MICROTCA.4 BASED SINGLE CAVITY REGULATION INCLUDING PIEZO CONTROLS

K. Przygoda [†], H. Schlarb, C. Schmidt, DESY, Hamburg, Germany
P. Echevarria, HZB, Berlin, Germany
R. Rybaniec, WUT, Warsaw, Poland

Abstract

We want to summarize the single cavity regulation with MTCA.4 electronics. Presented solution is based on the one MTCA.4 crate integrating both RF field control and piezo tuner control systems. The RF field control electronics consists of RTM for cavity probes sensing and high voltage power source driving, AMC for fast data processing and digital feedback operation. The piezo control system has been setup with high voltage RTM piezo driver and low cost AMC based FMC carrier. The communication between both control systems is performed using low latency link over the AMC backplane with data throughput up to the 3.125 Gbps. First results from CW operation of the RF field controller and the cavity active resonance control with the piezo tuners are demonstrated and briefly discussed.

INTRODUCTION

The 1.3 GHz superconducting radio frequency (SCRF) cavities of modern linear accelerators like FLASH and European X-Ray Free Electron Linac (XFEL) are operated in short pulse (SP) mode with 1300 µs RF-pulse and repetition rate up to 10 Hz at high loaded quality factor (Q_L) above $3 \cdot 10^6$. During SP operation of the cavity, the 650 µs of RF-pulse can be efficiently used to accelerate up to 27.000 number of bunches per second (averaged over 10 successive RF pulses) with minimum bunch spacing of 222 ns and maximum charge per bunch of 1 nC. Since the bandwidth of the cavity resonator operated in SP mode is 433 Hz for FLASH and 283 Hz for XFEL (Q_L=$4.6 \cdot 10^6$) with nominal operating gradient of 23.6 MV/m, the dominating effect of the RF field disturbance is Lorentz force detuning (LFD). As LFD is repetitive from pulse to pulse, adaptive feedforward methods for active compensation using piezo tuners can be applied [1]. For the continuous wave (CW) mode of operation of SCRF cavity at quality factor of more than $1.5 \cdot 10^7$ (5 times less bandwidth), the unpredictable microphonics becomes the main RF field disturbance source. In order to achieve stable acceleration of 100.000 number of bunches per second with nominal operating gradient of 7 MV/m (CW operation scenario for XFEL machine), the RF field stability requirements better than 0.01% for the amplitude and 0.01 degrees for the phase are the real challenge. Therefore, new control algorithms need to be developed and evaluated for the real environment conditions. Nowadays higher numbers of high energy research centers are switching from multi cavity (MC) to single cavity approach (SCA) operation. The SCA solution is giving a possibility of establishing in a short time a small facilities where the high current and low emittance (below 1 mm x mrad) CW electron beam at 2 ps rms bunch duration are the main goals for the experiment, i.e. Berlin Energy Recovery Linac Project bERLinPro at Helmholtz Zentrum Berlin (HZB).

SUPERCONDUCTING RF CAVITY OPERATION IN CW MODE

In order to operate SCRF cavity in CW mode, the several limitations need to be taken into account [2]. First of all the heat load at 2 K (1.8 K) shouldn't exceed 20 W when considering single cryomodule (CM) consisted of 8 cavities. Heating of the higher order modes (HOM) couplers must not cause quenching of the cavity. Due to the fact all end-groups are cooled by means of heat conduction. The cryo plant capacity needs to be doubled due to increased dynamic heat load (max. 16 W for single CM). Finally, the CW high power RF sources need to be applied. The most promising solutions are Inductive Output Tubes (IOTs) with nominal output power of 120 kW or Solid State Power Amplifiers (max. output power of 3.8 kW per device). When considering all above constraints the following operating conditions for CW mode are defined (FLASH and XFEL):

- Accelerating field gradient per cavity Eacc ~ 7 MV/m.
- Nominal loaded Q of input coupler $Q_L \sim 1.5 \cdot 10^7$
- Maximum peak RF power per cavity ~ 3.8 kW
- Maximum number of bunches per second ~ 100.000
- Minimum spacing between bunches ~ 10 µs
- Nominal/ Maximum charge per bunch ~ 0.1/ 0.5 nC
- Nominal beam current ~0.010 mA.

