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STATUS OF LLRF AND RESONANCE CONTROL DEDICATED ALGORITHMS EXTENSION FOR PolFEL

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Abstract

PolFEL (POLish Free Electron Laser) is the new superconducting-based facility, which is under construction in Poland. It will provide a continuous electron beam with energy up to 160 MeV, which will be converted to light pulses with wavelengths as short as 150 nm. CW (Continuous Wave) operation of the superconducting linear accelerator with narrow bandwidth and high electromagnetic field gradient (presumably above 30 MV/m for single structure) creates new challenges while dealing with RF field stability, the influence of mechanical de-tuning of resonating structures and must consider all limits induced by power amplifiers and cryo-system. The real-time control algorithm responsible for RF field, motor tuners, and piezo control must strictly interact with each other to provide the satisfactory performance of the whole facility. In addition, constant monitoring of such parameters as detuning, bandwidth, power margins of the amplifier, state of cavities must be done. The paper presents the status of implementation of PolFEL's LLRF Controller (extending GDR to other modes of operation as SEL, PLL) and Piezo Controller (both hardware and firmware layers).

INTRODUCTION

PolFEL (Polish Free Electron Laser) is the free electron laser facility, which is under construction in Poland. The main operation modes of its superconducting based linear accelerator will be Continuous Wave (CW) and Long Pulse. The accelerator itself will consist of 4 cryo-modules with 8 TESLA superconducting cavities in total and will provide continuous electron beam with energies from 120 MeV up to 160 MeV. The beam will be passed through VUV undulators to generate radiation with wave lengths staring at 0.3 mm down to 150 nm (50 nm for third harmonic) – the total photon pulse energy will reach 100 uJ with repetition rate of 100 kHz. After leaving undulators, the beam will be used for neutron generation or Compton scattering experiments. The estimated end of construction and commissioning of the whole facility is in 2023.

PolFEL will use relatively high accelerating electromagnetic field gradients (presumably above 30 MV/m for single structure). Work in such conditions requires either high input power (which exceeds limits achievable by existing high-power amplifiers and power distribution systems) or increase of input power coupling, which corresponds to Loaded Quality of the resonator and in the result narrows down system bandwidth to several Hertz. Under these circumstances any detuning of the resonating frequency of the cavity (either caused by microphonics or Lorentz Force) will have big influence on stability of the RF Accelerating field (up to the point where no operation is possible). Therefore, it must be compensated by interaction between cavity tuning system/algorithms based on piezo actuators and dedicated RF control algorithms with special functionality related to out of band operations.

The Department of Microelectronics and Computer Science, Lodz University of Technology, with all its experience gathered during work in such experiments as Flash, EuXFEL and ESS, is involved in design and development of several subsystems of the facility.

SCOPE OF WORK

As part of the work, dedicated hardware device for resonance control system will be designed and manufactured. It will be implemented in a form of standalone integrated 19” box and will contain at least 18 piezo drivers able to drive 16 piezo stacks (2 per superconducting cavity) in LINAC section and additional 2 stacks at RF-Gun cavity.

Resonance Control Hardware must be integrated with other uTCA based systems (especially LLRF) to provide consistent platform for algorithm execution and control system integrations. These will be achieved by using external communication links and special adapters on LLRF system side.

In addition to the hardware platform, the several control algorithms will be implemented. These are divided into two groups:

- Field Control Algorithms -The algorithms must ensure overall stability of the RF Accelerating Field parameters to deliver electron beam of required quality and provide additional information for other systems (i.e. resonance control) and operators to improve operation and prevent unexpected faults.
- Resonance Control Algorithms - The algorithms and hardware subsystems for piezo control must be able to compensate both Lorentz Force Detuning (LFD) and frequency deviations caused by environmental mechanical vibrations (microphonics). This can be achieved using such algorithms like online cavity parameters identification and adaptive noise compensation.

As stated before, both groups of the algorithms implemented must exchange data and closely interact with each other to make the operation with required field parameters possible.

RESONANCE CONTROLLER REQUIREMENTS

The superconductive cavities are mounted inside cryomodule using fixture equipped with motor tuner and two piezo stacks. In many applications one of the stacks is used

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as mechanical actuator, while the other one is used as a piezo sensor to read back mechanical properties. Depending on the set-points used during operation, the total LFD [1] and microphonics detuning may exceed range achievable by single actuator – in such cases both piezo elements will be used as actuators to increase the tuning range.

