CONTROL AND PROTECTION ASPECTS OF THE MEGAWATT PROTON ACCELERATOR AT PSI

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Abstract

At the Paul Scherrer Institut a high intensity proton accelerator complex is routinely operated with a final kinetic energy of 590 MeV and with a beam current of 2.2 mA. In the future the beam current will be increased to 3 mA, which will then result in a beam power of 1.8 MW. Operating a facility at such a high beam power needs not only a performing and fast protection mechanism against failures but also protection against activation of the facility. This presents a particular challenge for the beam diagnostics since a high dynamic range of currents has to be handled. This paper will present the machine protection system together with several tools, control loops and procedures which are of utmost importance for minimizing the ever present losses in the facility.

A new challenge for our facility is the new ultra cold neutron (UCN) facility, which will come into operation later this year and which will require the switch over from one beam line to another for a duration of 8 seconds at full beam power. Using a short pilot pulse of a few milliseconds the beam position is measured and the beam centered in preparation for the long pulse. We will show the diagnostics that are involved and how we overcome the constraints imposed by the machine protection system.

INTRODUCTION

Any accelerator facility producing an intensive particle beam has to consider, besides beam loss leading to activation of the facility, a partial or complete loss of the particle beam leading to severe damage to the facility (Fig. 1). In our high power proton facility circa 10 milliseconds would be enough to melt stainless steel with a wrongly steered beam [1]. This could potentially occur due to the failure of components like magnets, RF components or other devices. Therefore, a system has to be implemented to protect the facility by switching off the particle beam within a few milliseconds to prevent damage. The whole system consisting of the machine protection system (MPS) itself, the devices delivering the signals for it (sensors) and the actuators shutting off the beam should be able to suppress the beam in less than 5 milliseconds. This demands for the individual components of the system reaction times in the sub-millisecond range. Furthermore the beam diagnostic devices covering many aspects of the beam and facility components and connected to the MPS have to evaluate the beam conditions and react also within a few milliseconds. These will be described later. However, in order to keep the number of "beam offs" as low as possible and therefore maintain also the high availability of the facility some compromises, where applicable, have been taken. An example of such a compromise is the suppression of "beam offs" when an acceleration cavity reflects its power for a very short time (in the order of 500 μs). In addition to the fast behavior of the machine protection system, many other requirements have been defined for the necessary behavior of the machine protection system and will be presented later on.

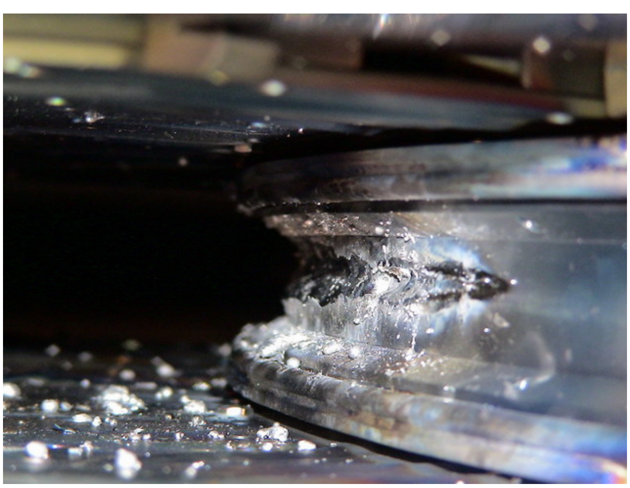

Figure 1: Cyclotron damage at injection, due to a lack of redundancy in the machine protection system.

This paper presents some aspects that have already been treated by previous papers, but tries to integrate these in a consistent way.

SAFETY PHILOSOPHY

Besides the protection of the facility against damage, many other systems are implemented. In our facility these systems comprise:

- Personal and radiation safety.
- Safety of the user facilities like the neutron spallation source (SINQ) or the new **U**ltra **C**old **N**eutron (UCN) source.
- Patient safety systems.

All these systems have as final goal the shut off the beam when detecting any problem. However instead of considering all the systems as a whole, our policy maintains a clear separation of the individual systems. Moreover for shutting off the beam different actuators, which are monitored by the MPS for their proper functioning, are used.

