A TOROID BASED BUNCH CHARGE MONITOR SYSTEM WITH MACHINE PROTECTION FEATURES FOR FLASH AND XFEL

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Abstract

For the superconducting linear accelerators FLASH and XFEL, a new toroid based charge measurement system has been designed as a standard diagnostic tool. It is also a sensor for the bunch charge stabilization feedback and for machine protection. The system is based on MTCA.4 technology and will offer a high dynamic range and high sensitivity. The machine protection features will cover recognition of poor transmission between adjacent toroid sensors, bunch pattern consistency checks, and protection of the beam dumps. The concept, an overview of the algorithms, and the implementation will be described. A summary of first operation experience at FLASH will be presented.

INTRODUCTION

In the FLASH accelerator, toroid based Beam Current Monitor (BCM) systems have been used from the beginning.

Other requirements came up when the beam current increased due to the increasing number of bunches per RF pulse and a redundancy for the beam loss monitors (BLMs) became mandatory. Namely, pairs of beam current signals had to be applied for transmission interlocks. At this time, a “Toroid Protection System” (TPS) was developed [1] to detect beam losses by analysing the amplitude differences within toroid pairs. The TPS used the existing analogue toroid signals as inputs, and in addition to the control system digitizers, separate ADC and FPGA based data processing chains were implemented in a dedicated box. Connections to the Control System were avoided so as to insure maximum safety against unintended changes.

When beam current stability became an issue, a beam current feedback system was developed [2], again with the analogue toroid signals as inputs. It was realized by still another FPGA based system, providing a fast digital fibre connection to the injector.

Another application of the toroid signals was the beam loading compensation for the cavities realized by the LLRF group [3].

For the new European XFEL [4], it was desired to implement all this functionality into a single system, creating even more requirements.

For the x-ray cameras in the experiments, a “veto” signal is required to disable data acquisition for improper bunches.

For the protection of sensitive components, it is necessary to check that the integrated bunch charge is below a certain limit and that the bunches are directed to the correct branches of the beamline.

Since the exchange of a damaged beam dump is a major issue, dedicated protection algorithms were desired for the different kinds of dumps (three main beam dumps and two diagnostic dumps at the XFEL).

Another important topic is the ability of the system to work (with some restrictions) if the control signals from the machine timing system (clock, trigger) are not available or corrupted. In this case, the system should still measure the bunch charge (with relaxed precision) and the safety must be maintained.

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HARDWARE SETUP

The hardware consists of the toroid device, the front-end device (signal combiner, filter, amplifier) and the MTCA backend (see Fig. 1). The front-end device will be contained in a box together with a test pulse generator close to the toroid, the backend will be composed of a dedicated Rear Transition Module (RTM) in combination with a commercial 10 channel 125 MSPS digitizer board (Struck SIS8300-L2), housed in an MTCA.4 crate. The digitizer board will communicate over the MTCA backplane with the CPU in the crate, and the CPU will be part of the control system within an Ethernet network. The digitizer modules offer an FPGA for fast data processing and direct communication over Gigabit links with a speed of up to 6.25 Gb/s with other modules.

High Dynamic Range Feature

For the possibility of extending the dynamic range to a value above the dynamic range of the ADC, a two-channel arrangement will be implemented with two amplifiers of different gains, see Fig. 1. The high gain amplifier will provide improved SNR for low signals [5]; the low gain amplifier is still in the linear range for high amplitudes.

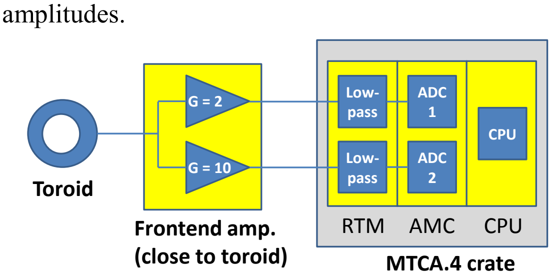

Figure 1: Hardware setup with high dynamic range feature (simplified).

OPERATION MODES

The system offers two basic operation modes: a self-triggered mode and a timing-triggered mode.

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Self-triggered Mode

This mode has to be used if correct clock and trigger signals from the timing system are not yet available in the commissioning phase and as a fallback in case of a timing system failure. In this mode bunches are detected by a threshold comparison of the digitized and pre-processed signal. This requires a bunch amplitude above a certain limit for reliable detection, and the precision is reduced because of the missing synchronization between bunch arrival times and ADC sampling.

In addition a technical alarm is issued to the MPS system to stop the (multi-bunch) machine operation.

