parameters variation over time. High gradient electromagnetic field inside cavities causes detuning due to the Lorentz force. In addition the quality factor of cavities can change during the RF field pulse. Currently used method for estimation of those parameters is based on the post-processing of the data recorded during operation of the RF. External servers calculate cavity parameters using cavity equation, forward power and probe signals collected during previous pulse. A novel [1] approach based on the component implemented in FPGA is presented. In the new method loaded quality factor and detuning are estimated in real-time during the RF pulse for increased reliability and better exception handling. Modified firmware of the LLRF control system based on the Micro Telecommunications Computing Architecture (MTCA.4) platform has been used for the method verification.

INTRODUCTION

Accelerators based on superconducting technology such as XFEL [2] currently build at DESY are very sensitive to changes in the parameters of the main building blocks – the RF cavities. Because of the high loaded quality factor ($Q_l \approx 3 \cdot 10^6$) and operating gradient reaching 30 MV/m, superconducting RF cavities are affected by the Lorentz force detuning and the phenomena of superconductivity loss – quench.

Estimated cavity detuning can be used to compensate for the mechanical changes in cavities, for example caused by Lorentz force. Currently used method is based on the calculated phase difference between incident RF wave voltage coupled to the cavity and the voltage from the RF probe inside the cavity. This method works well in conjunction with the feed forward control scheme in pulsed operation but is not feasible for the long pulse or continuous wave (CW) operation mode [3].

Currently used method for quench detection uses computer installed outside of the MTCA.4 system [4]. The diagnostic server running on this computer calculates the Q_L during decay phase of the pulse and then analyses the patterns in the quench detection algorithm. Unexpected drop (averaged after tens of the RF pulse) detected in the Q_L is interpreted as a quench and causes a signal to be send to the MTCA.4 system. The message received by the controller decreases the power level of the RF pulse in case of exception is detected. Server based solution works reliable and reasonably well but the delay introduced by the Ethernet link between the server and the MTCA.4 crate makes impossible to react on the exception during the RF pulse.

In this paper a new approach to the estimation problem is presented, in which the algorithm is completely implemented in FPGA to obtain fast reaction time.

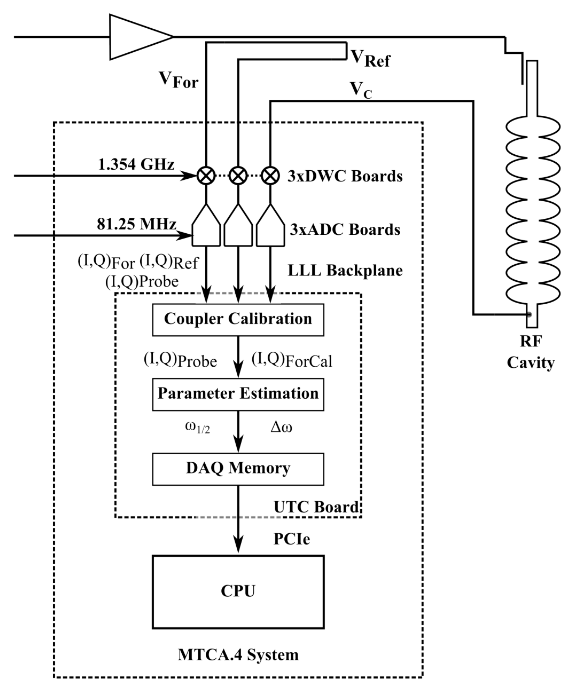

Figure 1: Simplified schematic diagram of the parameters estimation method.

PROPOSED METHOD

Simplified schematic diagram of the proposed parameter estimation method is shown in Fig. 1. Three RF signals: $\mathbf{V_C}$ – RF field voltage inside cavity, $\mathbf{V_{For}}$ – voltage of the forward RF wave from the power amplifier and $\mathbf{V_{Ref}}$ – voltage of the RF wave reflected from the cavity. Then signals are downconverted to a lower frequency (DWC) and converted into the digital IQ representation (ADC). $\mathbf{V_C}$, $\mathbf{V_{For}}$, and $\mathbf{V_{Ref}}$ are complex signals and can be also represented by three IQ pairs:

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$$\mathbf{V_C} = I_C + j \cdot Q_C$$
$$\mathbf{V_{For}} = I_{For} + j \cdot Q_{For}$$
$$\mathbf{V_{Ref}} = I_{Ref} + j \cdot Q_{Ref}$$

Digitized IQ pairs: $(I,Q)_{Probe}$, $(I,Q)_{For}$ and $(I,Q)_{Ref}$ are sent from the digitizers to the RF field controller (UTC) via Low Latency Links (LLL) on the MTCA.4 backplane. Algorithm implemented in the FPGA calculates detuning ($\Delta\omega$) and half bandwidth ($\omega_{1/2}$) of the cavity for each of the data samples. Computed values are stored in the Data Acquisition memory (DAQ) to be read out by the CPU and displayed for the diagnostics. Currently the computed data are not used for the control purposes, but it is foreseen to do so in future.