MICROPHONICS AND PIEZO TUNERS

The cavities are detuned by external mechanical forces _ microphonics. The CW operated cavity with high loaded quality factor of order of $1.5 \cdot 10^7$ and narrow bandwidth of 87 Hz is very susceptible to disturbances of this kind. The first measurements carried out from XFEL CM installed in Cryo Module Test Bench (CMTB) facility at DESY show vacuum pumps as the main source of microphonics. As seen in Figure 1 the disturbance caused by vacuum pumps has dominant frequency of approx. 50 Hz with varying amplitude and phase. In addition slowly varying operating conditions such as helium pressure fluctuations can also cause detuning of the cavities. The peak-peak microphonics of more than 10 Hz can strongly modulate resonance frequency of 1.3 GHz of the cavity, especially when operated at gradient of 7 MV/m and

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[†] konrad.przygoda@desy.de

above. In order to compensate for the microphonics, fast mechanical tuners equipped with piezo elements can be applied.

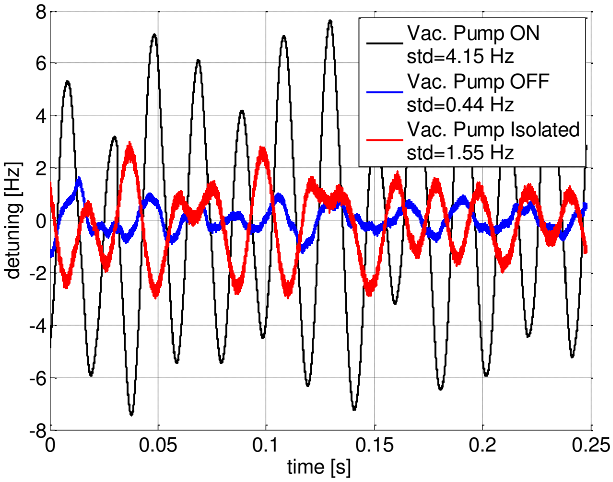

Figure 1: Microphonics noise measurements using RF signals at CMTB.

The Saclay II type of XFEL cavity mechanical tuner framework is equipped with double piezo elements. The first piezo can be used as actuator, while in the same time the second element can act as a sensor. Alternatively second piezo can be used as a spare actuator. The Blade model of coaxial tuners can be attractive alternative for many new experiments such in HZB (see Figure 2).

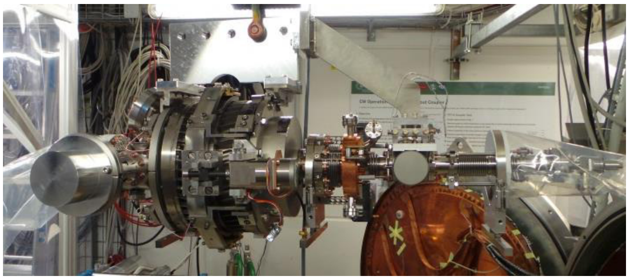

Figure 2: Coaxial tuner with quad piezos assembled to the gun cavity at HZB [3].

SINGLE CAVITY APPROACH

The single cavity approach consists of the RF cavity (horizontal or vertical cryostat) equipped with mechanical tuner (coarse tuning with motors and fine tuning with piezos). The dedicated RF power source needs to be provided to feed the cavity with required RF input power. The machine protection system (MPS) with interlock signals is essential to avoid system failure. The precise RF reference signal is generated by use of laboratory master oscillator (LABMO) device. The RF synchronization signals (REF, LO, CLK) are provided using local oscillator generation module (LOGM). The MTCA.4 crate is used to host control electronics. It consists of integrated cooling units, redundant power supply modules (PM), MicroTCA Carrier Hub (MCH) as well as central processing unit (CPU) with built-in SSD discs. The RF signals are sensed by use of Rear Transition Module (RTM) downconverter (DWC). The high power RF source is driven by vector modulator (VM) RTM. The analogue down conversion products are sensed using Advanced Mezzanine Card (AMC) based digitizers (ADC) and controlled by different algorithm blocks (CTL). The piezo driver (PZT) RTM module is applied to drive piezo elements with high voltages. The mechanical tuners of the cavity are controllable by use of motor driver (MD22) Fast Mezzanine Card (FMC). The MTCA.4 components are locally synchronized to RF using AMC based X2TIMER module. The MTCA.4 crate can be accessed using Ethernet. The RF power signals calibration is supported by analogue power meters. The block diagram of the system is shown in Figure 3.

