FROM PULSE TO CONTINOUS WAVE OPERATION OF TESLA CRYOMODULES LLRF SYSTEM SOFTWARE MODIFICATION AND DEVELOPEMENT*

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Abstract

Higher efficiency of TESLA based free electron lasers (FLASH, XFEL) by means of increased quantity of photon bursts can be achieved using continuous wave (CW) operation mode. In order to maintain constant beam acceleration in superconducting cavities and keep short pulse to CW operation transition costs reasonably low some substantial modification of accelerator subsystems are necessary. Changes in: RF power source, cryo systems, electron beam source, etc. have to be also accompanied by adjustments in LLRF system. In this paper challenges for well established pulsed mode LLRF system are discussed (in case of CW and long pulse (LP) scenarios). Firmware, software modifications needed for maintaining high performance of cavities field parameters regulation (for CW and LP cryomodule operation) are described. Results from studies of vector sum amplitude and phase control in case of resonators high Ql factor settings (Ql=1.5e7) are shown. Proposed modifications implemented in VME and microTCA (MTCA.4) based LLRF system have been tested during studies at CryoModule Test Bench (CMTB) in DESY. Results from these tests together with achieved regulation performance data are also presented and discussed

INTRODUCTION

Although the European X-ray Free Electron Laser (XFEL) [1] is still in the construction stage possible facility upgrades are already under discussion. The possibility of constant beam acceleration is one of the attractive option of future laser operation. In order to evaluate the potential impact of the operation scenario change to the existing infrastructure and define initial requirements for linac systems adjustments set of tests have been done on single TESLA cryomodule test bench (CryoModule Test Bench CMTB).

One of most important limitation concerning CW operation in pulsed-designed machine (as XFEL) is the increased load on the cryogenic system (caused by continuous cavities operation). As the cryogenic system has limited capacity it has been evaluated that the cryogenic losses should be kept below 20 W per cryomodule, in order to avoid costly modifications of the cryogenic plant in the future [2].

* Work supported by National Science Center (Poland) grant no 5593/B/T02/2010/39

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Additionally the current design of the superconducting cavities input couplers puts limitations concerning acceptable power level. This limitation have to be also obey during CW and LP to avoid fundamental power coupler breakdown.

In order to fulfill mentioned conditions the CW and LP operation have been tested for modified cavities work parameters. Cavities ability of energy storage has been increased in order to achieve higher accelerating field gradients with lower input power level by means of external quality factor adjustment. Additionally the prototype power supply tube IOT, has been used in place of 10MW klystron which is in operation for standard short pulse operation.

All these modifications have been accompanied by LLRF system adjustments in terms of controller firmware and software parts.

CW/LP TEST ENVIRONEMENT

The CMTB facility has been equipped with the infrastructure needed for 8 TESLA cavities cryomodule examination. Presence of cryogenics system, high power RF sources (klystron for pulse operation study and IOT for CW, LP), LLRF system infrastructure, slow motor frequency tuners, piezo tuners control system allows for various tests scenarios in wide range of module working parameters (for example cavities operation above 40MV/m pulse operation).

IOT for Cavities Supply

Dedicated RF source has been built for described tests. The Inductive Output Tube prototype produced by CPI has been installed in the module cave. This device is designed for CW operation with frequency of 1.3GHz. Its measured output power of 85 kW is enough for the single cryomodule evaluation.

Although it can be used for both scenarios (CW and LP) experience shows it is much more stable in operation for continuous operation. Pulses achieved from the tube during LP studies suffered occasionally from overshoots and oscillations caused most probably by drops in the cathode voltage. Next prototype version is in production and is expected to be delivered before the end of 2013. The LLRF feedback system can compensate for the problems

ISBN 978-3-95450-139-7

mentioned above. This control loop was able to maintain smooth cavity loading profile. Such conditions allowed for IOT initial oscillation suppression.

In order to evaluate tube behavior in RF feedback loop its transfer characteristic has been measured (in limited parameters range) (see Fig. 1). Encountered nonlinearity has to be rechecked and measured in full operational range of the tube. Presence of amplitude and phase transfer func-

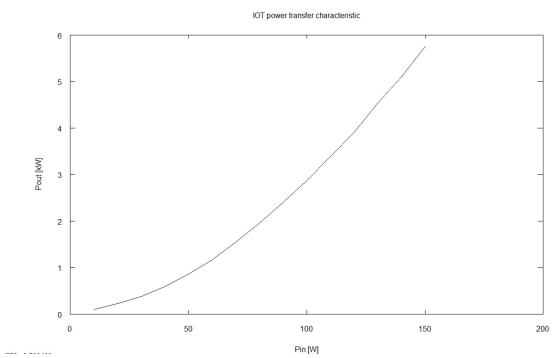

Figure 1: IOT power transfer characteristics.

tions nonlinearities has been bothersome especially during open loop operation. That is why further tube examination is foreseen as well as linearization module implementation (to be realized on the firmware side).