To relax requirements induced on resonance control layer, special modes of LLRF operations are needed. Such modes as Self Excited Loop (SEL) or VCO mode allow efficient cavity loading at resonance possible and are not influenced by effective detuning, but do not allow precise phase control.

Piezoelectric stacks used for TESLA type cavities are commonly available also for other applications. They are driven by monopolar high voltage rated up to 200 V at room temperature, however, for HEP operations they are cooled down well below 4K where the piezo elements might be operated in bipolar mode with lower amplitude. The typical piezo stack used for TESLA cavities has a capacitance of around 3 uF and length of 3 to 4 cm. The elongation for voltage up to 120 V is in range of few microns which is sufficient to compensate the Lorentz force and microphonics and change the resonance frequency of the cavity in range of hundreds of Hertz (depending on the cavity Q factor). The control signals bandwidth is in a range well below 1 kHz since the mechanical reaction of cavity is around 300 Hz [2][3].

Direct approach which assumes that piezo is a capacitor shows that maximum current which should be delivered by piezo driver can be calculated via formula:

$$I^{max} = \pm V_{pp} \pi C f$$

Which shows that the Imax should not exceed 188mA in case of Vpp=100 V, C= 3 uF and fmax=200 Hz:

$$I^{max} = \pm 100\pi \cdot 3 \times 10^{-6} \cdot 200 = \pm 188mA$$

There are many online calculators like the one presented on PiezoDrive [4] website. However according to observation and experience from previous experiments, the impedance of piezo stack should not be considered as a pure capacitor. The admittance of piezo ceramics changes with the voltage amplitude, the temperature, and the mechanical load, to up to 200 % of the unloaded, small-signal, room-temperature value. The results of research are presented by piezo stack manufacturer at their website. Such a change must be taken into consideration when the control system is designed to avoid overcurrent issue and overheating of the device. Moreover, there are many studies about the power consumption change of powered piezo stack. The conclusions from previous experiments show, that the control system should be able to provide at least x2 the current calculated from small signal analysis.

RESONANCE CONTROLLER HARDWARE

During definition of hardware specification, several off -the-shelf components were considered:

- DRTM-PZT4
- PZT16 Piezo Box

Both modules were developed at DESY [5] for the purpose of FLASH and XFEL facilities and their functionality is already verified. Due to the used form factors, there are several limitations (i.e. limited number of channels on PZT4 module), but in general they could be used for the purpose of PolFEL (although in some conditions driven to the limit).

Additional integrated piezo driver modules (from PiezoDrive company) were analyzed and measured:

- PDm200 - +/-100 V drive signal capable of delivering of up to 120 mA rms current (>300mA peak current)
- MX200 – 0-200 V drive signal with up to 500 mA rms current (1 A peak current).

Parameters of both modules were measured (output currents, bandwidth, output voltages) and compared with manufacturer specs. Despite some inconsistencies have been found, the modules are capable to fulfil all PolFEL's requirements.

The ready to use verified piezo driver platforms used in already working facility seem to be natural choice for PolFEL's solution. Unfortunately, unstable situation on component market causes long production delays and it cannot be estimated when the platforms will be available. This collides with facility schedule.

For the abovementioned reason it has been decided to implement custom solution using stable piezo driver modules manufactured by external vendor, which have reasonable delivery time. The modules will be mounted in a 19" box and configured in bridged configuration, extended by additional electronics such as medium speed ADCs and DACs to provide control signals and additional layer of communication links to interact and integrate with control system.

The structure of the specified controller is presented in Figure 1. The device is equipped with 9 driver channels able to drive +/- 100 V voltage with 550 mA RMS output current using bridged configuration. The additional 9 inputs can be used to interface with piezo sensors. If the operation mode of accelerator requires driving of both piezo stacks, the channel structure can be reconfigured using dedicated relays to provide single ended 200 V drive signal and appropriate bias voltage. The box will integrate with uTCA systems using dedicated RTM module.

CONTROL ALGORITHMS

The scope of work covers implementation of the various RF field control algorithms. Due to the overall mode of operation of the machine, special considerations must be taken.