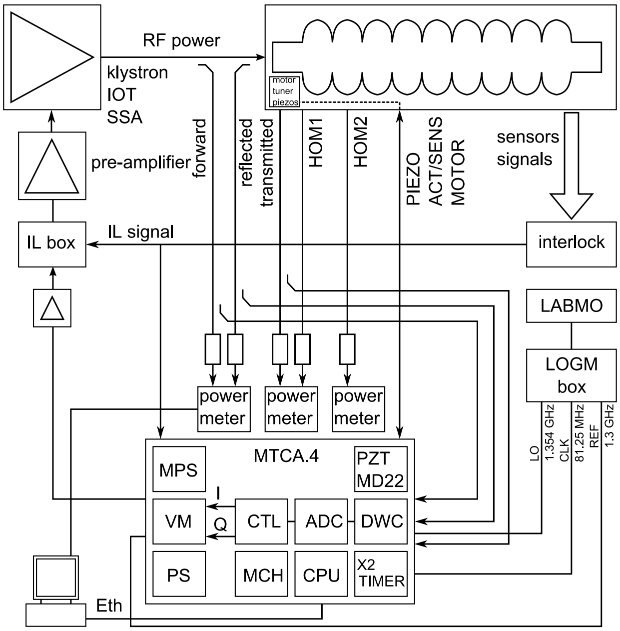

Figure 3: The block diagram of single cavity cryostat.

Data Processing and Controllers

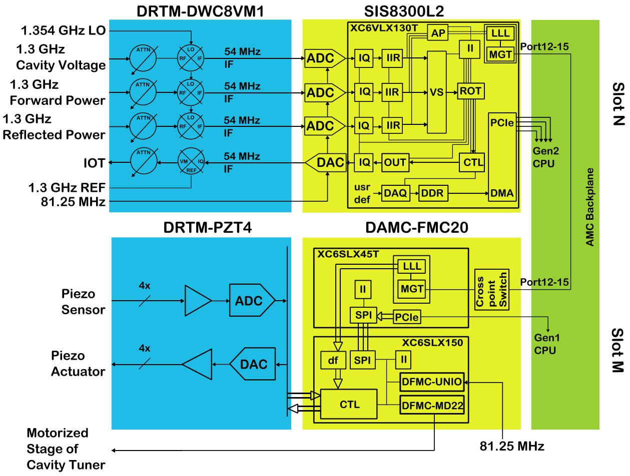

Figure 4: The MTCA.4 based RF and piezo controls.

The measured 1.3 GHz cavity RF signals (forward, reflected and cavity voltage) are down converted to intermediate frequency (IF) of 54 MHz using analogue mixers driven by LO signal of 1.354 GHz. The digital up conversion from IF to RF frequency (1.3 GHz reference) is performed in order to control the RF power source (DRTM-DWC8VM1). The raw data are sampled with 81.25 MHz (FS) and next demodulated to I and Q components which provide the amplitude and phase information of the RF signals (see Figure 4). The none-IQ demodulation scheme with ratio of 3 times IF frequency that equals to 2 times FS frequency is chosen. The bandpass filtering (undersampling) of 1st aliasing frequency of 27 MHz is reconstructed without any information lost using 3 samples averaged over 3 corresponding periods. It gives effective sampling rate of I and Q pairs of 9 MHz (see Figure 5).

