PROTECTION MECANISMS FOR A HIGH POWER ACCELERATOR

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ABSTRACT

At the Paul Scherrer Institute, we run a high intensity proton accelerator with a final energy of 590 MeV and with a beam current of up to 2 mA. When handling a beam of over 1 Megawatt power, the protection and control mechanisms of the facility become crucial and require reliable protection mechanisms as well as appropriate diagnostics and controls. In particular the high dynamic range needed for currents between less than 1 and up to 2000 µA is a big challenge for the beam diagnostics and has to be accounted for by the control system.

Here we present what has been done to successfully protect the facility through our Run Permit System with its associated devices and controls software. Some recent improvements triggered by failures of the system will be presented too. We will also outline some difficulties in the operation of the facility and the solutions that have been adopted.

INTRODUCTION

In order to run successfully a high intensity accelerator some key problems have to be solved. These problems are situated in several domains and span from physical to technical issues.

One of the main technical problems is to avoid severe damage to the facility. For this purpose a complex system has to be implemented that can fulfil this requirement. In case of a beam hitting the vacuum chamber or other components like septa or collimators, damage may be caused already within a few milliseconds (Fig. 1). The consequences of damage in complicated parts of the facility (e.g. in the Target E region) could be that the beam production has to be interrupted for a period of up to one year.

The machine protection system therefore plays a key role. We will discuss the implementation and philosophy of this system in further detail.

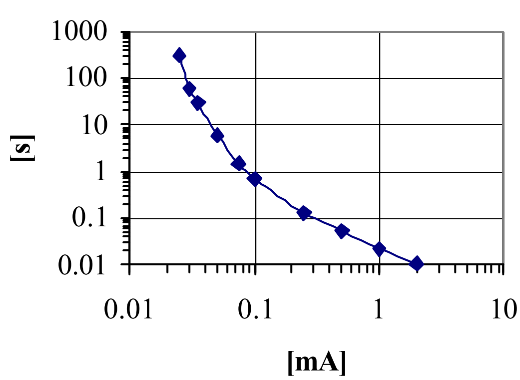

Figure 1: Time for melting steel at E=590 MeV for a beam with sigma = 1mm [1]

Another problem, worth to be mentioned, is the need to be able to measure the beam position at any current (from 100 nA to 2000 µA) in order to align the beam. The required high dynamic range is a great challenge for the beam position monitoring system, in particular in view of the electronically noisy environment.

To produce as high a beam current as possible, with losses as low as possible, in order to protect the facility and to avoid activation as much as possible is of course a challenge where many things come together. We do not only have to care for the problems mentioned above, but also clearly need the right tools and diagnostic systems. [2].

THE RUN PERMIT SYSTEM

Requirements

The run permit system (RPS) has to be able to switch off the beam in a few milliseconds to prevent damage. This means that all the devices connected to it as well as the RPS logic hardware have to react in the sub-millisecond range. Of course, beneath this requirement, we have additional constraints:

- The system must be **highly reliable** in order to keep its availability and its functionality as high as possible. It has to meet a high safety standard, but it should also allow beam development, i.e. special operations where some RPS elements are disabled, etc.
- Besides the immediate goal to prevent damage, the RPS should switch the beam off when the losses exceed a particular level in order to keep the **activation** of the components as low as achievable.
- Since we deal with many modes of operation in our facility (beam splitting mode, beam dump mode, spallation source mode, isotope production mode, low and high intensity modes), the RPS has to be **reconfigurable**, geographically and logically.
- The RPS should make a check for the **consistency** of the wiring between the modules and it should indicate disconnected signals and shorts in cables.
- To solve the timing problem of the occurring events, the system has to be **deterministic**. For example we need to know if an accelerating cavity triggered the switching off of the beam, or if the beam load has disappeared by another event, provoking thereby a trip of this cavity.

Very important is, of course, the know-how of the experts in all disciplines (machine, diagnostics, operations) to bring the system to the required protection level without compromising the availability of the facility.