Timing-triggered Mode

The timing-triggered mode can be used if the timing information (clock, trigger and bunch pattern) is available. This mode offers the full performance and is mandatory for multi-bunch operation with activated MPS.

MACHINE PROTECTION FEATURES

The BCM system is an important alarm supplier to the Machine Protection System (MPS) [6] and will offer the following features:

Differential Interlock

The main system to protect the XFEL and FLASH accelerator against extended beam losses will be the Beam Loss Monitor (BLM) system, based on scintillator panels connected to photomultipliers. While BLMs are very sensitive, they are localized – so losses at hidden locations can be invisible to BLMs. A BCM based transmission interlock can overcome this constraint, and it can also provide redundancy to the BLM system - therefore it was decided to implement this functionality. The principle is illustrated in Fig. 2. If a beam loss happens in a section between two BCM devices, the downstream BCM will show less charge than the upstream BCM (disregarding secondary emission inside the beam pipe). The amplitudes will be transmitted digitally via optical fibre links between the BCM devices. If the difference (calculated in the upstream BCM) is too big, an alarm will be generated with latency below 1 µs to stop the beam via the MPS system.

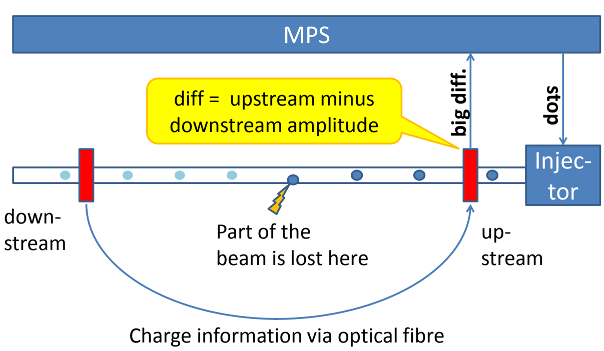

Figure 2: Principle of the differential interlock: a beam loss between two BCMs leads to reduced amplitude at the downstream BCM.

To monitor the whole accelerator, a chain of differential interlocks can be installed, see Fig. 3.

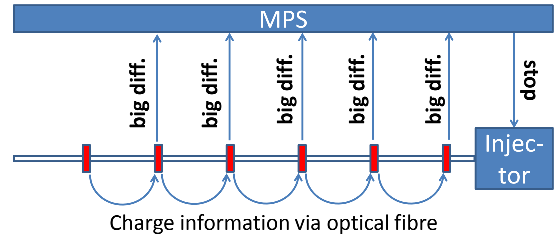

Figure 3: Non-interlaced differential interlock chain.

If a single BCM in this arrangement fails, it cannot any more receive and transmit the bunch charge information, so two sections between BCMs are “invisible”. To avoid this risk, a redundant arrangement will be used in XFEL and FLASH with two interlaced optical fibre chains, see Fig. 4. A single failure of any BCM except the leftmost and the rightmost device will not affect the safety of the whole system.

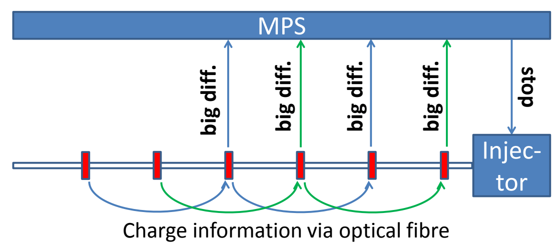

Figure 4: Interlaced differential interlock chain.

The differential interlock can also be applied to branches of the beam pipe. In this case the receiving BCM has to provide two fibre link inputs – one for either branch. A simple method to check for beam losses would be to add the signals from the two branches arithmetically and compare with the common signal before the branch. However, at XFEL and FLASH the direction of each bunch is known in advance from the bunch pattern (see next chapter) – this information can be used to decrease the noise. The principle is shown in Fig. 5 for the non-interlaced case and in Fig. 6 for the interlaced case.

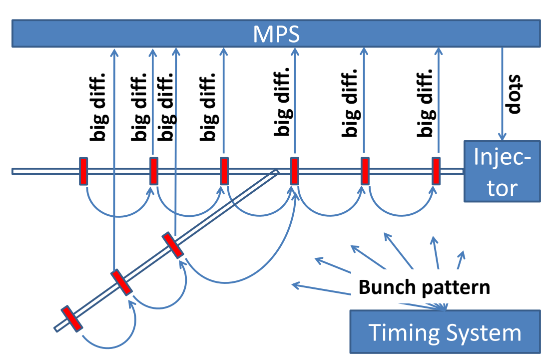

Figure 5: Differential interlock for a branch.

