LOW LEVEL RF CONTROL IMPLEMENTATION AND SIMULTANEOUS OPERATION OF TWO FEL UNDULATOR BEAMLINES AT FLASH

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Abstract

The Free-Electron Laser in Hamburg (FLASH) is a user facility delivering femtosecond short radiation pulses in the wavelength range between 4.2 and 52 nm using the SASE principle. The tests performed in the last few years have shown that two FLASH undulator beamlines can deliver FEL radiation simultaneously to users with a large variety of parameters such as radiation wavelength, pulse duration, intra-bunch spacing etc. FLASH has two injector lasers on the cathode of the gun to deliver different bunch trains with different charges, needed for different bunch lengths. Because the compression settings depend on the charge of bunches, the low level RF (LLRF) system needs to be able to supply different compression for both beamlines. The functionality of the controller has been extended to provide intra-pulse amplitude and phase changes while maintaining the RF field amplitude and the phase stability requirements. The RF parameter adjustment and tuning for RF gun and accelerating modules can be done independently for both laser systems. Having different amplitudes and phases within the RF pulse in several RF stations simultaneous lasing of both systems has been demonstrated.

INTRODUCTION

FLASH has been in operation as a user facility since summer 2005 [1]. In the mean time as a test facility, FLASH is in use for testing the superconducting accelerator technology for European XFEL [2] and ILC [3] projects. The first effort to operate accelerating modules at different gradients with alternating RF pulses was motivated by the ILC and European XFEL and initially has been demonstrated in year 2008 [4].

FLASH2 [5] is the second undulator beam line with variable gap built in a separate tunnel. It will make full use of the existing FLASH accelerator. Part of the bunch trains are kicked from the main beamline (FLASH1) into the new undulator beamline. In order to double the beamtime, users of both beamlines would need the 10 Hz repetition rate. A fast kicker in combination with a DC septum is used to deflect the beam into the second undulator line. In addition, the large variety in beam parameters should be available at both beamlines independently in order to ensure a maximum flexibility in planning of the beamtime. For this reason two cathode lasers are in use, each with its own bunch train. A variable delay between the two lasers within the RF pulse gun and accelerating modules ensures that users from both beamlines get their own set of parameters.

In addition, the start time of the kicker pulse is shifted with respect to the start time of the laser pulse and the RF amplitude and phase of the gun and each of the modules can be tuned for optimal conditions for both users. During the initial tests it was shown that the RF system is able to handle the flexibility needed to compress the beam independently for FLASH1 and FLASH2 beamlines.

LOW LEVEL RF CONTROL FOR MULTI-BEAMLINES

RF Control Specifics for Multi-beamline Case

During the multi-beam line operation, within limits given by the beam delivery system, the bunch pattern and beam energy should be adjusted independently for each beam line, suggesting a time-sliced operation. For the FLASH2 beamline RF amplitude and phase changes within the pulse are required within a short time (less than 50µs). Different beam loadings are foreseen for different beamlines. Particularly the ability of gradient tuning of the last two RF stations is needed for wavelength scans for the FLASH1 beamline and the ability of phase tuning at injector for variation in compression at FLASH1 and FLASH2. From the operation point of view, the most important requirement is to have the ability of independent RF operational parameters adjustments for both beamlines.

LLRF System Overview

The layout of the FLASH facility including the new beamline is described in [6] and shown in Fig. 1. Its accelerator comprises a normal conducting RF gun, a first 8-cavity cryomodule, a third harmonic cryomodule with 4 cavities, a first bunch compressor, a second accelerating RF station (16 cavities), a second bunch compressor, and another two RF stations, with 16 cavities each. FLASH is operated in pulsed mode with repetition rate 10Hz. RF pulse duration is 1.3ms, 500µs for filling and 800µs flattop (beam acceleration). The RF power coming from 10MW klystrons is equally distributed to all cavities through the waveguide distribution system. The current stage of the LLRF control is implemented based on the MTCA.4 system [7]. The goal of the system is to control the accelerating gradient in amplitude and phase for each RF station based on vector sum control of cavity gradients [8]. The main components of the LLRF system are depicted in Fig. 2. For every cavity, the forward (PFWD), reflected (PREF) and transmitted signals or probes (PRB) are first down-converted to an intermediate frequency (IF) by the down-converters (uDWC) and then digitized

