XFEL MACHINE PROTECTION SYSTEM (MPS) BASED ON UTCA

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Abstract

For the operation of a machine like the linear accelerator XFEL at DESY Hamburg, a safety system keeping the beam from damaging components is obligatory. This machine protection system (MPS) must detect failures of the RF system, magnets, and other critical components in various sections of the XFEL as well as monitor beam and dark current losses, and react in an appropriate way by limiting average beam power, dumping parts of the macro-pulse, or, in the worst case, shutting down the whole accelerator. It has to consider the influence of various machine modes selected by the timing system. The MPS provides the operators with clear indications of error sources, and offers for every input channel the possibility to set dedicated machine modes to facilitate the operation of the machine. In addition, redundant installation of critical MPS components will help to avoid unnecessary downtime.

This paper summarizes the requirements on the machine protection system and includes plans for its architecture and for needed hardware components. It will show up the clear way of configuring this system - not programming.

Also a look into the financial aspects (manpower / maintenance / integration) is presented.

INTRODUCTION

The European X-Ray Free Electron Laser (XFEL) linear accelerator will bring an electron beam to the energy of up to 20 GeV and use it to generate extremely brilliant pulses of spatially coherent x-rays in an array of undulators using the Self-Amplified Spontaneous Emission (SASE) process. With a design average beam power of 600 kW and beam spot sizes down to few micrometers, the machine will hold a serious damage potential unless countermeasures are taken. To ensure safe operation of the accelerator, dangerous situations have to be detected by closely monitoring beam losses and the status of critical components, and to react appropriately. This is the task of the fast machine protection system (MPS) described in this paper. Several design features of the system have been influenced by experience from existing facilities, particularly the Free Electron Laser in Hamburg (FLASH).

A high flexibility of the MPS is essential to guarantee minimum downtime of the accelerator. In contrast to a storage ring where a beam dump typically implies a time-consuming refill of the machine, a linac offers the possibility to limit the length of the bunch train individually for each macro-pulse. Hence the reaction to failures of subsystems or even parts of the MPS can be much more specific—a dynamic limitation of the total beam power or a selective veto on beam transport into a particular branch of the beamline are possible. Experience with FLASH has also shown that the operation of the machine profits from an MPS whose behaviour can be changed or extended in a simple way. Apart from all of this, overall limitations, like power density, have to be respected.

XFEL ARCHITECTURE

The present chapter provides a brief overview of the XFEL facility (Figure 1). The major tunnel sections accommodate the following systems:

- injector
- linear accelerator (linac)
- beam distribution system
- undulators
- photon beam lines
- experimental stations

These components are distributed along an essentially linear geometry, 3.4 km long, starting on the Deutsches Elektronen-Synchrotron (DESY) laboratory campus in the north west part of the city of Hamburg, and ending in the neighboring federal state of Schleswig-Holstein, south of the city of Schenefeld, where the experimental hall will be located.

In the injector, electron bunches are extracted from a photocathode by a laser beam, focused and accelerated in a radio frequency (RF) gun and a superconducting acceleration module, and directed towards the linac with an exit energy of 120 MeV. After further acceleration, the bunches are longitudinally compressed in two bunch compressors, BC1 and BC2, at energies of 500 MeV and 2 GeV. In the subsequent main linac, the beam is brought to energies of up to 20 GeV (17.5 GeV is the energy foreseen for normal operation of the XFEL) before passing the collimation section. Afterwards, a fast kicker can send single bunches into a beam dump and the beam will be limited. The remaining bunch train can be sent into two undulator lines by the beam distribution kicker with a rise time of less than 20 µs. Each of the undulator lines ends in an electron beam dump, and each of the three main beam dumps is designed to withstand only half of the nominal beam power, i.e. 300 kW.

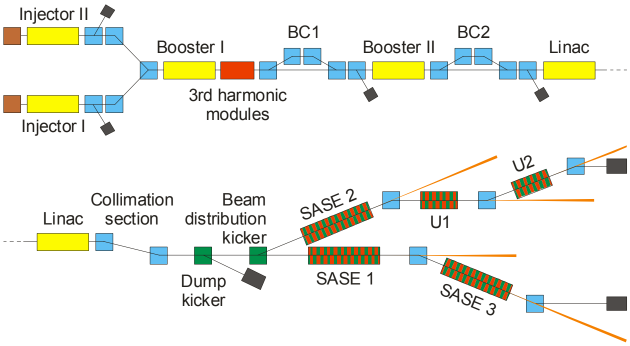

Figure 1: Schematic of the XFEL beam line.