This separation of concerns is of utmost importance for the licensing of the facility. It is easier to describe and convince the Swiss authorities of the correct behaviour and safety of the individual systems when these aspects are completely separated from the other systems. Besides the behaviour of these systems, only the integration of the final actuators and their survey by the MPS has then to be described.

The actuators used at PSI are the first beam stop at the energy of 870 KeV, kicker magnets at 60 and 870 KeV used by the individual systems and in case of malfunctioning of these devices shutting down of the ion source.

MACHINE PROTECTION

Requirements

Beneath the requirement of the system to be inherently fast as has been mentioned above, a well designed machine protection should present several 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 be **flexible** allowing beam development, i.e. special operations where some MPS 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 MPS 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.
- The system should be highly **redundant** not only in respect to the devices protecting the facility, but also in respect to the internal paths in the system as well as a high redundancy in the actuators shutting off the beam.
- **Local intelligence** at the devices, that nowadays can be easily integrated, will give a still higher level of safety and will be described in the devices section of this paper.

Very important is, of course, the know-how of the experts in all disciplines to bring the system to the required protection level without compromising the availability of the facility. Therefore special mechanisms have to be introduced as will be mentioned in the next section.

Devices and Mechanisms

Many devices with local intelligence are connected to the MPS in contrast to simple devices like temperatures, valves, water flow devices and position switches [1]. 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 (Fig. 2). 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, therefore limiting the activation of the facility in case of too high losses. Another feature integrated in the logic of the electronics is a dynamic window representing a low and high limit as function of the beam current. This prevents from too high losses as well as to low losses as function of the beam current during the ramping up. A possible malfunctioning of the device or a beam loss before the monitor can also be detected. Figure 3 shows for the target E region the actual losses, the limits and the limits given by the dynamic window.

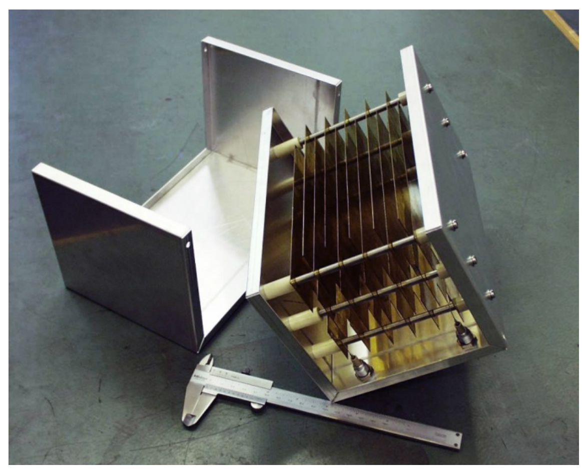

Figure 2: Ionization chamber for measuring beam losses.

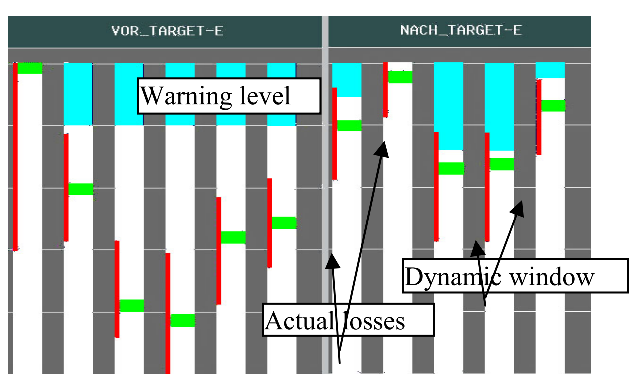

Figure 3: Loss display with fixed and beam current dependent warning and interlock limits.

- **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. The electronics will also check the balancing of the currents on each segmented foil and is also used for a correct positioning of the beam. An example of a 200 kW collimator with segmented foils can be seen in Fig. 4.
- **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%. These monitors use a rather complicated validity window (Fig. 5) taking into account the more complex situation at the beam targets [2].
- **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. In case 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.