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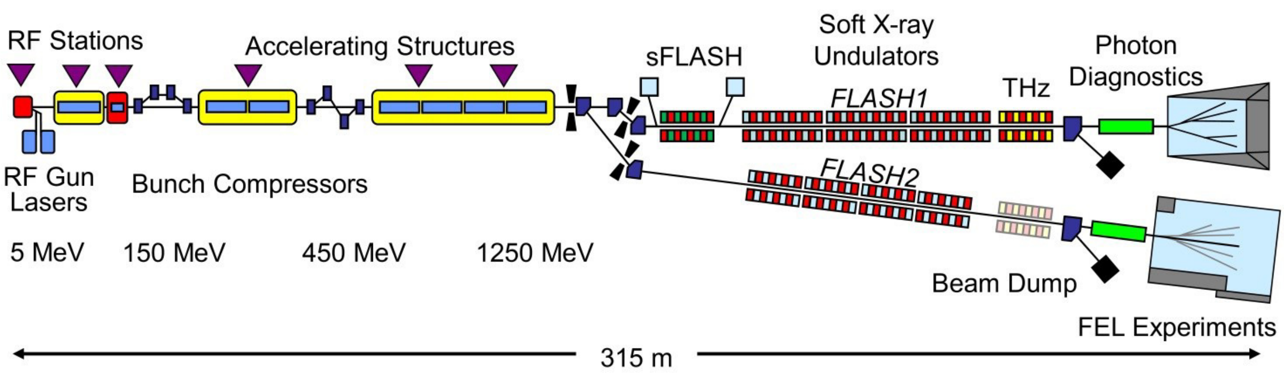

Figure 1: Schematic layout of the FLASH facility. The electron gun is on the left, the experimental hall on the right. Behind the last accelerating module, the beam is switched between FLASH1 and FLASH2 beamlines.

(uADC). The sampled signals are pre-processed by the uADC and then sent over the MTCA.4 backplane to the main LLRF controller (uTC) which performs all control computations. The uTC then generates the drive signal which is up-converted to RF frequency by the vector modulator (uVM). The LLRF drive signal is pre-amplified and then sent to the klystron (KLY). The master oscillator (MO) provides the 1.3 GHz reference signal (RF), required by the local oscillator generation module (LOGM) to generate the LO and clocks (CLK) signals used by the down-converters, and to distribute the reference signal to the uVM. The power supply module (PSM) provides DC voltages to external modules. Finally, the piezo driver module (PZ16M) digitizes the piezo sensor data and drives the piezo actuator for detuning and microphonics compensation. Communication between the PZ16M and the MTCA.4 system is performed through an optical link to the main LLRF controller, the uTC. This setup can be easily extended to control the sum of 16 cavities.

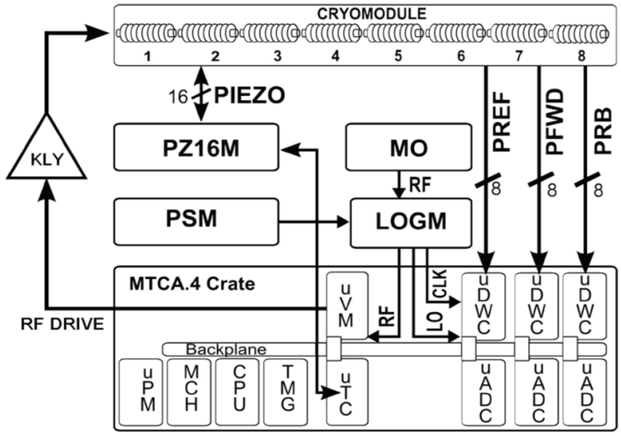

Figure 2: LLRF system block diagram for one cryogenic module.

