CONTROL OF A 1 MW BEAM

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The handling of a beam power of over 1 Megawatt is a big challenge for the beam diagnostics as well as for the control system. Particular problems arise from the high dynamic range of currents between less than 1 μA up to 2000 μA. We will present what has been done from the operational and control system point of view to successfully produce a beam of that power and emphasise the problems that had to be solved. Ideas for further improvements of reliability and smooth operation of the facility will be outlined as well.

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 problems.

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 a damage in critical 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.
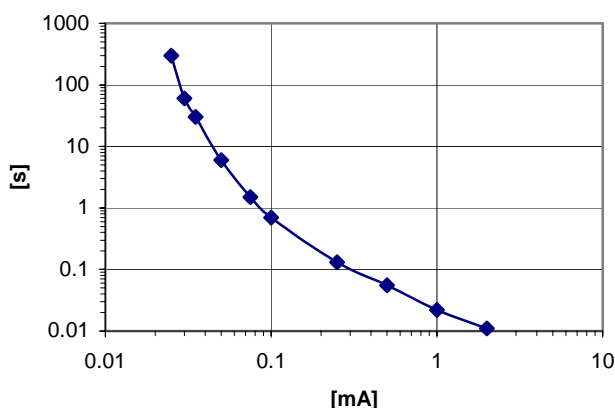

Fig. 1: Time for melting steel at E=590 MeV for a beam with sigma = 1 mm [1]

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

Another problem, worth to be mentioned, is the requirement 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.

The problems that bothers all cyclotrons with electrostatic injection and extraction elements and accelerating cavities are the RF and high voltage discharges. A discharge of such an element causes perturbations in the beam trajectory which leads to the

need to switch off the beam. We will discuss this problem and some strategies to reduce its effects.

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 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, and it must be able to run in special modes, 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 low.

- 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 broken 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 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 done by a soft ramping of the beam current.

Devices

Many devices with local intelligence are connected to the RPS in addition to simple devices like temperatures, valves, water flow devices and position switches. These devices will generate the appropriate signals depending on the appropriate logical. 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 in our facility. These elements also generate interlock 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 be at least 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. This way we can avoid the beam hitting the vacuum chamber while the loss monitors do not stop the beam due to the self-shielding of the radiation provided by the iron yoke.

- **Settings 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.

The above mentioned hardware is mostly based on CAMAC modules, but a series of VME equipment has already been developed. This was mainly done in view of the PROSCAN project; the new elements can now also be implemented in the high intensity proton facility.

DIAGNOSTIC DEVICES AND TOOLS

Devices and tools

Many of the diagnostics and tools have already been presented in previous papers [3]. 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:
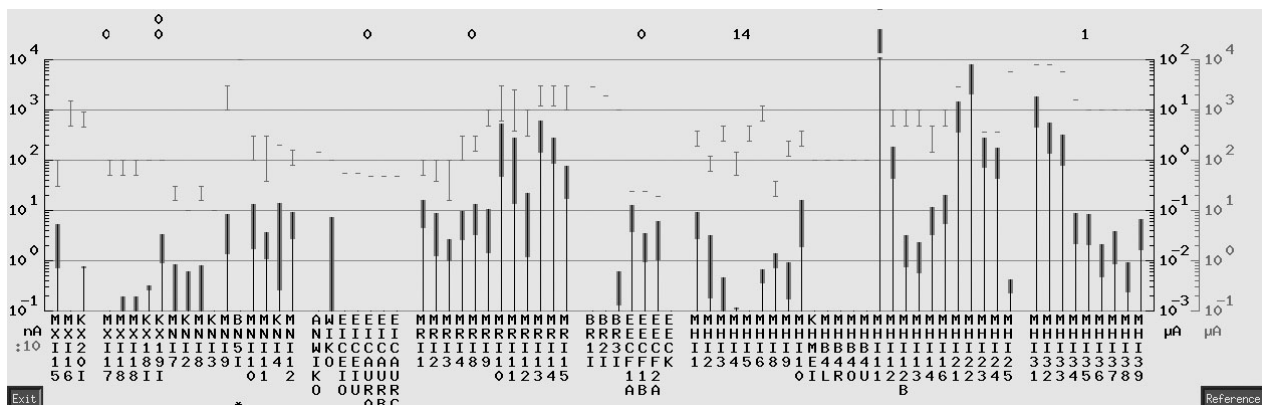

Fig. 2: Beam loss display, this representation of the losses uses a reference set selected by the operator at high beam intensity. The actual losses appear as green or red bars indicating the difference to this reference.

- To measure the **beam losses** (ionization chambers, collimators) for interlock and display purposes. The display of these losses is also very important to give the operator an appropriate feedback for minimizing the losses (Fig.2). 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.

Fig. 3 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).