Original VME-based LLRF System

The LLRF setup for first CW measurement consisted of two acquisition/control boards (SIMCON-DSP) widely used for accelerating field control in FLASH accelerator [3] (see Fig. 2). In this setup main board was responsi-

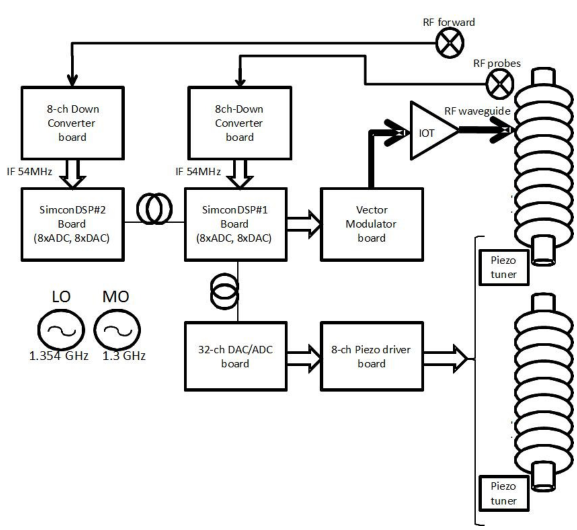

Figure 2: Former hardware setup for initail CW tests.

ble for cavities probes signal determination and realization of proportional LLRF feedback. Second (slave) board has been also used as a source of information of cavities input signal phases. The forward power and probe signal phase difference, calculated on the main board, was error signal for the cavity frequency fine tuning realized by the piezo controller.

Current LLRF System Based on MTCA.4 Platform

The newest LLRF system configuration based on the hardware components from MTCA.4 family [4]. Individual cavity forward power, reflected power and probe

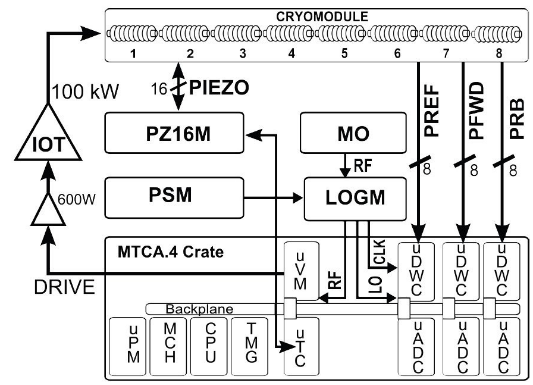

Figure 3: MTCA.4 based LLRF system configuration [2].

signals are down-converted from 1,3GHz with intermediate frequency of 54MHz. Signals sampling (with Fs = 81 MHz) is realized in acquisition boards (uADC). The new setup allows not only for better precision concerning signal acquisition but also offers much more computation resources for fast algorithm realization. That is why each acquisition board (uADC) calculates vector-sum from the digitized data (which is fundamental for RF feedback) but also provides amplitude/phase data representation. As for the previous CW test, phases from the cavity input power and probe were subtracted in order to achieve error signal for piezo based feedback. Both RF field parameters regulation and cavity fine tuning feedback were realized in uTC board that is also responsible for controller response signal preparation and distribution (to vector modulator uVM for up-conversion in case of RF feedback and to piezo-box PZ16M in case of active detuning compensation).

CONTROL ALGORITHMS

Currently there are two fast feedback loops implemented in LLRF controller for CW/LP operation. While one loop (RF feedback) is responsible for whole module vector-sum amplitude and phase control according to the given setpoint, the other (piezo feedback) consists of 8 actuators which main task is to keep single cavity in resonance.

RF Feedback

The RF feedback loop had been implemented as proportional controller (or MIMO depending on configuration). Input signal for this controller is prepared from down-converted, scaled and rotated cavities signals that are

ISBN 978-3-95450-139-7

summed up to composite module vector-sum. Then it is compared with desired set-point values and achieved error is scaled by the proportional gain factor. Then, the resulting signal is added to the feed-forward excitation. In the last step drive signal is scaled and rotated (according to determined loop phase). Then the signal is up-converted and after amplification by preamplifier and IOT is send to individual cavities by wave-guide distribution system.

