A LASER PULSE CONTROLLER FOR THE INJECTOR LASER AT FLASH AND EUROPEAN XFEL

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Abstract

FLASH is a multi-beamline free-electron laser user facility which provides femtosecond long high brilliant photon pulses in the extreme-UV and soft-X ray wavelength range. One pulsed superconducting linac accelerates electron bunches for two undulator beamlines, while a third beamline is under construction. Within each RF-pulse, trains of hundreds of electron bunches are produced in a photocathode RF gun, accelerated in the linac and distributed by fast kickers into the undulator beamlines. In order to fulfill the parameter ranges of the multiple user experiments each bunch train can be tuned individually in bunch number from 0 - 800, spacing from 1 µs - 25 µs and intensity from 0.1 nC - 1 nC. To make this possible, three injector laser systems are used and this allows FLASH to vary independently the laser settings for the designated undulator beamlines. A laser controller has been developed to make a multi-users operation mode possible. The controller uses a Field Programmable Gate Array (FPGA) to control the time structure of the laser pulses and it provides the interface for the timing and the machine protection system. The controller has been implemented using the MicroTCA.4 technology. The controller was ported to the injector laser system at the European XFEL facility and is in operation since end 2015.

INTRODUCTION

The Free-Electron Laser in Hamburg FLASH [1, 2] at DESY delivers high brilliance XUV and soft X-ray photon pulses to two simultaneous operating photon experiments. The photoinjector, consisting of a normal conducting RF photo cathode gun (RF-gun) and a system of three UV injector lasers, is capable of producing 800 µs long bursts of electron bunches at a repetition rate of 10 Hz. The bursts, called macropulses, are accelerated by a superconducting linac which is equipped with seven 1.3 GHz TESLA-type accelerator modules. The maximum beam energy is 1250 MeV. The complete burst consists of two subtrains of electron bunches. One sub-train is injected into the FLASH1 undulator beamline and the other one is deflected by a system of a flat top kicker and a DC septum magnet into the FLASH2 undulator beamline. This allows FLASH to serve simultaneously various FEL user experiments with bursts of hundreds of photon pulses with the same repetition rate of 10 Hz. In the near future there will be an upgrade of a third beamline which will be operated in a similar way.

For a multi-user FEL operation like at FLASH it is a basic requirement to ensure that it is possible to change the beam parameters individually for the various undulator beamlines. Therefore each of the sub-bunch trains is produced by a different injector laser and each laser has got a different set of parameters. The pattern and the charge can be changed individually for each laser. In addition it is also possible to adjust other beam parameters like energy or bunch compression for each beamline to ensure the highest flexibility of beam parameters for the various user experiments. The repetition rate of the bunches within the sub-bunch trains can be varied between 40 kHz and 1 MHz. A gap of 50 µs between the sub-bunch trains is needed to adapt the RF settings (amplitude and phase of the accelerating field) and for the transition time of the kicker system. A schematic diagram of the bunch patterns for the two FLASH beamlines is shown in Fig. 1.

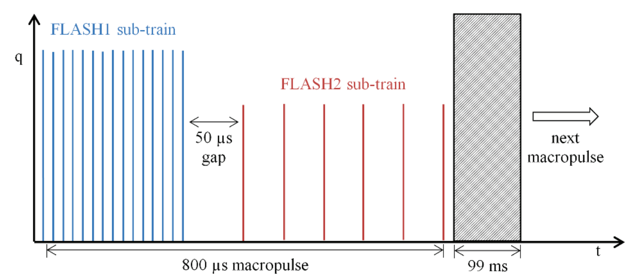

Figure 1: Example of bunch patterns for two FLASH beamlines FLASH1 and FLASH2 with different settings of the injector lasers.

The European XFEL facility [3] is being constructed at DESY and the operating mode will be similar to FLASH. A 17.5 GeV superconducting linac will drive three undulator beamlines that can be operated simultaneously. The XFEL injector is equipped with a UV injector laser, a 1.3 GHz RF-gun, a TESLA-type 1.3 GHz accelerator module, a third harmonic RF system, a laser heater, and diagnostic section. The injector is capable of producing 600 µs long bunch trains with 10 Hz and each burst consists of 2700 bunches. The commissioning of the Injector started in 2015 and the first long bunch train operation has been demonstrated in 2016 [4].