Realization

The system is actually realized through a tree of many (ca. 150) interconnected modules [2] reacting on about 1500 primary signals connected to these modules. Many of these signals are provided by “intelligent” equipment, which generate a stop signal in case of a non-appropriate condition. The RPS with its modules, as well as most of the equipment connected to it, is developed in house.

The above-mentioned hardware is mostly based on CAMAC modules, but a series of VME equipment has already been developed and deployed for the PROSCAN project and the new elements will also be implemented in the high intensity proton facility.

The new RPS hardware is composed of the Industry Pack Carrier Board (IPCB) of the VICB8003.3 VME64x type connecting up to four Run Permit System IP’s (RPSIP) and of the RPS Transition Board. Every RPSIP is connected via RPS Transition Board to ten physical 3-wires I/O-ports, two of which are hardwired as inputs and the remaining eight can be firmware-configured as IN or OUT. One RPSIP supports up to 16 input channels and up to 8 output channels (Figures 2 and 3).

Input channels are sourced either from physical IN–ports, or from the internal bus between RPSIP’s (up to 21 lines), or from the IPCB via IP–Bus. The mapping of inputs sources to the 16 input channels is defined by RPSIP–specific firmware configuration. The eight output channels can drive either physical 3-wires OUT-ports or the internal bus lines. The mapping of output channels is the matter of RPSIP–specific firmware configuration.

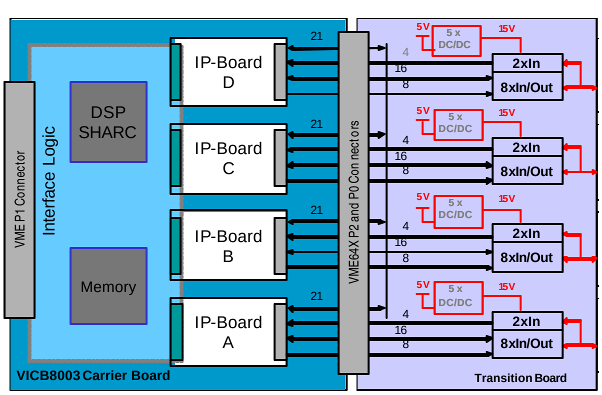

Figure 2 : HYTEC carrierboard with DSP

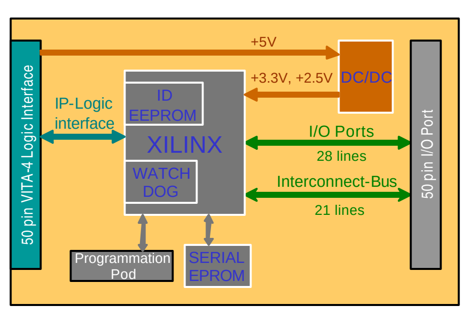

Figure 3: RPS IP-Module

The Run Permit System Module (RPSM) has been designed using the Mentor Graphics FPGA Advantage development system including the ModuleWare library. Before the module is used in the accelerator control system, it has to be configured to meet specific requirements regarding:

- RPSM identification and XILINX download check.
- Activation of input and output channels.
- Connections of signals to input and output channels.
- Signal conditioning and timing.
- Input/Output functionality.

A RPS Module can be considered as a set of configurable library modules complemented with a specific logic module. These, when compiled, compose a Xilinx configuration file to be downloaded to a serial PROM.

The RPS hardware is constantly monitored in the control room on an operators console showing the state of the facility and all the signals (primary signals as well as all the interconnections). In case of a switch off the events are displayed. The software also triggers the automatic switching on of the beam. In case the automatic mode has been selected by the operator and in case of a resettable error signal, it will perform a chain of actions to switch the beam on again, which is provided with a soft ramping up of the beam current.