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 changes significantly. This is mainly due to changing space charge effects [4] 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 Fig. 3, where the trajectory of the beam (black line in lower part) shows the beam up to 25 mm off-center for a current of 7 μA, whereas it is well centered at 1800 μA.
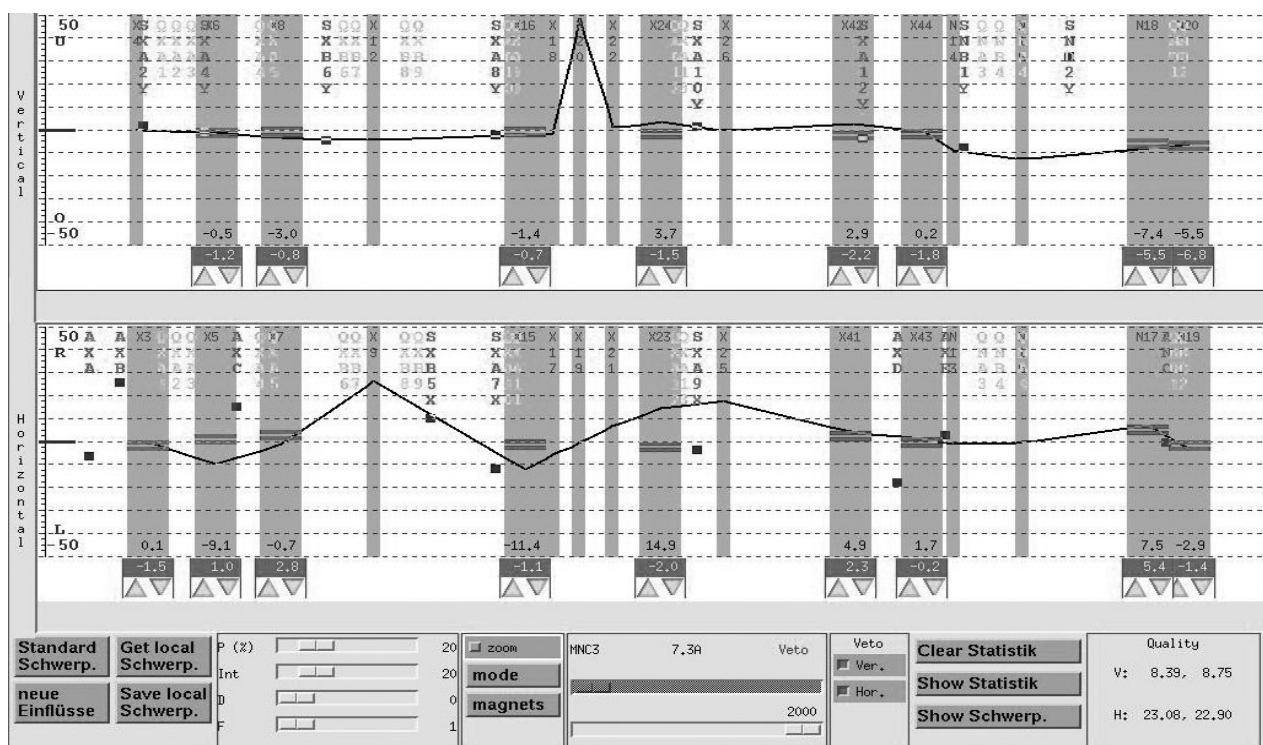

Fig. 3: Automated centering utility showing in the upper part, the vertical beam position and in the lower part the horizontal beam positions

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, but for very low currents below 0.5 µA the feed-forward utility will still be necessary.

DISCHARGES

Many short interruptions in the beam production are caused by the electrostatic high voltage devices in our facility. The accelerating devices and the septa inside the cyclotrons cause a switch off by the RPS whenever a discharge occurs. These beam trips reach from 300 trips/week to 2000 trips/week depending on the state of the septum devices. In case of the accelerating cavities, most of the sparks have a duration inferior to 500 µs, so that we could decide not to turn off the beam [4]. Of course, in case of a longer spark, the cavity has to be turned off and the beam switched off.

IMPROVEMENTS

While we cannot avoid the previously mentioned discharges and therefore the beam trips, we have to improve the reliability of the ramping procedure or find other methods to overcome a short discharge. The following measures are under consideration:

- Improvement of the ramping procedure:

  1. 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.

  2. We will modify the motor driver of the phase selecting collimator, in order to make its closing and opening times shorter. This would reduce the actual dead time of 10 seconds in the recovery procedure. The bending magnets have of course to follow the faster ramping. We can overcome this, when we allow initially 100 µA to be accelerated. We can then ramp the beam current up in about 10 seconds. A faster ramping up is excluded by thermal effects in the spallation neutron target.

- Short beam interruption: the beam could be kicked out at 870 KeV for some short period (<1 s, rise time about 1 ms). A power supply with these characteristics should then be installed and connected to an already existing kicker magnet. We would probably have to limit the current to about 200-300 µA when switching back, because the amplitude control of the ring flattop cavity does not accept larger intensity changes performed in a step function.

- Another interesting possibility would be to limit the duration of the "non-availability" of these elements to the order of milliseconds by some major modifications in order to prevent the beam interruption. This works for the RF as mentioned before, but may be a problem for the electrostatic elements.

CONCLUSION

To run a high intensity facility, where a small problem can lead to a major damage and therefore to longer interruptions for repair, an efficient 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. Also the correct functioning of RPS has to be tested periodically.

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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