Brief Description of Control Algorithm

The feedback algorithm is implemented in FPGAs firmware and DOOCS [9] control system server. The control algorithm employs tables for feed-forward, set-point and feedback gain settings to allow time varying of those parameters. High frequency probe signals are used to measure the accelerating field in the individual cavities. These 1.3 GHz (3.9 GHz) signals are down-converted to 54 MHz and sampled by uADCs at 81.25 MHz. The digitized signals are going to the digital field detector which extracts the real and imaginary parts of the cavity field vectors from the input stream. The resulting field vector of each cavity is multiplied by a rotation matrix to calibrate amplitude and phases. Then the sum of individual field vectors is calculated and rotated to adjust the loop phase. The vector sum of the cavities 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 is used to scale the feed-forward table to provide fast feed-forward corrections if the beam current varies. The controller server software handles: generation of control tables from basic settings, rotation matrices for the cavity field vectors, start-up configuration files, feedback and exception handling control parameters, etc. The interrupt service routines are used to start the data reading from the controller boards. The parameters of the feedback algorithm are modified by the FPGA programs in the time slot between pulses.

Application Software

A set of generic and especially devoted programs provides the tools for the operators to control the RF system. Some of them are created based on the MATLAB, others as 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 vector sum calibration, automated operation of the frequency tuners, phasing of cavities, adjustment of various control system parameters, etc. Extensive diagnostics inform the operator about cavity quenches, cavity detuning, and an excessive increase in control power.

RF control functionality extension for FLASH2

The RF pulse is shared between the electron bunch trains for FLASH1 and FLASH2. For the full RF pulse length, the total maximum number of bunches, with bunch repetition rate of 1 MHz is 800. The bunch pattern (number of bunches and intra-train repetition rate) and bunch charge can be different for FLASH1 and FLASH2, which is realized by using two independent injector lasers. Timing events from FLASH accelerator are used to synchronize all accelerator subsystems and are managed by DOOCS timing server. Programmable timers are triggered by these events to generate the start pulses for the klystrons, FPGAs or uADCs. A timer unit provides several independent output channels. Some machine parameters that change from macro pulse to macro pulse are delivered to run all digital feedback loops in parallel. This information is available for the LLRF controller server. The control tables are generated through the LLRF library from the operational setting according to the provided timing information. Parameters such as beam start time, number of bunches, bunch repetition rates are extracted from the timing server for both beamlines. Other parameters like RF transition time, offsets with respect to beam pulse, etc. are adjustable. LLRF control software follows any changes of the timing parameters. Fig. 3 illustrates the timing setup for two beamlines.

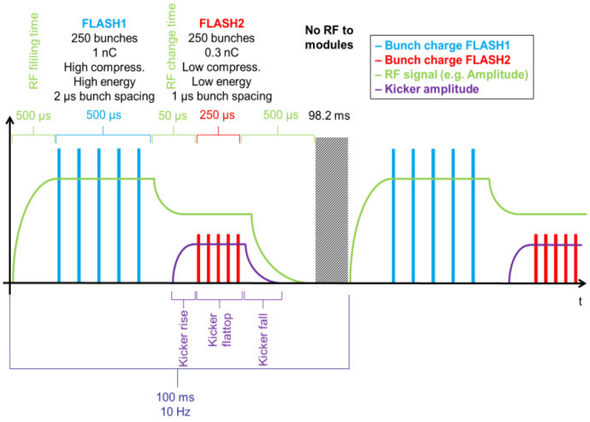

Figure 3: An example of FLASH timing settings.

