OPERATIONAL ASPECTS OF THE MEGAWATT PROTON ACCELERATOR AT PSI

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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 mA. In the future the beam current will be increased to 3 mA, then carrying, a beam power of 1.8 MW. Undesired beam losses in the accelerator chain are kept within the lower 10^{-4} range. Operating a facility at such a high beam power results in demanding requirements for the control system, diagnostics as well as the protection mechanisms needed to allow for a safe operation of the facility. We will describe the different aspects that are needed to successfully produce a high power beam and mention the problems that were encountered and had to be solved.

I. INTRODUCTION

Running a high intensity proton accelerator requires a careful design, optimized in view of very low average beam losses. Beam losses activate the accelerator components and make the servicing of the facility difficult. At certain locations, like cyclotron injection or extraction and target regions, where losses cannot be avoided, the design becomes of uttermost importance and scenarios of handling the components have to be developed. Besides the activation problem care has to be taken to avoid a severe damage to the facility by the high power beam. A fast and reliable machine protection system had to be implemented to ensure a safe operation. In case of the beam hitting a component or the vacuum chamber, damage would already be caused on a very short time scale of 5-10 millisecond range (Fig. 1). Such damage has severe consequences in complicated sections of the facility like the target region. Because of the high activation levels the repair work would be complicated and cause a long interruption of the operation.

Diagnostic devices like ionization chambers, collimators and current monitors as well as transmission monitors are essential for running the facility. The diagnostics and electronics responsible for detecting unacceptable losses and producing a "beam stop" in this case have to be extremely reliable. On the other hand a high dynamic range is required (up to 5 decades), because of the large range of accelerated beam currents that occur in practice.

Non intercepting beam position monitors (BPM's) are used for steering the beam to the center of the beam pipe and to an optimal trajectory for the injection elements of the main cyclotron. The desirable dynamic range covers currents from 100 nA during beam commissioning, up to the production current of 2 mA. These BPM's are essential for a fast and precise setup of the beam trajectory. A challenging issue is noise pick-up on the relatively long cables between BPM's and electronics. The long cables are necessary to avoid radiation damage of the electronics.

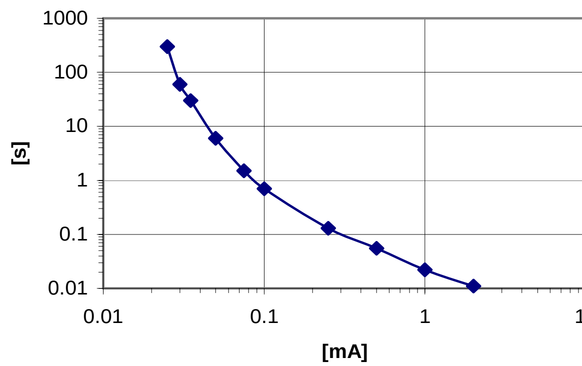

Fig. 1: Time for melting steel at E=590 MeV for a round beam with an rms width of 1 mm.

II. THE MACHINE PROTECTION SYSTEM

As mentioned before, the machine protection system must be able to switch the beam off within a few milliseconds to prevent damage. The system was originally realized in a version using CAMAC modules, but recently new VME modules have been integrated. The total number of signals which are constantly processed amounts to 1500. The system contains about 150 modules in a tree like manner. The requirement of switching off the beam in a few milliseconds demands for these modules to react in the sub-millisecond range. The beam diagnostic electronics generating a "beam off" signal reacts in a few milliseconds. The main diagnostic elements we rely on are the following:

Ionization chambers as the main beam loss monitors are simple and reliable devices (Fig. 2). Their signal scales linearly with the losses over a wide range of amplitude. Fixed limits for alarms and interlock triggers are implemented in the electronics as well as limits that are adjusted dynamically depending on the beam current

(Fig. 3). The electronics allows detecting losses exceeding the predefined level, but also losses that fall below a certain level, a case that indicates a possible malfunction of the device or a beam lost before the monitor. Besides reacting on the instantaneous loss rate the monitors will also switch off the beam when the time-integrated losses exceed a predefined warning level for a certain time. In this way it is possible to optimize the accelerator under temporarily worse conditions without losing the beam.

Besides the interlock functionality the loss display presents a sensitive feedback for the operator to optimize many parameters in the facility. In combination with customized “knobs”, i.e. control variables that allow to change several parameters simultaneously according to a predefined mathematical relation, a powerful tool for optimization is given to the operator.

