LLRF CONTROL SYSTEM UPGRADE AT FLASH

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Abstract

The Free Electron Laser in Hamburg (FLASH) [1] is a user facility providing high brilliant laser light for experiments. It is also a unique facility for testing the superconducting accelerator technology for the European XFEL and the International Linear Collider. As a test facility, the accelerator undergoes a constant modification and expansion. The last upgrade was started in autumn 2009 and has finished recently [2]. The beam energy is increased to 1.2 GeV by installing a 7th superconducting accelerating module. The new module is a prototype for the European XFEL. In order to increase the free-electron laser (FEL) radiation intensity by linearization of the beam phase space the 3rd harmonic superconducting RF cavities are installed in the injector. The old DSP based LLRF control system [3] has been completely upgraded to latest generation controller boards, down-converters for higher intermediate frequency, algorithms like beam loading compensation, feed-forward waveform generation, etc. are improved. In order to improve the reference frequency signals the master oscillator and frequency distribution system has been upgraded as well.

INTRODUCTION

The FLASH injector consists of a laser-driven photocathode in a 1.5-cell RF cavity operating at 1.3 GHz with a peak accelerating field of 40MV/m on the cathode. The electron injector section is followed by a total of seven TESLA type 12.2 m long accelerating modules each containing eight 9-cell superconducting niobium cavities. The accelerating gradients of the cavities are typically between 20 MV/m and 25 MV/m. Four cavities of sixth module and seventh module are providing gradients above 30 MV/m. The accelerating modules are powered by four RF stations consisting a klystron (tree 5 MW klystrons and one 10 MW multi-beam klystron), a high voltage pulse transformer and a pulsed power supply (modulator). In addition, the RF gun has its own RF station with a 5 MW klystron. The gradient and phase accelerating field (vector sum) of the RF gun and the accelerating modules are controlled by dedicated LLRF regulation system which has been completely upgraded during shutdown period. The FEL radiation is provided by 30 m long undulator section. The undulator consists of periodic structure of permanent magnets which have a fixed gap of 12 mm. The wavelength of the FEL radiation depends on the energy of the accelerated electrons. It can be tuned between 4.3 nm and 120 nm.

After the upgrade a successful operation of FLASH at a wavelength of 4.45 nm has been achieved [2]. For 4.45 nm radiation wavelength the accelerator provides beam energy of 1.207 GeV.

PRINCIPLES FOR LLRF CONTROL

The RF system signal flow is shown in figure 1. The cavity probe signal is converted from the cavity frequency of 1.3 GHz to an intermediate frequency (IF) of 250 kHz for superconducting modules and 54 MHz for 3rd harmonic module. This lower IF holds the original amplitude and phase information of the field inside the cavity. It is digitized with ADCs (sampling rates of 1 MHz or 81 MHz are used). The digitized signal is going to the digital field detector which extracts the I and Q components out of the input stream. We use two different methods: IQ-sampling and so-called non-IQ-sampling or IF-sampling. The resulting field vector of each cavity is multiplied by a rotation matrix to calibrate amplitude and phases. Finally the field vectors of 8 cavities are summed up for the vector sum of a whole cryogenic module, and those of 2 cryogenic modules are summed up to the vector sum of the RF station which is driven by single klystron. The vector sum of the 16 cavity fields represents the total voltage and phase seen by the beam. This signal is regulated by a feedback control algorithm which calculates corrections to the driving signal of the klystron. The measured vector sum is subtracted from the set-point table and the resulting error signal is amplified and filtered to provide a feedback signal to the vector modulator controlling the incident wave. A feed-forward signal is added to correct the averaged repetitive error components. Beam current information (measured by toroids) is used to scale the feed-forward table to provide fast feed-forward corrections if the beam current varies. The cavity detuning is determined from forward power, reflected power, and probe signal and is used to control the fast piezo tuners to reduce cavity detuning errors to less than a tenth of the cavity bandwidth.

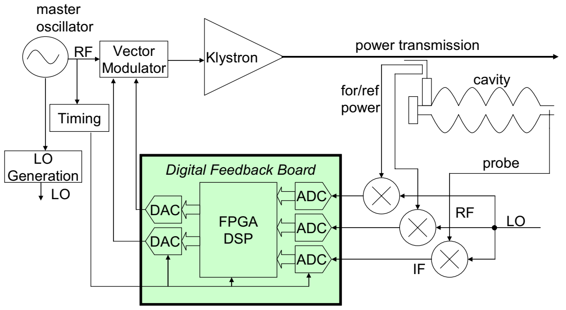

Figure 1: Architecture of the LLRF system.