Piezo Actuators Based Feedback

The cavity loaded quality factor modification was one of the conditions of CW operation. But it has to be emphasized that change from nominal 3e6 to 1.5e7 resulted in structure half-bandwidth reduction down to 45Hz (for operational frequency of 1.3GHz). In such environment cavities detuning caused by microphonics start to play important role in accelerating field parameters regulation.

In order to cope with this challenge the proportional-integral controller has been proposed. Unlike in RF loop case the piezo feedback acts on individual cavity. The input signal to the controller consists of difference between cavity input power signal phase and cavity output signal phase. This difference as corresponding to the cavity detuning has to be minimized by this loop. The error signal is processed by the P and I components of the loop and then resulting signal is send to the band-pass filter (IIR).The main goal of this filter is to target the feedback regulation on the frequencies identified as dominant disturbances.

The output of controller is connected to the piezo driver which is responsible for driving signal amplification and supplying piezos on the cavities side.

FIRMWARE AND SOFTWARE STRUCTURES

Main RF loop control algorithm implementation does not differ much from the one used for the regular pulse operation but in order to provide CW or LP operation conditions several changes are required both on the low level firmware side and also on the management software side.

Firmware Implementation

Designed firmware is divided between acquisition boards and controller board.

Main tasks for the firmware designed for acquisition boards are:

- cavity signal In-phase/Quadrature (I/Q) coordinates detection,
- cavity signal scaling and rotation,
- I/Q signal conversion to Amplitude/Phase,
- conditioning of the vector-sum (VS) signal,
- VS transfer to the controller,
- transfer of phase signals to the controller board,
- data conditioning and DMA transfer.

The controller board firmware can be summarized as follows:

- preparation of RF feedback P controller signal,
- preparation of error signal for piezo controller loop (phase difference calculation),
- preparation of piezo-feedback algorithm signal,
- data preparation and DMA transfer.

The standard FLASH/XFEL implementation of RF feedback is based on algorithm realization with the 9MHz clock output rate. For the usual short pulse operation at FLASH or XFEL pulses of 1,3ms length and 10Hz repetition rate are used. In such case the control tables (for FB set-point, feed-forward, gain definitions) have been chosen on the 16384 samples level. Not only control tables but also measured cavities and controller waveforms used by other higher level software are represented as 16k samples tables (signal acquisition window of 1.8ms).

Although it was sufficient for specified short pulse operation, it has not been correct for long pulse or continuous wave operation. In order to cover 1s acquisition time it has been decided to use the same controller speed (9MHz) and other acquisition buffer sampling frequency and size. The acquisition sampling frequency (Fs) has been increased up to 1MHz. However the 1M samples data transfer was not stable on tested hardware platform with used DMA transfers (through PCIE). Possible source of the high transfer rate problem was insufficient power management among the components in the UTCA crate. Finally 65k samples tables size have been chosen for CW operation. It has to be noticed that for more precise study the acquisition rate has been modified dynamically from 65kHz up to 9 MHz.

Software Implementation

The parameters management and data visualization functionality is realized by the DOOCS [5] front-end server - LLRF server. This software component although originally prepared for short pulse operation has been modified and extended to fulfill all the requirements from CW and LP.

Initial functionality allowed for control tables generation, pulse duration parameters specification, feed-forward and RF feedback parameters configuration and management. Additionally cavity and controller signals have been available from the DMA transfer for visualization and external user access.

The server has been enhanced to cover piezo control loop parameters management. The P and I gains, piezo offset voltage control interface are provided. Also constant monitoring of the detuning error signal as well as piezo controller output signal are available.

Thanks to the interface to firmware registers on acquisition card and controller hardware flexible acquisition speed configuration is possible. The RF feedback update rate can also be adjusted with these settings..

ISBN 978-3-95450-139-7

TESTS RESULTS

As the cryomodule test begun at CMTB in 2011 long pulse operation and CW operation have been tested for different module gradients (5-12 MV/m) and wide spectrum of duty factor settings [6]. The first study resulted in vector sum stabilization in 3e-3 peak-to-peak amplitude, using static piezo tuning and with feedforward and feedback for LLRF controller (for CW with 5 MV/m average cavity gradient and LP up to 12 MV/m average gradient).