LASER PULSE CONTROLLER

System Overview and Connected Systems

To fulfill the requirements of a multi-beamline operation each injector laser is controlled by a laser pulse controller based on the MicroTCA.4 technology [5]. The timing system [6] distributes the desired bunch pattern information to the laser controller. Each bunch is defined by a 32 bit long data vector called bunch pattern word which specifies the intended undulator beamline and the injector laser responsible for each bunch. The bunch pattern table is an array consisting of 7222 bunch pattern words. Each element of this table

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represents a possible bunch position with a detailed specification of the foreseen bunch parameters. The time pattern of the table offers the possibility to produce a bunch train with 7222 bunches at a rate of 9 MHz which corresponds to a burst length of 802 µs. At FLASH the maximum bunch repetition rate for normal operation is 1 MHz thus every 9th element represents a valid bunch position. At the European XFEL the maximum repetition rate is 4.5 MHz and every second element is a valid position. The bunch pattern words of invalid or unused bunch positions are set to zero. The content of the bunch pattern table can be changed with a rate of 10 Hz and the complete table is being send to the laser controller at the same rate.

The transmitted bunch pattern table is the result of the desired pattern which has been selected by the machine operator and a mask which is applied by the machine protection system (MPS). The MPS [7] collects the alarm data of all subsystems in the accelerator and limits the number of bunches per macropulse or even blocks the complete beam when necessary to prevent the machine from damage. The limitation mask can be changed at a rate of 10 Hz. Without taking the signal propagation delay into account, this concept produces by definition a signal latency of 100 ms and therefore this mechanism is called “slow protection”. However, it might be necessary to stop the beam operation immediately within the macropulse, for example if beam losses occur within pulse trains. In this case, the MPS sends inhibit signals directly to the laser controller using the so-called “fast alarm signal lanes”. This allows the MPS to stop a bunch train within the macropulse. The response time of this fast protection was tested by producing a test alarm at the last beam loss monitor (BLM) upstream of the FLASH2 dump beamline and then measuring the time the complete system needed until the laser controller stopped the bunch train. The test alarm signal produced by the BLM electronics had to pass three separated processing boards of the MPS and a distance of 300m using an optical fiber. The propagation time of the signal was measured to be 4.5 µs. The response time of the laser controller alone is 60 ns. This time is dominated by the hardware latency. The controller firmware needs two clock cycles (18.5 ns) for processing the inhibit signal.

The FLASH toroid protection system (TPS) [8] measures bunch charge differences along the beamline within a particular section. These sections are the FLASH1 undulator beamline, the FLASH2 undulator beamline and the injector beamline up to the bifurcation between FLASH1 and FLASH2. The laser controller sends a trigger signal to a TPS module if the connected laser is producing bunches for that given beamline section. The TPS thus verifies the validation of beam for the particular section.

Firmware Features

The laser pulse controller is responsible for controlling the injector laser pulse pattern according to the timing pattern and the fast alarm signals. In addition, the controller creates triggers for the different TPS modules if beam is produced for the particular beamline.

The controller receives the timing pattern which is assigned to the laser by the particular laser bit of the bunch pattern word. An internal pulse limiter corrects the pattern if necessary. The maximum pulse repetition rate and the maximum number of pulses per macropulse are limited by the controller to ensure safe operation of the laser and the accelerator. These limiter settings depend on the laser and the accelerator mode. A hardware dongle connected to the inputs of the controller assigns an identification number (ID) to it. The internal limiter settings are set according to this ID to the particular values and they can not be changed by other systems. Using the ID dongle makes it possible to run all injector lasers with identical hardware and software to keep maintenance as simple as possible. Additionally the controller compares the beamline bit of the bunch pattern word with the inhibit input signals of the MPS. If there is a valid MPS inhibit signal for the particular beamline the controller is blocking the pulse pattern. In the last step the controller shapes the output signal according to the requirements of the laser electronics which are also set by the laser ID dongle. The generated output pattern is used to select the desired sequence of laser pulses out of an existing laser burst by gating a fast Pockels cell in the laser beam path.

A DOOCS control system server [9] is used to display the status register of the laser controller and to control a laser shutter connected to the controller that allows for blocking the laser beam completely. The MPS is able to overwrite the server data and to close the shutter by sending a shutter inhibit signal for a certain beamline. The controller compares the inhibit signal with the beamline information of the bunch pattern word and closes the shutter when the signal is valid regardless of the server data.

Using the two mechanisms described above, the pulse controller can block the laser beam, and thus also the electron beam, in two ways: either the Pockels cell gates can be blocked or the laser shutter can be closed. The controller chooses the method depending on the incoming beamline inhibit signals from the MPS (Pockels cell inhibit and/or shutter inhibit). The beamline inhibit signal is only valid for the respective controller if the connected laser is producing bunches for that beamline section (FLASH1 or FLASH2). The controller ensures that an alarm for the FLASH1 beamline does not affect the beam of the FLASH2 laser and vice versa. Blocking the Pockels cell gates takes less than 1 µs and closing the laser shutter takes about 1 s. The difference of time for both mechanisms is caused by the mechanical construction of the laser shutter. The controller logic is the same for both mechanisms.