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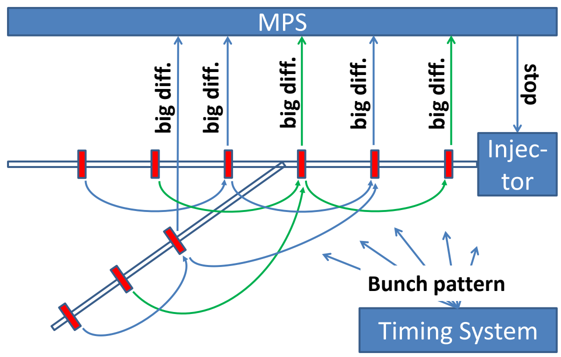

Figure 6: Interlaced differential interlock for a branch.

Bunch Pattern Consistency Check

The Timing System transmits information ("bunch pattern") about the destination of each bunch to all BCMs and other diagnostic devices ahead of each macropulse. For safe operation of the accelerator, the bunch pattern announced by the Timing System has to be consistent with the real bunch pattern.

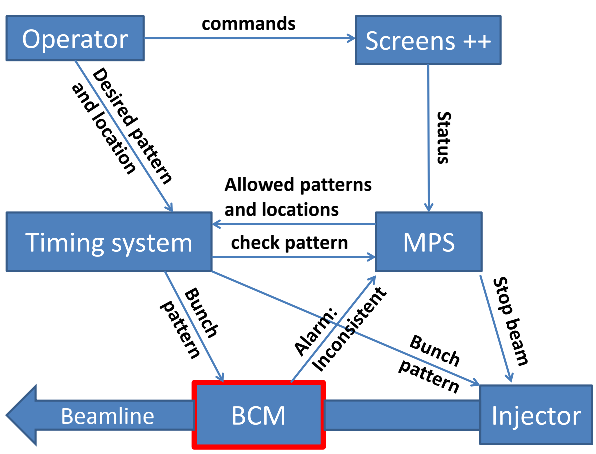

Figure 7: Bunch pattern consistency check.

The bunch pattern will be derived from the operation requirements, combined with the restrictions from the MPS, and then transmitted to all devices (see Fig. 7). So the injector generates bunches according to the bunch pattern. Every BCM can check if the announced bunch pattern is consistent with the pattern in the corresponding accelerator section. If bunches appear in wrong accelerator sections or time slots, the MPS will stop the injector.

Direct Protection of XFEL Dumps

Three main dumps and two diagnostic dumps will be installed in the XFEL accelerator. While any of the main dumps can absorb about 50% of the design beam power, the diagnostic dumps are very limited in beam power and current [7]. For every dump a dedicated BCM exists which monitors only the beam going to this dump. If the limit is exceeded, the beam will be stopped.

Indirect Protection of XFEL Diagnostic Dumps

One of the two diagnostic dumps in the XFEL is very delicate – only a given integrated charge (corresponding to only a few bunches) is allowed per macropulse in order to stay below the damage level. For the direct protection discussed above, the beam stop latency would be too large due to the given distance between BCM and injector, see chapter "Reaction times" in [6].

To overcome this problem, the indirect protection can be applied, using a BCM directly behind the injector. The bunch pattern informs the system which bunches are designated for the delicate dump. Only these bunches are used for the protection algorithm. Then the latency is very short because of the small distance between BCM and injector.

For first operation, a slow bending magnet will be used to steer the beam into the diagnostic dump or not. So the status of this magnet will be communicated via the MPS to the Timing System where the bunch pattern information will be composed, see Fig. 8.

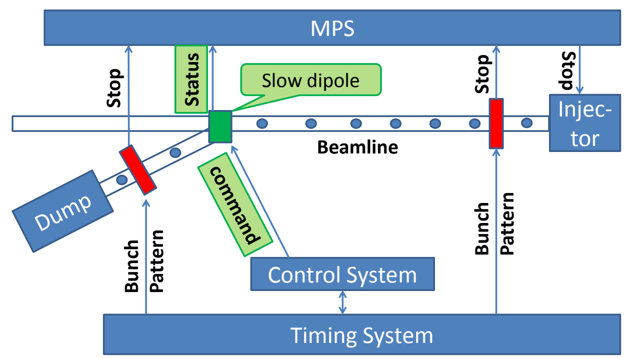

Figure 8: indirect protection of XFEL diagnostic dumps with beam steering by a slow dipole.

For later operation, it is desired to pick out bunches for the diagnostic dump by a fast kicker. This needs another protection scheme: The command to kick a bunch will be communicated by the bunch pattern from the Timing System to the kicker. The bunch pattern will also inform the BCM that this bunch will be steered to the diagnostic dump, see Fig. 9.