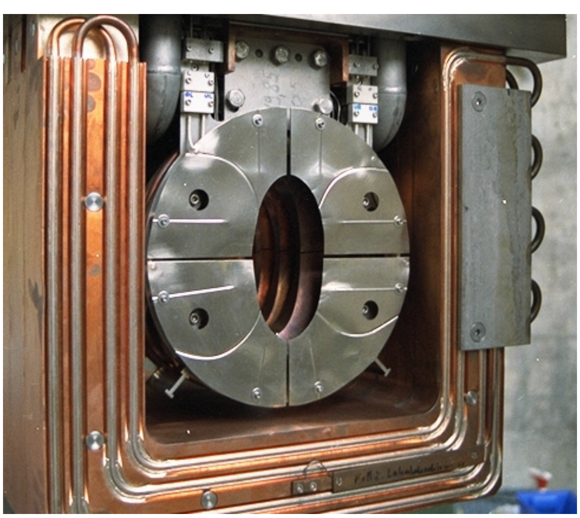

Figure 4: Segmented asymmetric collimator with readout of the four segments for measuring the currents.

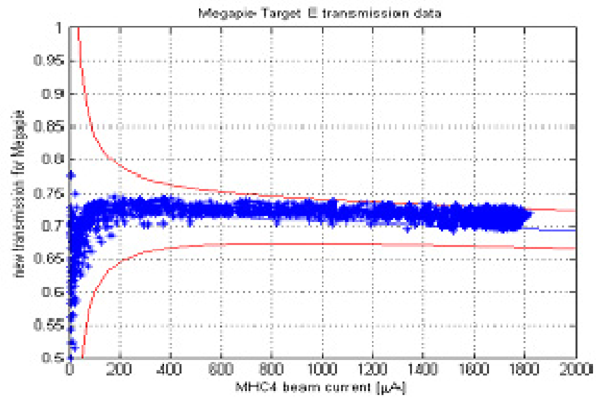

Figure 5: Validity window for the Target E transmission.

OPERATIONAL TOOLS

Minimizing the beam loss is essential in any accelerator facility. To achieve this, first a performing loss monitoring system has to be present. We use for beam loss detection, ionization chambers and collimators. **Ionization chambers** as the main beam loss monitors are simple and reliable devices and their signal scales linearly with the losses over a wide range of amplitude. Tuning the beam losses to a minimum requires optimizing many different parameters and the issue is not only how well this can be done, but also how fast. Naturally the skill of the operators may differ and the control system should give them with appropriated tools an optimum aid. One of the important tools at PSI is the losses display (Fig. .6), where the operator will be presented red (when higher losses) or green changes (when lower losses) against a reference. The reference can be taken over at any time from the existing losses and is normally taken when the losses get more minimized. By twiddling the machine parameters, the operator will reduce the losses to a minimum. In principle automatic learning applications could take this problem over, but introducing such applications would ask for a big effort and where the success is not assured, while dealing with a multidimensional space with local minima and while during the process tripping of the system has to be prevented.

Other tools of interest for optimizing the losses are measurements using appropriate diagnostics. In a cyclotron environment the internal phases as well as precession at extraction have to be tuned to obtain the cyclotrons best setting. Measurements and calculated corrections will lead to more or less losses shown by the loss display tool and the operator will use this information to obtain the best possible parameters. Another important tool is the automatic beam centering tool. With this tool the operator has the possibility to optimize the beam trajectory and minimize losses in the beam line as well in the cyclotrons by correctly injecting the beam [2].