REQUIREMENTS FOR THE MACHINE PROTECTION SYSTEM

The main requirements for the MPS may be summarizing in three points, in the order of their importance:

1. protect accelerator components and devices in the vicinity of the accelerator from direct and indirect damage by the beam
2. facilitate easy handling of the machine—impair machine operation only if necessary
3. limit activation of accelerator components to preserve their maintainability

While it is obvious that the protection from damage is of paramount priority, any machine can only serve its purpose if it can be operated. Beam time at the XFEL will be in high demand, and the goal should be to limit downtimes to their necessary extent. In this respect, it is of no importance whether downtimes are caused by hardware failures or operating errors; the MPS should be both highly reliable and "user-friendly".

Failsafe Behavior

Since most of the MPS electronics will be located in the accelerator tunnel, an elevated radiation background must be expected. An analysis on the behavior of FPGAs has been carried out at DESY [1] and shows that neutron-induced single event upsets (SEUs) are the major source of malfunctions. Therefore, the design of the electronics should ensure as far as possible that SEUs do not lead to unsafe or uncontrolled behavior of the system. Problems caused by power cuts or simple cable breaks must also be considered.

Reaction Times

In the XFEL, the distance from the injector lasers to the last undulators is approximately 3 km. Thus, at the speed of light, a signal needs about 10 µs to travel from one end to the other. Since the bunch frequency of the XFEL is 5 MHz, a maximum of 50 bunches could be moving within the accelerator at any given time.

Table 1: Minimum Number of Lost Bunches at Various Locations, According to Reaction Times of MPS, Assuming a Signal Velocity of 2/3 c

Beam loss location	**Distance from injector**	**Distance from dump kicker**	**min. num. of lost bunches**
Injector	0 m	–1970 m	0
bunch compr. 1	160 m	–1810 m	7
bunch compr. 2	360 m	–1610 m	15
linac center	1040 m	–930 m	44
linac end	1650 m	–320 m	69
beam distribution kicker	2010 m	40 m	2
last undulator	3010m	1040m	44

From this follows that, if beam losses are detected near the end of the machine, at least 100 bunches carrying a total energy of about 2.2 kJ would arrive at the position of the loss before the injector laser could be switched off.

To reduce this reaction time, the MPS clearly needs a second location for disposing the beam. The dump kicker, part of the beam switchyard at about 2.1 km along the machine, is the natural choice for this interaction. Table 1 lists the minimum possible reaction times and the minimum number of lost bunches at several possible locations of MPS alarms.

MPS ARCHITECTURE

The large scale of the XFEL imposes a severe technical issue: latency of electronics and signal transport speed of 3/4c in copper cables and 2/3c in optical fibers lead to a signal delay and in consequence additional lost bunches. To provide a short reaction time, the MPS implements a distributed Master/Slave architecture keeping short distances between components. Also every Master/Slave does a pre-processing of all incoming alarm signals that we have a here a real distributed system with distributed processing units.

The optical fibers are planned in a way that a set of fibers connects each RF section (4 cryogenic modules, 1 klystron) to the injector building XSE. Various points in the undulator sections are connected to the hall XS1, fiber sets from the experimental stations are collected in the hall XHEXP1. There are fiber connections between XSE, XS1 and XHEXP1. Each of the RF sections will be equipped with 2 MPS modules (Figure 2). Loops in the bunch compressors and SASE sections will contain 3 to 5 MPS modules.

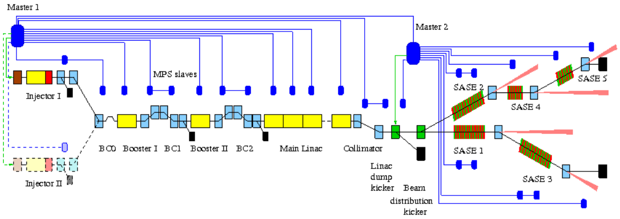

Figure 2: MPS distributed in XFEL.