ALGORITHM

Well known first order differential equation of the cavity envelope equation in the complex space can be used to model changes in the RF field voltage signal inside superconducting structure [5]:

$$\frac{d\mathbf{V_c}}{dt} - (\omega_{1/2} - j\Delta\omega)\mathbf{V_c} = 2\omega_{1/2}\mathbf{V_{For}} \qquad (1)$$

Because of the coupler directivity, $\mathbf{V_{For}}$ has to be corrected for the leakage from the reflected signal. This is done by the following formula [6]:

$$\mathbf{V_{ForCal}} = \mathbf{a} \cdot \mathbf{V_{For}} + \mathbf{b} \cdot \mathbf{V_{Ref}},$$

where $\mathbf{a}$ and $\mathbf{b}$ are the complex calibration coefficients that includes the cross-coupling effect between forward and reflected signals. Those are computed outside of the FPGA, and can be calculated once for many pulses. After transformations of (1) to calculate the parameters and switching to the IQ signals, following formulas are obtained [1]:

$$\begin{aligned}\omega_{1/2} &= \frac{I_C \cdot (2 \cdot K \cdot I_{ForCal} - \frac{dI_C}{dt})}{I_C^2 + Q_C^2} \\ &+ \frac{Q_C \cdot \left(2 \cdot K \cdot Q_{ForCal} - \frac{dQ_C}{dt}\right)}{I_C^2 + Q_C^2}\end{aligned} \qquad (2)$$

$$\begin{aligned}\Delta\omega &= \frac{I_C \cdot \left(\frac{dQ_C}{dt} - 2 \cdot K \cdot Q_{ForCal}\right)}{I_C^2 + Q_C^2} \\ &+ \frac{Q_C \cdot (2 \cdot K \cdot I_{ForCal} - \frac{dI_C}{dt})}{I_C^2 + Q_C^2}\end{aligned}, \qquad (3)$$

where K - is a coefficient related to $\omega_{1/2}$ factor in the right side of (1) and is treated as a constant during RF pulse. To compute Q_L from $\omega_{1/2}$, following expression can be used:

$$Q_L = \frac{f_0 \cdot \pi}{\omega_{1/2}},$$

where f_0 is the cavity resonance frequency (1.3 GHz for the TESLA type cavities).

IMPLEMENTATION

Schematic of the implementation for the $\omega_{1/2}$ calculation algorithm is shown in Fig. 2. Numerical differentiation is used for the derivative calculation and the look-up table (LUT) with linear interpolator provides division operation. Internal data width used in calculations is 25 bits signed with fixed arithmetic. Design is implemented with usage of the Xilinx DSP48 blocks. Each multiplication operation is done with usage of two DSP blocks to obtain 35 and 25 bits input word widths [7]. The proposed design is fully pipelined, so that it enables calculation of parameters for more than one cavity simultaneously (one clock cycle is needed for each additional structure). Low-pass filtering of the output signals is needed to handle significant noise introduced by the derivative calculation. This is realized using a second order IIR filters.

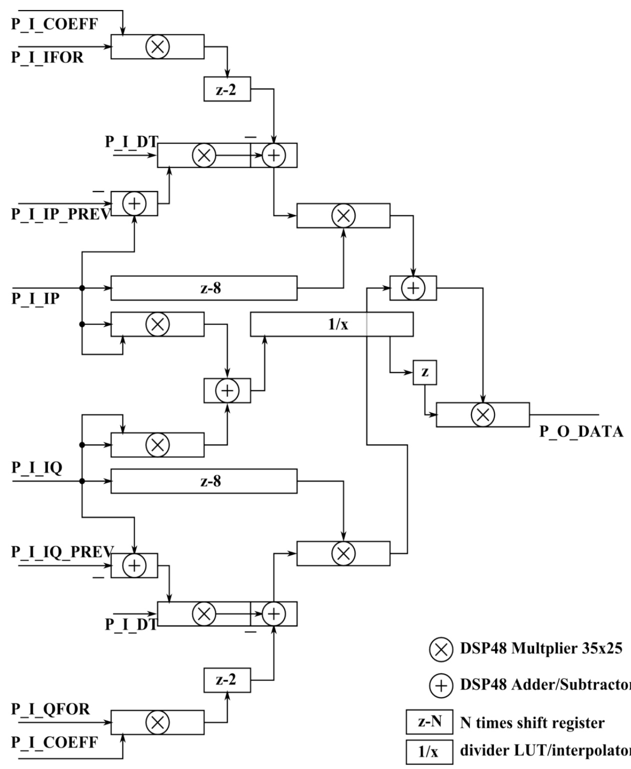

Figure 2: Schematic of the implementation of the $\omega_{1/2}$ estimation algorithm.