MTCA.4 Based System Tests Results

Following tests have been performed using described MTCA.4 based LLRF system. During the latest tests the CW and LP scenarios have been tested on the large grain niobium cavities cryomodule named XM-2 (pre XFEL mass production module). For CW operation at gradient of 7MV/m per cavity achieved vector sum amplitude stability was at the level of 2e-4 dA/A RMS.During that part of the test both feedback loops (RF and piezo) where used in order to optimize accelerating field parameters and to keep cavities in resonance - even during the change of the module energy. The cryo losses measured during this tests were around 14W (see Fig. 4) which was far below acceptable 20 W losses. The CW operation was possible up to 9MV/m with reasonable cryo losses measured for lower cryogenic temperature (1.8K).

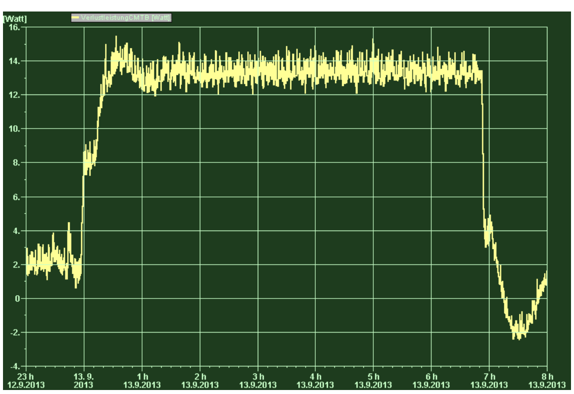

Figure 4: Cryolosses measured during the CW operation with gradient around 7MV/m.

POSSIBLE IMPROVEMENTS

As the CW operation level was achieved according to expectation the LP was not successful for LLRF/piezo loops for operation with higher gradients (above 10 MV/m). Perturbation that is visible in the system in range of 50Hz have not been successfully suppressed. This additional excitation that is visible in the system has been caused be the cryo pumps installed near to the module. Because of its mechanical nature this distortion has been expected to be minimized by the reliable piezo FB loop. Although the tuner feedback was able to reduce the impact of this oscillations (in limited range) its performance has to be improved (see Fig. 5).

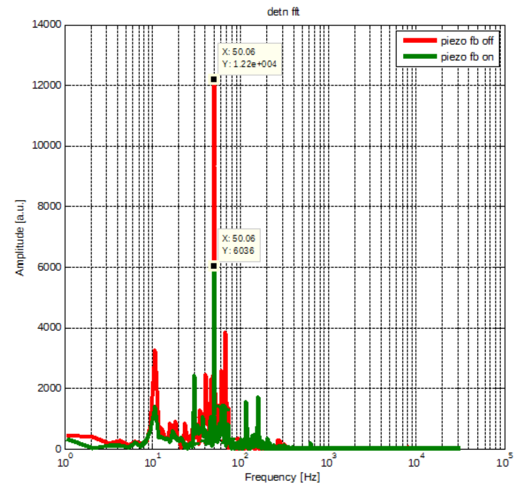

Figure 5: Cavity detuning suppression with active piezo feedback.

SUMMARY

The successful tests of CW and LP operation of TESLA cryomodule has been presented. Development of control algorithms as well as firmware/software infrastructure towards this test was beneficial in achieved RF and piezo feedback loop performance. Achieved field regulation is near to the X-FEL specification.Options for improvements have been identified, further tests will be performed to identify main microphnics sources and minimize field parameters regulation error.

REFERENCES

[1] Editors: R. Brinkmann et al., TESLA XFEL Technical Design Report-Supplement, DESY, 2002-167, TESLA- FEL 2002-09, Hamburg, 2002.

[2] J. Sekutowicz et al., "Feasibility of CW and LP operation of the XFEL linac", FEL13, New York, USA, August 26-30 2013

[3] V. Ayvazyan et al., "LLRF control system upgrade at FLASH", PCaPAC2010, Saskatoon, Canada, 2010.

[4] J. Branlard et al., "The European XFEL LLRF System", IPAC2012, New Orleans, Louisiana, USA, 2012

[5] http://doocs.desy.de

[6] J. Sekutowicz et al., "Test results of components for cw and near-cw operation of a superconducting linac, Linac10, Tsukuba, Japan, September 12-17, 2010.

ISBN 978-3-95450-139-7