The backbone of the XFEL Machine Protection System consists of roughly 130 MPS slave modules distributed along the machine. Each of these modules has digital inputs for "beam OK" signals from critical subsystems, accelerator components, or beam loss detection hardware. It also has fast serial input and output ports to connect to other MPS modules; to avoid problems with electromagnetic interference, these serial connections use fibre optic cables.

All modules are developed to provide high flexibility. They could be used as an intelligent data distribution knot, as standalone knot or just as a simple data collector, with single or redundant communication links.

Two master modules are located near the injector and near the linac dump kicker (Figure 2). The FPGA logic of these "MPS masters" defines the behavior of the system.

They have direct connections to the injector lasers and to the dump kicker, allowing them to stop the production of new bunches and to dump bunches that are already in the machine. Both Masters are working very close together and can be seen as one Master. The latency between the two masters is negligible, as both masters have different tasks and the information interchange is only informal.

Referring to the XFEL Timing System [2], the complete MPS system is working asynchronously.

The serial connections between MPS masters and slaves form loops carrying a steady data stream. Within reasonable limits, the number of loops connected to each master can be chosen freely, while the number of slave modules in each loop is limited mainly by the desired latency of less than 1 µs excluding cable delays.

Simulations have shown that with current FPGA technology, the input latency per board is in the range of 42 ns (RS 422 input → FPGA).

Due to the used structure, the system is also easily scalable without major cabling work as of new slaves could be added to existing knots.

INTERFACES

The MPS slaves receive digital status signals from external systems via RTM / RS422 signal lines and information of the Timing System via the µTCA backplane. A cable break or short circuit within the RS422 lines will be detected and reported as an alarm without distinguishing between real alarm or cable break.

The main MPS master is connected to the Timing System to provide the information about possible Beam Modes (Figure 3) and Section patterns (Figure 4). Beam Modes representing the maximum allowed bunches and power within the linac sections (1 Bunch, single, medium, full). Section Patterns are showing the health status of sections. Also, since MPS slaves and masters constantly communicate with each other, this communication is watched by special algorithms to guaranty a failsafe operation.

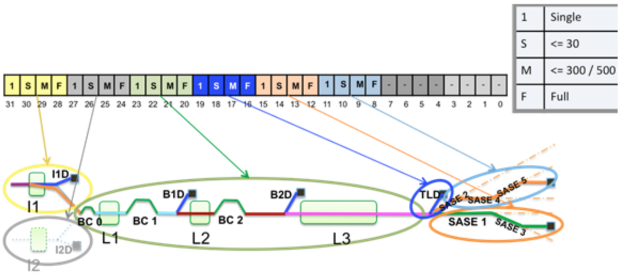

Figure 3: XFEL Beam Modes.

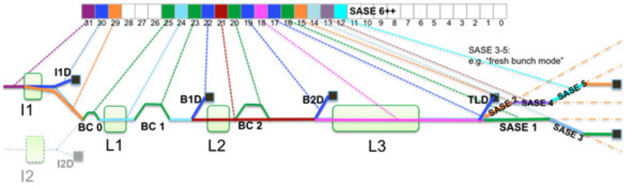

Figure 4: XFEL Section Patterns.

All incoming alarm signals are handled equally. There is no difference between slow (e.g. relay) or fast (e.g. electronic) signals.

µTCA TECHNOLOGY

MPS as most of the control components of XFEL will use the µTCA technology for the following reasons:

- Modular + modern architecture
- Reusability + PCIe + Ethernet
- High availability
- Redundant power and fan optional
- Well defined management protocoll
- High performance:
    - Very low analog distortions
    - 4 lanes PCIe: 400 MB/s ... 3.2 GB/s

XFEL fast electronics will be based on MTCA.4: with more than 200 Crates [3]

HARDWARE

The Master and Slave stations are equipped with the DESY DAMC2 (FPGA, PCIe, SFP) board and the appropriate Rear Transition Module (RTM) (galvanic separated RS422 IOs).

This strategy offers a large flexibility in case of technical problems as the DAMC2 is used everywhere inside the XFEL and MPS will take profit out of external developments, soft- and hardware wise. To receive digital alarm signals at DAMC2, a Rear Transition Module (RTM) has been developed for MPS. A schematic diagram is shown in Figure 5.