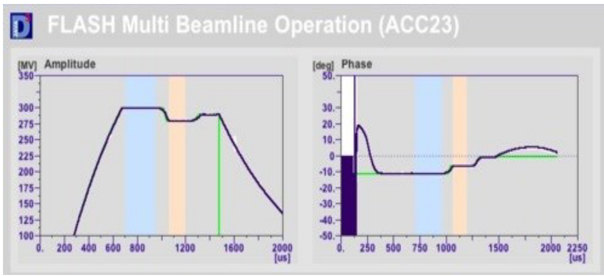

Figure 4: Energy and phase variation within RF pulse.

Energy and phase variations are possible to allow for charge dependent compression and wavelength fine tuning. A future extension with an additional beamline is already foreseen, as can be seen by the three different levels of RF pulse (Fig. 4). Background colours show the beam start time and bunch train duration time for FLASH1 and FLASH2 beamlines. In order to avoid operational settings changes in unacceptable ranges, limits for FLASH2 operational parameters with respect to FLASH1 are implemented as well. An adaptive learning algorithm which minimizes repetitive control errors tends to limit these transition changes. In order to avoid oscillations, it is possible to deactivate adaptations for certain regions.

PERFORMANCE OF SIMULTANEOUS OPERATION OF FLASH1 AND FLASH2

In the initial stage of the project several tests have been performed to show that simultaneous operation of both beamlines is possible [10]. Fig. 5 shows lasing of two bunch trains which were generated with separate injector lasers, separated by 80µs: a) with the same charge of about 0.5 nC and b) with a factor of 2 difference in charge, e.g. of 0.5 nC for the first and 0.25 nC for the second bunch train. The blue line indicates the actual SASE pulse energy produced by each individual electron bunch in the macro-pulse. The green line is the time average of this signal. The yellow line indicates the maximum SASE level which occurred since the measurement was started. Both bunch trains have a repetition rate of 1 MHz. The number of bunches in this case was 30 and 20 respectively. During this test only RF parameters were changed within the RF pulse and orbit was adjusted behind the FLASH2 extraction point. Because the FLASH2 beam line was under construction in that time, this test has been performed at FLASH1 beamline. Careful adjustment was done to make sure that both injector lasers hit the cathode under the same angle to make sure that the electron beams have the same trajectory. This condition was relaxed in the later situation, since the orbit in the FLASH1 and FLASH2 undulators can be adjusted independently to optimize lasing.

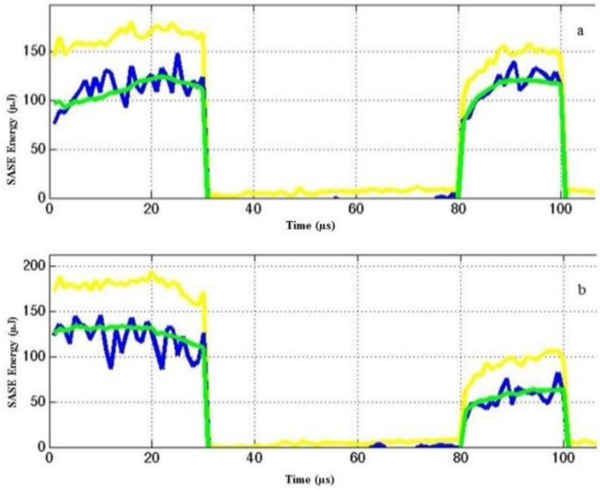

Figure 5: Lasing of two independent bunch trains with different charges and a variable delay in time.

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Since 2014 tests have been performed with FLASH1 and FLASH2 in operation. First SASE operation in FLASH2 was achieved at wavelength 40 nm on August 20, 2014 [11] during FLASH1 operation with 250 bunches at 13.5 nm.