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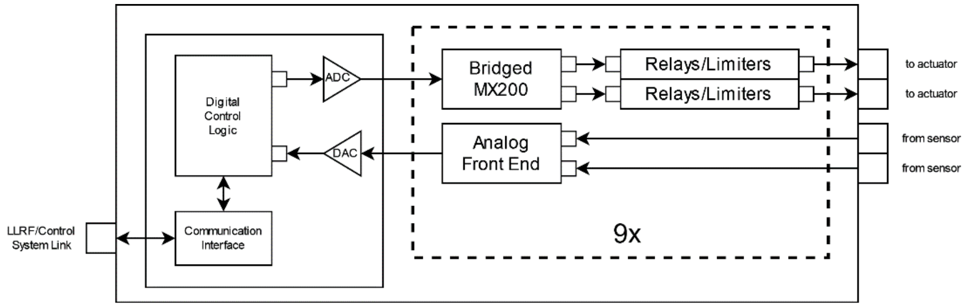

Figure 1: Structure of Resonance Controller Box.

Detuning and power margin analysis shows that Generator Driven Resonator (GDR) mode itself will not be sufficient to load the cavities under the required conditions.

- LFD Compensation - Excessive LFD caused by high accelerating field gradients requires direct interaction between LLRF controller and resonance control system. The LFD will be compensated using Proportional-Integral (PI) feedback controller with additional Feed Forward tables using actual detuning measured by LLRF control system. To further relax requirements for compensation algorithms and high-power amplifier chains, additional Self Excited Loop (SEL) mode will be implemented on the RF field controller side.
- Microphonics Compensation - Resonance Control part must also handle all disturbances caused by external mechanical vibrations visible on the cavities. The experiments show that the best way to do it is to use various Adaptive Noise Cancellation (ANC). As the part of the application ANC VSS LMS [6] block will be implemented.
- Cavity Parameter Identification - The LLRF filed controller must implement additional algorithms to identify cavity parameters, which will be used as part of diagnostics, fault prevention and other compensations. These includes Loaded Q, Cavity Detuning and Expected Cavity Response
- High Power Amplifier Linearization

SIMULATION/VERIFICATION INFRASTRUCTURE

The availability of the similar facilities (superconducting, CW, high EM gradient) around the world is very limited and developed algorithms will not be tested on the real machine (or tested in a very limited way) before commissioning. For this reason, the dedicated system simulator has been implemented. It includes modelling of RF and mechanical properties of the superconducting TESLA cavities. The whole setup is also extended by simple piezo driver and piezo element model to be able to test compensation/operation modes. The prepared setup can be used on the High Level using such tools as MATLAB as well as on the HDL simulator level or even directly on hardware side (implemented in FPGA). The simulator became the part of dedicated FPGA firmware running on FPGA based evaluation board. The structure of the algorithm test-bench is presented in Figure 2.

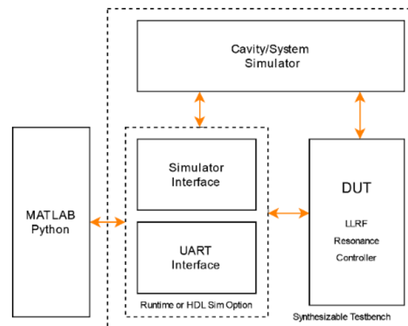

Figure 2: Structure of the Test-Bench.

The test-bench can be used for both HDL simulations and execution on the real hardware. In both cases input and output data is delivered from external tools (MATLAB, python scripts or others) These provides effective and fast way to simulate functionality, verify resource usage and test real hardware timing properties of implemented designs.

STATUS AND TIME SCHEDULE

The part of the work described in the paper is already completed including analysis of the available piezo solutions and market research, initial measurements of COTS modules to evaluate declared and actual parameters, initial specification of piezo boxes and interfaces, high Level Language Implementation of cavity models, implementation of HDL and co-simulation test benches and their integrations into MATLAB environment.

The remaining tasks including production of piezo boxes as well as final implementation and tests of algorithms in the real environment are to be completed until commissioning of the PolFEL facility in 2023.

SUMMARY

The paper presents the general concept, schedule, and status of selected firmware/hardware components of LLRF system of PolFEL. The infrastructure is under development and will be finished by the end of 2023. Special focus is placed on hardware part of resonance control system.

The analysis and executed test and measurements show that we are ready and able to start design works and fulfil assumed schedule of the facility.

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