RESULTS

Algorithm was tested at FLASH facility with no beam. Computed values of for the Q_L before and during a hard quench are shown in Fig. 3 and 4. Computed detuning during RF pulse is shown in Fig. 5. For the verification purposes results of the algorithm calculations in MATLAB are also provided. Histogram of the static detuning, computed as an average of the detuning during 2000 pulses is shown in Fig. 6. The histogram can be interpreted as a measurement of the microphonic noise.

CONCLUSIONS

In this paper a novel method for estimation of RF cavity parameters is presented. Results from the first experiments conducted with this method proved that it can be successfully applied for online identification of

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the cavity parameters. Furthermore it can be used for fast exception handling and control purposes. This work will be continued and ideas presented below have to be developed and verified:

- Implementation of the fast quench detection module based on the drop of the cavity Q_L factor estimated by the algorithm.
- Inclusion of the beam current signal into the equations and adaptation of the algorithm appropriately.
- Application of the model based methods for derivative computation for more robust noise handling.
- Calculation of the parameters for more than one cavity in the pipeline

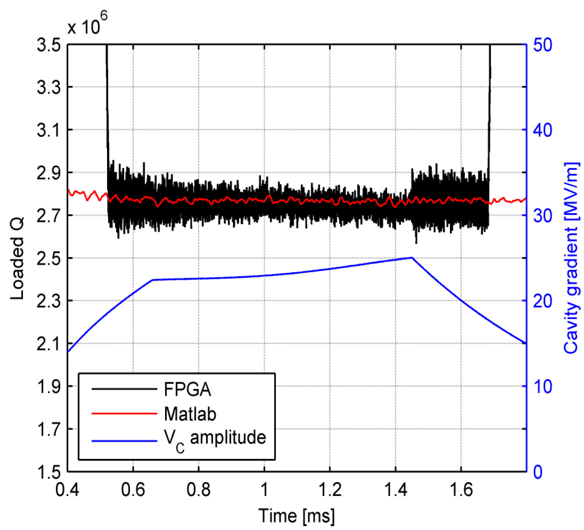

Figure 3: Loaded quality factor computed for pulse before the quench event.

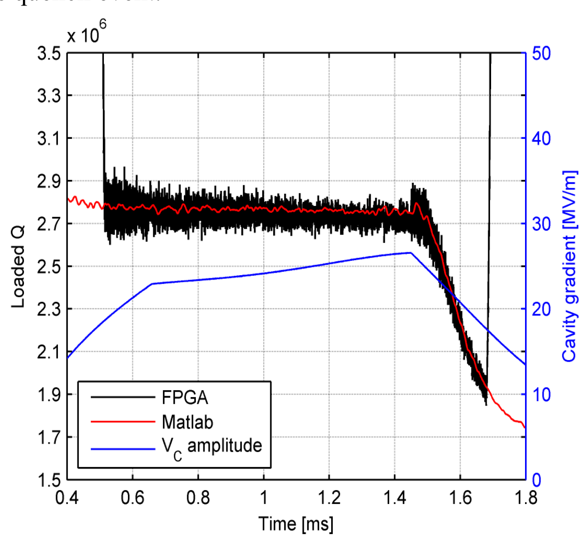

Figure 4: Loaded quality computed for the pulse during the hard quench.

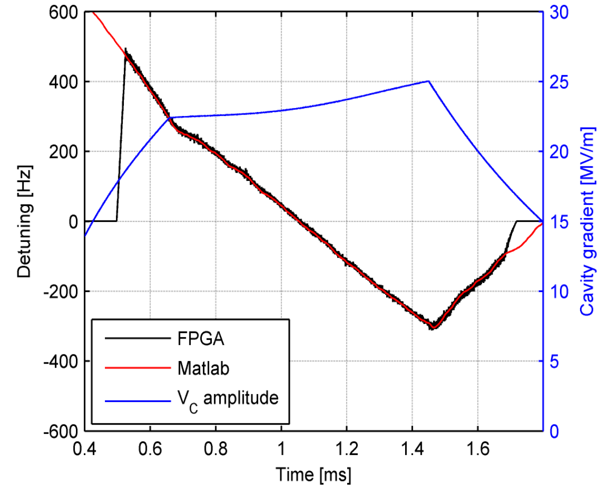

Figure 5: Computed cavity detuning during the RF pulse.

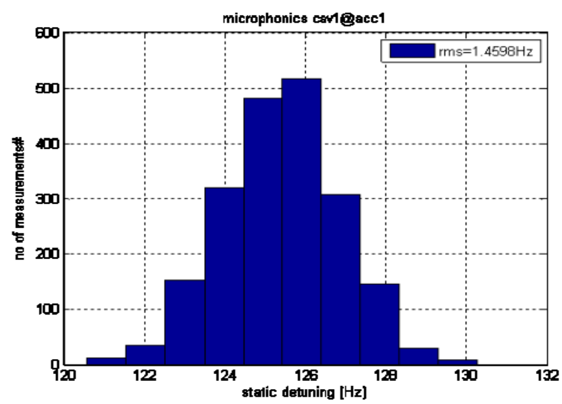

Figure 6: Computed microphonics noise for 2000 pulses.

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