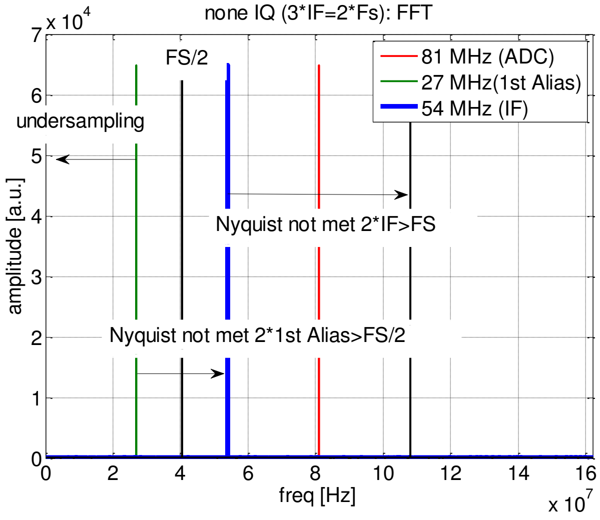

Figure 5: The spectral analysis of none IQ demodulation of IF signals.

The proportional (P) and Multi Input Multi Output (MIMO) RF feedback controllers are used to provide amplitude of RF vector field stability (SIS8300L2). For the phase stability, RF feedback is not fully sufficient. The cavity detuning caused by the helium pressure fluctuations and microphonics can variate over the time and even exceeds the half bandwidth of the cavity (43.5 Hz). Due to the fact a dedicated piezo feedback control needs to be considered (DRTM-PZT4). The least mean-squares (LMS) optimization algorithm that tracks the phase and amplitude change of the error signal and applies the compensation signal in advance can give the significant rejection of the external disturbance effect. The active noise cancellation (ANC) approach is proposed to modulate the cavity resonance frequency with piezo tuners. It is designed to handle up to four different disturbance frequencies and can be adjustable with delay and sampling frequency parameters (DAMC-FMC20). The first performance measurement of single cavity approach applied for the RF cavity operated at 2 K in CW with high quality factor of $1.5 \cdot 10^7$ is shown in Figure 6.

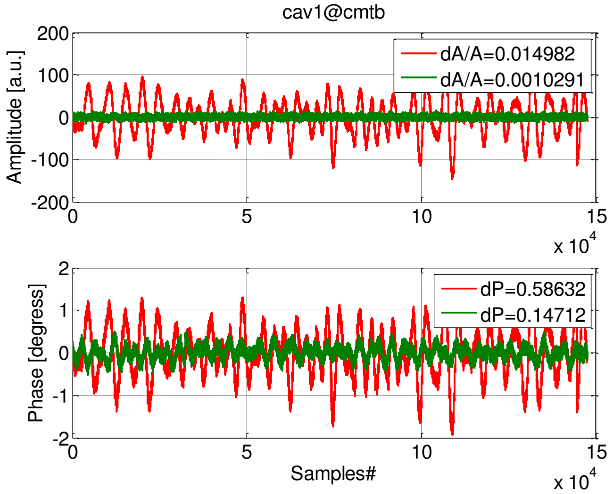

Figure 6: The RF field amplitude and phase stabilization using MTCA.4 based single cavity approach.

CONCLUSION

The single cavity approach has been successfully tested using single 9-cel XFEL cavity operated at CMTB in DESY. The RF field amplitude and phase stability of 0.001% and 0.1 degrees has been achieved. The amplitude stability fulfils the requirements. The phase stability still needs to be improved. The authors are planning to integrate full MIMO controller of 21 parameters and if possible add piezo sensors feedback information to the piezo control loop. One of the possible future applications can be bERLinPro at HZB [3]. The project goal will be the generation of a high current (100 mA), low emittance (below 1 mm mrad) CW electron beam at 2 ps rms bunch duration. The LLRF control system will be implemented using the MTCA.4 technology and due to the fact each cavity of the accelerator will be fed by its own RF power source (klystrons for the gun and booster and SSA for the linac). All of the cavities will be equipped with a blade tuner which will be driven by a stepper motor for slow coarse tuning and four piezo actuators for a fine fast compensation.

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