The trigger signals for the TPS are generated simultaneously with the Pockels cell gates. The controller sends the trigger to the TPS module for the given section according to the beamline information of the bunch pattern word. By using the doocs server is is possible to delay the TPS trigger referring to the Pockels cell gates. For the operation of the TPS it is necessary to match the arrival time of the laser trigger with the arrival time of the toroid signal. The delay between both signals can be adjusted between 148.68 ns and

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2502.33 ns in steps of 9.23 ns. A stacked digital delay is used to realize delays longer than the repetition rate of the Pockels cell gates. The timing of all three TPS gate signals can be adjusted separately for each beamline section. All controllers are linked to each other. One controller collects all TPS signals from various lasers and sends the collective data to the respective TPS module.

Hardware

The controller was developed using the DESY Advanced Mezzanine Card DAMC2. This advanced mezzanine card (AMC) is based on the MTCA.4 standard and was optimized for digital data acquisition systems. The AMC board provides a VIRTEX5 field programmable gate array (FPGA) from XILINX into which the laser controller logic is implemented. Using the FPGA technology guarantees fast data processing which is mandatory to ensure safe operation of the injector laser. All injector lasers are equipped with a MTCA.4 system including a chassis, crate management controller, CPU AMC, X2-timer AMC, analogue-to-digital converter (ADC) AMC and the DAMC2 controller board. The FPGA board communicates with the CPU-AMC via the PCI express bus and with the timing system via the M-LVDS bus. A transceiver for both data bus systems was implemented into the laser controller FPGA logic to communicate with these bus systems. The boards are connected to each other via the crate backplane and this backplane provides dedicated lines to connect all AMCs to the particular data bus. In addition to the pattern information the timing system delivers a 108 MHz FPGA clock and a 10 Hz macropulse start trigger to the laser controller using the same data bus system. The DOOCS server is running on the crate CPU and the CPU-AMC is part of the of the machine control system within an GigE-Ethernet connection.

An MPS-type rear transition module (RTM) is used for the communication with the laser hardware, the MPS and the TPS. The laser controller receives a shutter and a Pockels cell inhibit signal for all undulator beamlines from the MPS and sends a status signal of the laser shutter back to it using the RTM I/O channels. The MPS is using the same RTM type and therefore a fast exchange of data can be ensured. The RTM provides seven output channels and 45 input channels and it is connected directly to the DAMC2 AMC. All channels are galvanic isolated and use the RS422 signal standard. The laser-ID dongle is also connected to the RTM. Since only the RS422 signal standard is supported by the RTM, an additional printed circuit board (PCB), the "laser interface", was developed to convert the RTM input and output signals into different signal standards needed for the laser hardware. The interface provides a 12 VDC I/O signal for the laser shutter, two 5 V TTL outputs for the Pockels cell gates and three 50 Ω line driver outputs for the TPS trigger. In addition several outputs were doubled to generate monitoring signals which can be connected to the A/D converter AMC. The interconnection of the complete system and the communication paths between the different systems are shown in Fig. 2.

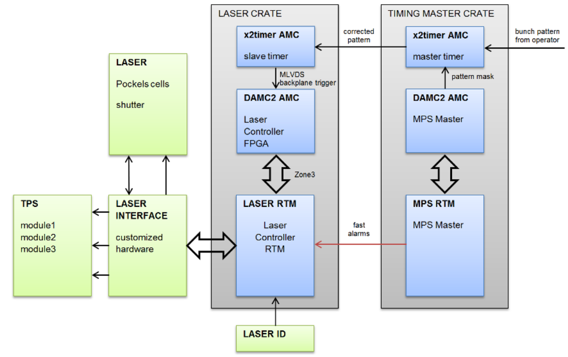

Figure 2: Overview of the communication paths between the laser controller and the connected systems. Blue: MTCA.4 Hardware. Green: Laser hardware and interface.

SUMMARY

A laser controller, implemented using the MTCA.4 technology, has been developed to make the multi-user operation mode possible. Up to three different injector lasers produce multiple subtrains of electron bunches within the macropulse, and each laser can have different parameters. All injector lasers at FLASH and XFEL are controlled by the laser controller and the systems are strongly linked to the timing and the machine protection system.

Simultaneous operation of three injector lasers with different patterns for the FLASH beamlines FLASH1 and FLASH2 was achieved. The European-XFEL injector produced burst with 2700 bunches per train in 2016. In the near future there will be an upgrade of a third FLASH beamline which will be operated in a similar way. The laser controller ensures that all beamlines can be operated independently from each other and MPS alarms from one beamline does not affect the other beamline.

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