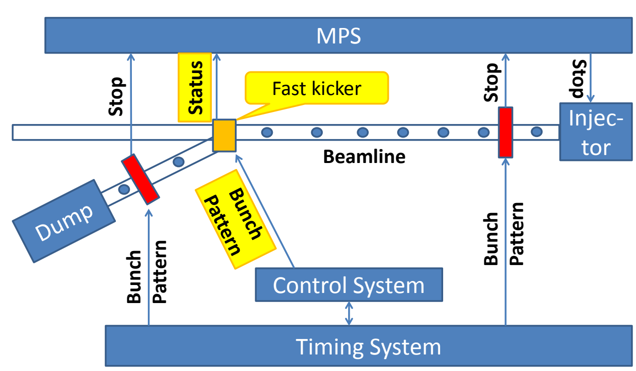

Figure 9: indirect protection of XFEL diagnostic dumps with beam steering by a fast kicker.

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Detection of too High Charge

If the charge exceeds a limit given by the bunch pattern telegram from the timing system, an alarm is triggered.

CHARGE CALCULATION ALGORITHMS

Basic Charge Calculation

For the current standard BCM implementation in FLASH, raw ADC samples (sampling frequency 108.333 MHz, bunch synchronous) are transmitted to a CPU where the bunch amplitudes are calculated in software. The algorithm [8] is shown in Fig. 10: At first, 4 samples are averaged to get the baseline value. Then 2 (optional 3) samples are ignored. The following 3 (optional 4) samples are averaged, and from this average the baseline value is subtracted to get the bunch charge.

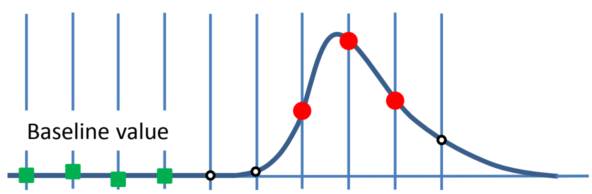

Figure 10: Basic charge calculation algorithm as currently implemented in software at the FLASH accelerator.

Improved Amplitude Calculation

The result of the basic charge calculation depends to some degree on sampling timing, especially on the time difference between the top of the curve and the center sampling point. To mitigate this dependence, a second order parabola fit algorithm can be used [9], [10]. More algorithms are currently under consideration.

Automatic Sampling Point Correction

In addition to a more precise integral of the signal, the parabola fit algorithm also generates an estimate for the time difference between the top of the curve and the center sampling point. For the new XFEL BCM system, it is foreseen to use this value to fine tune the ADC sampling phase, as also implemented in [9], [10]. This time tracking algorithm can be combined with the basic or improved amplitude calculation.

FIRST OPERATION AT FLASH

First data acquisitions have been demonstrated in the FLASH accelerator with a commercial RTM (Struck SIS8900), connected to a SIS8300 digitizer board, using the self-triggered mode. The basic charge calculation algorithm (see above) was implemented in FPGA firmware together with a maximum search algorithm and a threshold comparator. A bunch is detected if a given trigger threshold is exceeded and a local maximum is found. The algorithm waits for the first bunch of each macropulse and then outputs values at a rate of 9 MHz – this is the granularity in which bunches can occur. If no bunch is detected, the algorithm outputs a zero value. During the test, the bunch repetition rate in FLASH was 1 MHz and Fig. 11 shows that the algorithm correctly shows this rate: bunches were detected at index 0, 10, 19, 28, 37 … which corresponds to the 1 MHz bunch spacing in 111 ns (1 / 9 MHz) units. The displayed variations of the amplitude (order of ± 4%) are caused by two effects: fluctuations of the beam charge and imperfectness of the basic charge calculation algorithm in connection with the self-triggered mode.

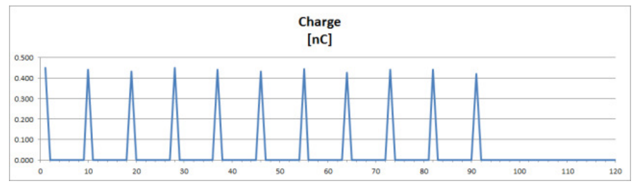

Figure 11: FPGA processed data from FLASH operation with 11 bunches at 1 MHz. Unit of X-axis: 111 ns buckets.

OUTLOOK

The development of a new RTM for the BCM system is under way and the features described above will be implemented in firmware as needed by the upcoming XFEL commissioning and operation. After successful commissioning in the lab, the XFEL Injector and the FLASH facility can be used for further functional verification, and finally the system is foreseen to be the standard BCM solution for XFEL and FLASH.

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