DIGITAL FEEDBACK HARDWARE

After upgrade RF Gun and all accelerating modules are controlled by similar modern FPGA based controller boards with unified firmware and software. The digital feedback hardware consists of Simcon-DSP board (figure 2) which has a VME interface, 10 ADCs to read the intermediate frequency signal from the field probe signals, FPGAs (Xlinnx Virtex II Pro) and DSPs (Tiger Sharc) to execute the control algorithms and 8 DACs, 2 of them drives the vector-modulator for field control. Other components include a timing and synchronization module. The field detection hardware consists of a down converter which converts the cavity field frequency of 1.3 GHz to an intermediate frequency. Additional features included variable input attenuators for level adjustment, an input for a calibration signal and a local oscillator distribution system. The challenging requirements of the down converter are low noise, good linearity over large dynamic range, and small crosstalk.

Figure 2: Simcon DSP board.

DIGITAL FEEDBACK SOFTWARE

The cavity field controller algorithm consists of the field detection scheme (figure 3), calculation of the calibrated vector sum, the field error measurement, the controller filter, a feed-forward signal, and the drive signal generation.

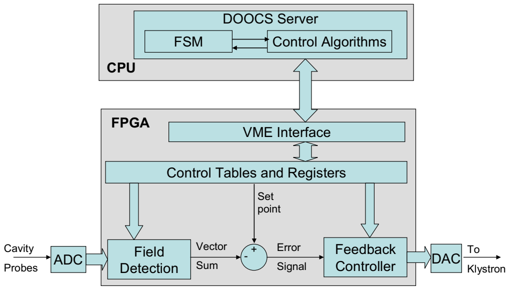

Figure 3: Controller firmware and software architecture.

Beam loading compensation through feed-forward and real time beam measurements are supported. The LLRF control system is integrated with FLASH control system DOOCS [4] by a development of device and middle layer servers. During the shutdown one DOOCS front-end server was developed for all 5 RF stations. Furthermore the DOOCS standard server is used for automation, like simple state machines, and the FLASH data acquisition system for bunch-to-bunch monitoring tasks, e.g. quench-detection.

The control system for the cavities which are driven by a single klystron is considered as a functionally complete unit of the RF system. The feedback algorithm is implemented in the FPGA system. The digital signal processing in turn gets its parameters from the controller server. The controller server software handles: generation of set-point, feed-forward and feedback gain tables from basic settings, rotation matrices for I and Q of each cavity, loop phase constant, start-up configuration files, feedback parameters and exception handler control parameters. The interrupt service routines are used to start the data reading from the controller board. The parameters of the feedback algorithm are modified by the FPGA programs in the time slot between beam macro pulses. It allows a save changing of the parameters of the control algorithm. The functionality of the server gives the user the opportunity to down/upload data into the FPGA (feedback algorithm parameters) and download and start the controller firmware. The server calculates and adjusts the set of the feedback algorithm parameters in accordance with the required field gradient and phase value.

PIEZO CONTROL

The cavities operating with high gradient are deformed due to Lorenz force that causes detuning of the order of the cavity bandwidth from resonance frequency. Detuned cavity reflects the supplied RF power that requires excessive RF driving. For the compensation of Lorenz force detuning (LFD) the piezo actuator is used to excite the cavity mechanically. Each cavity in new accelerating modules (1st, 6th and 7th) is equipped with double piezos that allow compensating of LFD and measurement of cavity vibrations simultaneously.