Devices

Many devices with local intelligence are connected to the RPS in contrast to simple devices like temperatures, valves, water flow devices and position switches. These devices will generate the appropriate signals depending on the combination of a bunch of conditions (interlock signals). We will mention here the most important ones we are using:

- **Beam loss monitors:** the losses in the facility are measured by about 110 ionization chambers. These will switch the beam off when the loss level exceeds some predefined value. They also switch the beam off when the losses integrated over time exceed another predefined value above the warning limit.
- **Collimators:** we have about 80 of these collimators in our facility. These elements also generate interlock signals as well as warning signals. They are used for beam collimation, protection of sensitive elements or for "Halo" detection.
- **Transmission monitors:** only a few of these are installed: they locally calculate the transmission by comparing the beam current at two critical spots. A switch off will be generated when the balance is incorrect. This kind of monitor is also used to prevent the beam from bypassing the main thick target, where the fraction of beam lost should at least be 30%.
- **Settings of bending magnets:** a window checking the setting values for the allowed interval is implemented directly in the bending magnet controllers to prevent severe missteering. For values outside this window a hardware interlock signal will be generated by the VME board and passed on to the RPS in order to switch off the beam. While the loss monitors do not stop the beam due to the shielding of the radiation provided by the iron yoke, by this check we can still avoid the beam hitting the vacuum chamber.
- **Setting of quadrupoles, steering and bending magnets, voltages, …**: In various controllers we implemented also a safety function, which locally compares the actual value of the magnet current with the required set value.

DIAGNOSTICS AND TOOLS

Devices and tools

Many of the diagnostics and tools have already been presented in previous papers. Therefore we will focus here on some specific problems that arise in our facility and on some tools we are currently using. As has been mentioned before, we need the appropriate diagnostics in order to measure meaningful values of the beam parameters. We need them from small beam currents up to the high beam currents. The most important diagnostic elements we have to rely on, are the following devices:

- To measure the **beam losses** (ionization chambers, collimators) for the RPS and the online display of them. The display of these losses is also very important to give the operator an appropriate feedback for minimizing the losses. Through fine-tuning of the machine setting using "knobs" the operator can then master the ever-changing beam halo.
- To measure the **beam phase** at different locations inside the cyclotrons and between them. These measurements must be accurate and are used to get the facility into operation as well as for a stable production beam. To correct drifting of these phase values and in case of perturbations (for example, the influence of the overhead crane in the experimental hall is noticeable and perturbs the beam phase of the main ring cyclotron) we feed them through an automated correction loop.
- The **beam profile monitors** and **halo monitors** are mainly used for accurate measurement of the beam characteristics and are thus very important to get information about beam envelopes and beam tails.
- The **beam position monitors** (BPM) are used for automated beam steering. These are the most important diagnostic devices in our facility. A high intensity beam can only be produced by correcting the beam position with an automated feedback mechanism that will account for any trajectory change.

Figure 4 shows the automated beam centering utility for the 72 MeV beam line. The operator has the full control over all the parameters involved in the centering. Not only the wanted beam position can be finely adjusted but also the PID parameters of the centering process and the threshold for the process to be activated (Veto).