After the demonstration of the first lasing at FLASH2 the SASE operation was established at various wavelengths. So far, the maximum number of bunches per burst during a parallel SASE operation of both beamlines has been 400 bunches in FLASH1 and 30 bunches in FLASH2, both with a bunch repetition rate of 1 MHz. Fig. 6 shows the SASE pulse energy along the bunch trains in FLASH1 and FLASH2. During parallel operation achieved pulse energy at FLASH1 was about 200µJ and about 100µJ at FLASH2 in the period from June 2015 to August 2015.

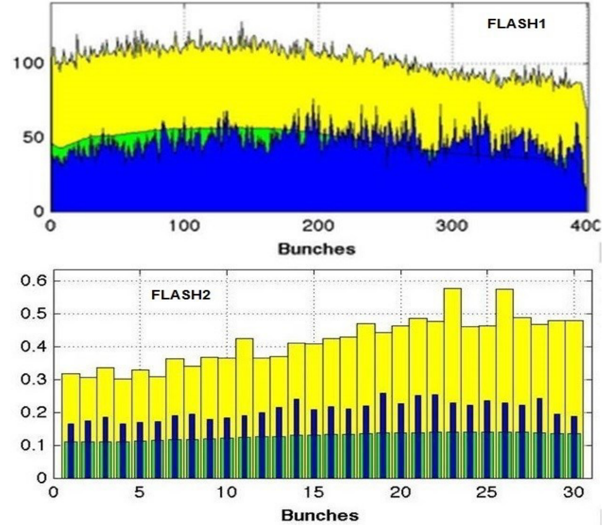

Figure 6 : SASE pulse energy per bunch (in a.u.). Top: 400 bunches in FLASH1. Bottom: 30 bunches in FLASH2. Blue: actual value, green: average, yellow: maximum.

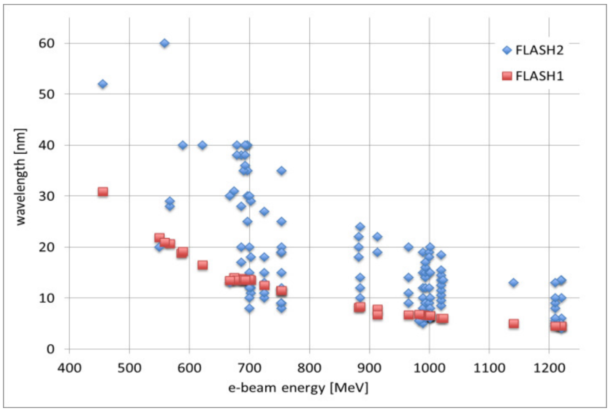

Figure 7: Photon wavelengths achieved in the FLASH1 and FLASH2 beamlines during parallel SASE operation.

In Fig. 7 [12] are shown photon wavelengths achieved in the FLASH1 and FLASH2 beamlines during parallel SASE operation in the period from August 2014 to August 2015. The photon wavelength in FLASH1 is determined - due to the fixed gap undulator - by the electron beam energy. Variable gap undulators in FLASH2 allow different photon wavelength at fixed beam energies.

SUMMARY AND OUTLOOK

Low level RF control functionality has been extended which makes simultaneous RF operation of multi-beamlines possible. Changes in RF settings within RF pulse can be achieved which allow different compression settings for different charges (and therefore different bunch lengths) while maintaining the RF field amplitude and the phase stability requirements.

Simultaneous operation of two beamlines and lasing of FLASH2 at the wavelength 40 nm was achieved, while FLASH1 was lasing simultaneously with multi-bunch mode at different wavelength (13.5 nm). SASE operation at various wavelengths was established.

Gained experience with simultaneous operation of two beamlines at FLASH is a good basis for successful commissioning of multi-beamline facility European XFEL which is foreseen for the second half of 2016. At XFEL, operation of alternating RF pulses (from pulse to pulse) is foreseen as well. This operation mode requires additional changes in the firmware/software structure, e.g. extending the amount of control tables. Furthermore, requirements to the timing system are increased to reliably trigger the correct mode of operation.

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