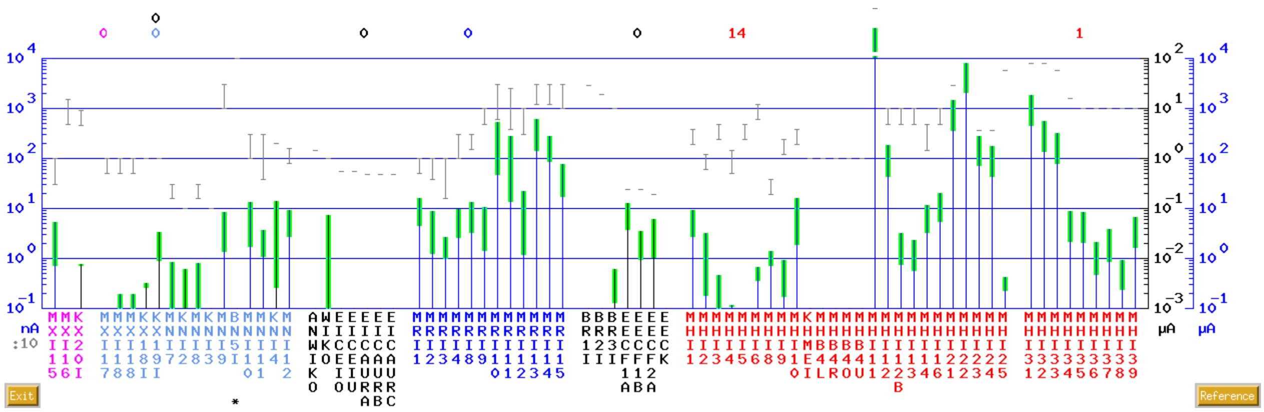

Figure 6: Beam losses display showing a reference with the actual losses as green or red change to this reference.

NEW CHALLENGES

Increase Beam Current

To further increase the beam current up to 3 mA (i.e. up to 1.8.MW of continuous beam) demands besides upgrading key elements of the facility like the inj2 resonators and the Collimators after the Target E [3]:

1) a careful operation of the facility and
2) a performant machine protection system.

The first point can be fulfilled with well designed operation tools and the knowledge and skill of all actors. The second point demands the integration of more and more devices with local intelligence and solutions dedicated to special situations (eg. MEGAPIE in the past and UCN in the future).

New Project UCN

A new project at PSI is in development and will probably be taken into user operation after the yearly shutdown of 2011. This project, called UCN, consists of a powerful ultra-cold neutron source producing its neutrons on a **spallation target** driven by the 580 MeV, 2.2 mA beam of PSI's proton facility. The proton beam which is normally directed to the main targets and spallation source SINQ will be switched over to the new beam line for UCN by means of a fast kicker magnet with a rise time of the order of 1 millisecond and with duration of 8 seconds every 800 seconds. Before this long pulse, a pilot pulse of duration of 5 milliseconds is sent to check the beam position in the beam line and to perform an eventual correction of the trajectory [4].

Due to the switching between the two beam lines high beam losses are produced during the transition. While this is detected by our machine protection system through the ionization chambers the beam would be turned off. To prevent this intervention of the machine protection system during the transition we have implemented a precise time scheme where at the beam transition the threshold of the ionization chambers are raised for 3 orders of magnitude for 3 milliseconds.

Since the beam transmission monitors "beam off" detection mechanism operates on a relatively slow (10ms) timescale, the transition is too fast to be detected and therefore does not cause problems during beam switching.

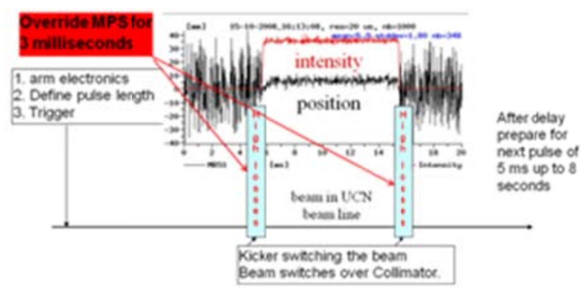

Figure 7: View of the timing system; during switching of the beam, the beam losses are raised by 3 magnitudes.

CONCLUSION

The PSI high intensity proton facility runs with over 1 MW of beam power. This order of magnitude of beam power demands special solutions for protecting the facility against damage and activation. We have proven that we can successfully fulfill these constraints by a careful design of the facility, a very performant machine protection system and diagnostic devices. Furthermore careful tuning of the relevant parameters, the support by excellent diagnostic tools and an efficient control system are important for successful operation.

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