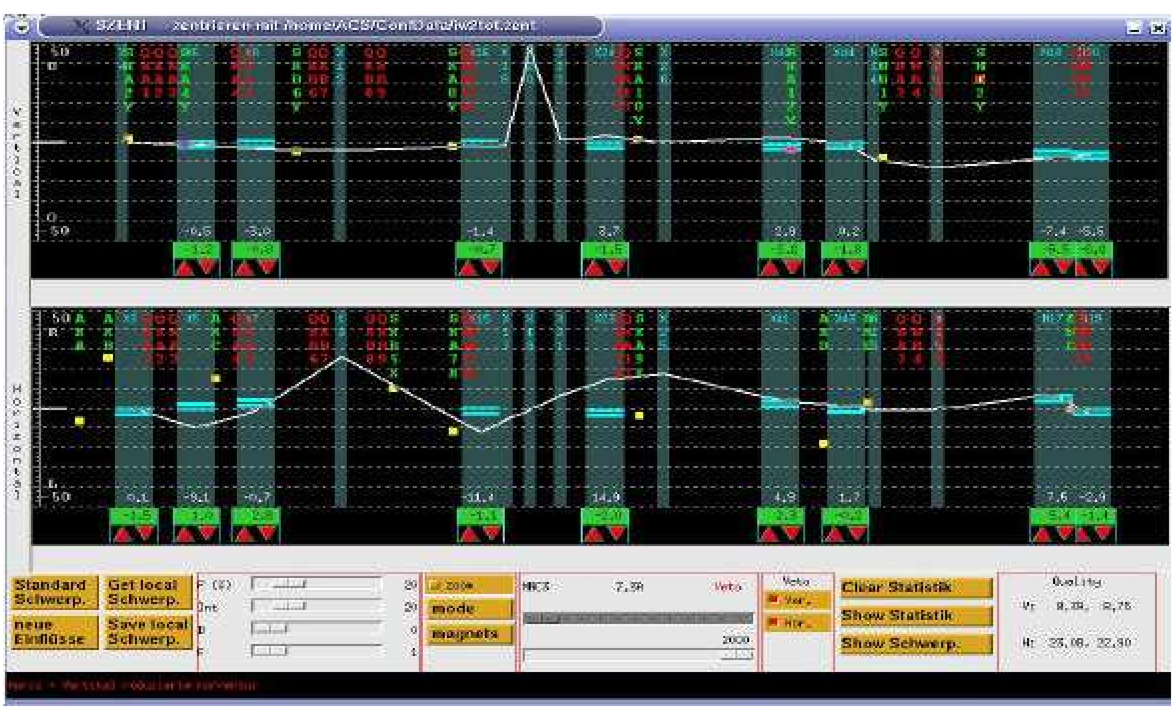

Figure 4: Automated centering utility showing in the upper part, the vertical beam position and in the lower part the horizontal beam positions

Difficulties

The beam can be well controlled with the centering utility, however, as we pointed out in the introduction, the beam position monitor electronics does not allow measuring the beam positions for currents below 5-10 μA.

During the ramping up of the beam current to the nominal production current, the trajectory of the beam gets heavily off-centered in the beam pipes. This is mainly due to changing space charge effects [3] as a function of the beam current, but is also caused by the way we regulate the beam current. Because, at low currents we cannot compensate for this with the centering utility, we would generate a switch off when the beam would hit some element (in our case it is often the injection element of the ring cyclotron). This can be seen in Figure 4, where the trajectory of the beam (white line in lower part) shows the beam up to 25 mm off-center for a current of 7 μA, whereas it would be well centered at 1800 μA.

In order to overcome this difficulty, a small feed-forward utility was provided where the operator can set some values for specified currents. This way an approximate trajectory can be defined for the low currents. But even with this approach, beam time can be wasted when trying to find appropriate values. Therefore new electronics having the necessary dynamic range are being developed now.

IMPROVEMENTS

In despite of the robustness of the system, a major damage of the facility last year, due to a defect in the RPS system, motivated us to improve the system further on. While we do not want to rely any more on a single hardware path to switch off the beam, we implemented therefore in last shutdown a second beam switch off path to the system. This second path contains a duplicate of the beam transmission signals and has to give the same count of interrupts due to transmission failures.

Beside this improvement, the software was extended to check the RPS interconnections as well as any errors or mode errors, signaling them to the operator. With the introduction of the new VME-Hardware some more improvements will be implemented:

- **Mode-dependent bypass disable:** bypass of RPS connections are now mode dependent
- **Hardwired validation of write commands:** write and complement write to enhance security of write commands

As has been mentioned before, in order to successfully run our accelerator, other equipment has to be improved as well. In particular the beam position has to be detected for currents much below the present lower limit of the electronics. This will hopefully happen in the next few months.

CONCLUSION

To run a high intensity facility, where a small problem can lead to a major damage and therefore to longer interruptions for repair, a performing and safe run permit system is necessary. The philosophy applied in PSI meets these requirements and the implementation has demonstrated its success. However, care has to be taken, that the above-mentioned devices detecting beam loss and their limiting values have been set up properly. As the main problem in our facility is the turning on of the beam after a longer switch off, we have to continue to improve the mechanisms described above.

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