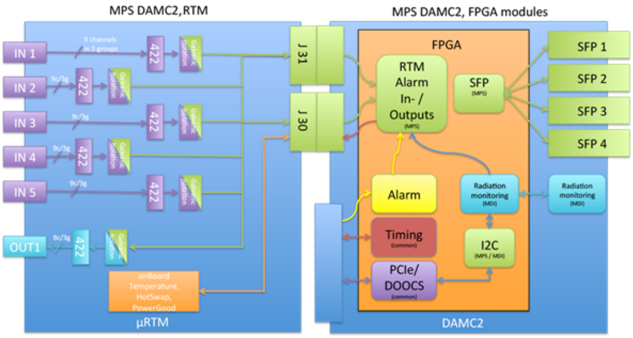

Figure 5: DAMC2 and RTM structure.

DAMC2 The DAMC2 board of Figure 5 has been developed by DESY and is equipped with a VIRTEX 5 FPGA. The documentation is available at DESY FEA group.

Figure 6: DAMC2 board.

MPS RTM The MPS RTM, shown in Figure 7, is the interface between RS422 in- and outputs and the DAMC2 board. It is developed at DESY and fulfills all requirements to be used with the DAMC2. The latency of an input signal from RTM to the FPGA of the DAMC2 has been measured with 42 ns per channel [4]. See also Figure 8 for more latency info. This has been measured in August 2013 and will be approved.

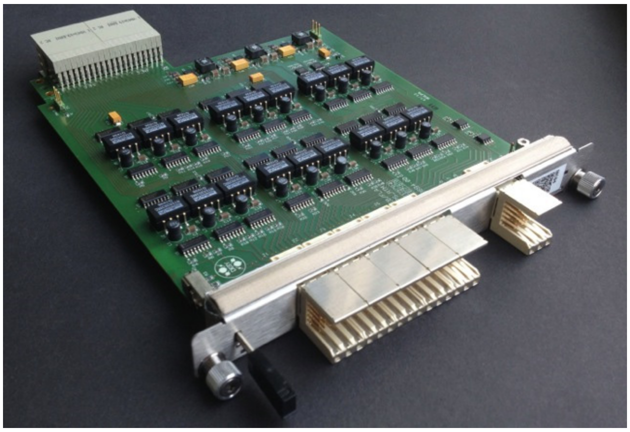

Figure 7: MPS RTM module.

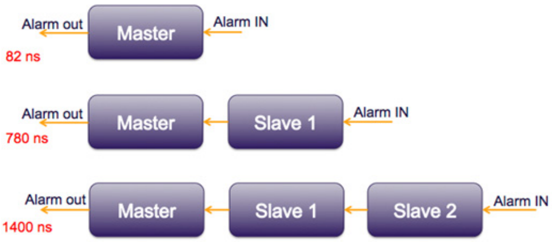

Figure 8: Latency measurement of several combinations of MPS modules.

CONTROL SYSTEM

The XFEL MPS is embedded inside the DOOCS control system [5]. DOOCS provides all necessary instances like GUIs, data logging and archiving, server functionality and other overlapping functionalities. DOOCS is used as interface for MPS configuration. It is not integrated into the safety-relevant process of the MPS. The MPS is running 100% self-reliance, if the connection to DOOCS is broken.

FINANCIAL ASPECTS

The importance to realize and design large facilities within a clear financial budget is evident. The amount of manpower and maintenance costs has to be taken into account from the beginning of every new project. For MPS it was calculated with 3 persons for the development phase and 2 persons for installation and running period. To achieve this goal, the MPS group has chosen existing hard- and software from the existing infrastructure. The only development of strictly necessary hardware inside this project is the µTCA RTM. The firmware in all MPS DAMC2 modules is the same, the additional maintenance is reduced to a minimum.

As basic idea of the whole concept, the International Linear Collider (ILC) is the force behind the design with an order of magnitude more units.

GLOSSARY

Macro-pulse

A shot in the linac of a train of electron bunches with duration of up to ~600 µs plus the filling and decay time of the cavities. Usually repeated every 10 Hz

Beam Mode

It defines the maximum number of bunches permitted per macro-pulse in a section of the accelerator. The MPS grants the mode by reading the machine settings and interlocks.

Section Pattern

Every bit in the pattern describes the status of a subsection. If the bit is set to '1', beam is permitted within this subsection

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[4] S. Karstensen, Function and Latency test at MPS-RTM, September 2012
[5] http://tesla.desy.de/doocs/doocs.html