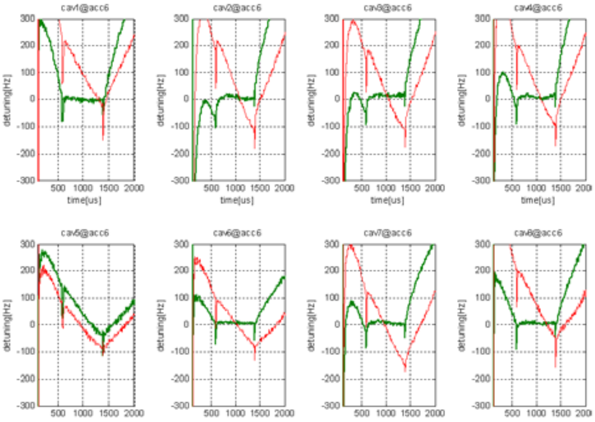

Figure 4: LFD compensation in 6th accelerating module (green – detuning with piezo compensation, red - without)

The piezo control system is able to compute detuning in each cavity basing on RF signals and calculates the parameters of compensating piezo excitation pulse. The signal from programmable generator is amplified by high power piezo driver. The amplitude of voltage applied to piezo can be up to ±70V and current up to 1A. The results of LFD compensation in 6th module is presented in figure 4. Using piezos the dynamic and static detuning was compensated to only few Hz during flattop in all cavities except the 5th one where piezo is not fixed properly.

APPLICATIONS

A set of generic and especially devoted programs provide the tools for the operators to control the RF system. Some of them are created based on the MATLAB, others, for example, vector sum calibration are implemented as a DOOCS middle layer servers. The adaptive feed-forward is implemented on a front end server, to allow pulse to pulse adaptation.

The application software includes automated operation of the frequency tuners, calibration, phasing of cavities, and adjustment of various control system parameters such as feedback gains, feed-forward tables, and set-point correction during cavity filling. Extensive diagnostics inform the operator about cavity quenches, cavities requiring tuning, and an excessive increase in control power.

Adaptive Control

The RF field regulation is subject to various, random and deterministic disturbance sources. Both disturbance contributions are reduced in closed loop operation by applying a feedback compensator. However repetitive disturbances are particularly suppressed by adaptation of the system input drive, using the known system response from previous pulses. The reference for the RF field is in general not changed very frequently, so the control task can be seen as a repetitive process for the pulsed operation mode of this accelerator. The basic update algorithm [5] is given by

$$u_{k+1}(t) = u_k(t) + L(t)\, e_k(t)$$

where u_k *and* e_k are defined as the system input and the deviation of the measured RF output to the given set-point for the pulse number k, respectively. $L(t)$ is a linear, non-causal, time varying filter based on the identified system model. The current implementation of the system allows changes of all controller tables inside the FPGA between two consecutive pulses. With the minimum computation time necessary for this algorithm, as well as fast data transfer is fast enough, the adaptation can be performed synchronized to the repetition rate of FLASH. Therefore three steps have to be performed between two pulses: Read from previous pulse the error and feed-forward signals e and u, compute the feed-forward signal of next pulse, and write the feed-forward signals to FPGA tables.

MASTER OSCILLATOR AND FREQUENCY DISTRIBUTION

LLRF system provides stable phase reference signals for diagnostics and experiments. The Master Oscillator (MO), which has been upgraded at 2008 already [6], generates various RF frequencies required for accelerator operation. The phase reference system distributes these signals to various locations in the accelerator with low phase noise and very low phase drift. The local oscillator signal is distributed to all of the down converter channels for cavities probe, forward and reflected signals. Typical stability requirements are: 100 fs for short term (few minutes) and 1 ps for long term (several hours).

During this upgrade several MO system components have been improved. The new 1.3 GHz signal generation hardware was installed with improved phase noise and drift performance. The short term stability of about 45 fs was achieved (phase noise integrated from 10 Hz to 1 MHz) directly at the MO output. The temperature coefficient of phase changes demonstrated by the new device does not exceed 200fs/°C, which significantly improved the long term phase reference stability. Additionally, new power amplifier with increased output power and several signal sub-distribution boxes were installed in order to provide the reference signal to bigger number of accelerator devices.

SUMMARY

The FLASH LLRF system regulating amplitude and phase of the accelerating fields has been upgraded to latest generation controller hardware. All modules are controlled by similar modern FPGA based controller boards with unified firmware and software. In addition beam diagnostics signals are in use for fast intra pulse feedback [7]. Algorithms are improved: beam loading compensation, feed-forward waveform generation, etc. For cavity frequency control piezo control has been implemented. In order to improve the reference frequency signals the master oscillator and frequency distribution system has been upgraded as well. FLASH achieved beam energy above 1.2 GeV and lasing below 5 nm with a remarkably improved LLRF control performance.

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