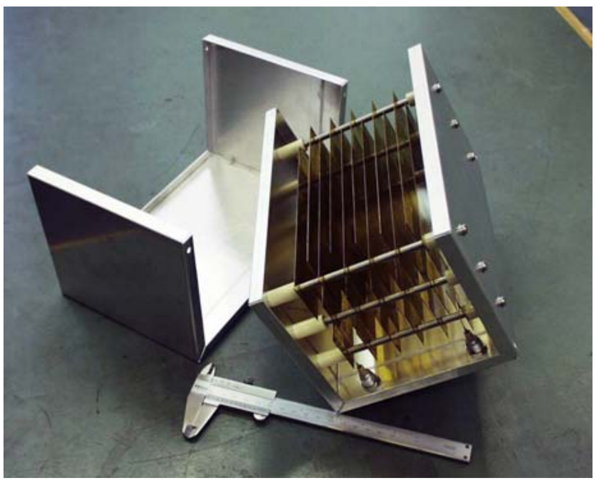

Fig. 2: Ionization chamber used as loss monitor.

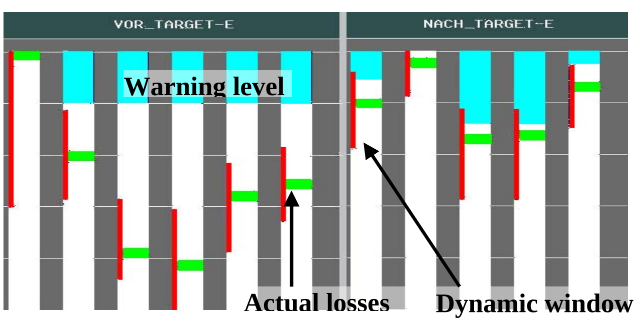

Fig. 3: Loss display with fixed and dynamic (beam current dependent) limits.

Segmented collimators allow to determine the scraped beam currents on left and right as well as up and down collimators. The asymmetry is used to center the beam in-between the jaws. Such a collimator is shown in Fig. 4. Many of these collimators are installed in the target region and in the beamline to the spallation target and are displayed to the operator in order to verify the correct centering of the beam.

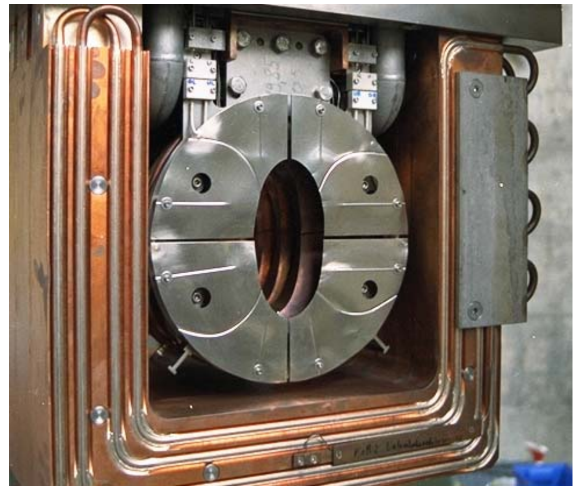

Fig. 4: Segmented asymmetric collimator with readout of the four segments for measuring the currents.

Current monitors measuring the beam current are used to verify the transmission of the beam through the Ring Cyclotron and the beam transport lines. The transmission measurement has to account for possible split-off beams, used to drive secondary proton beam lines. In this case three current monitors are used to verify the transmission. For the transmission on the Meson production target E [1], which consists of 4 cm graphite, the valid tolerance window is variable as a function of current (Fig.5). At high currents only small losses are acceptable and the relative resolution of the monitors is greatly enhanced, which leads to tighter limits. Furthermore the transmission changes slightly as a function of the beam current due to thermal expansion of material in combination with the collimation after the target. The correct scattering of the beam at the Meson production target is of great importance also for the safe operation of the SINQ spallation target. Because of cooling limitations the SINQ target can accept a maximum current density of roughly 50 $\mu A/cm^2$, i.e. the transverse beam dimensions should be kept above $\sigma_x \cdot \sigma_y = 6.4\ cm^2$. The beam emittance, on the other hand, is basically determined by scattering at the target E. If the beam would accidentally bypass the target, the beam density would be too high at SINQ. One of three interlock systems to avoid this scenario is based on the described transmission measurement, requiring the transmission through target E to stay below a certain percentage, as shown in Fig. 5.

The redundant layout of the machine protection system is very important. After damage to the facility which occurred in 2004 due to a defect in one of the critical modules of the system, we added an additional path for the beam transmission interlocks. In case of a failure in a module, the second path will still trigger a “beam off” and the operator will be warned of an off-normal behavior of the system.

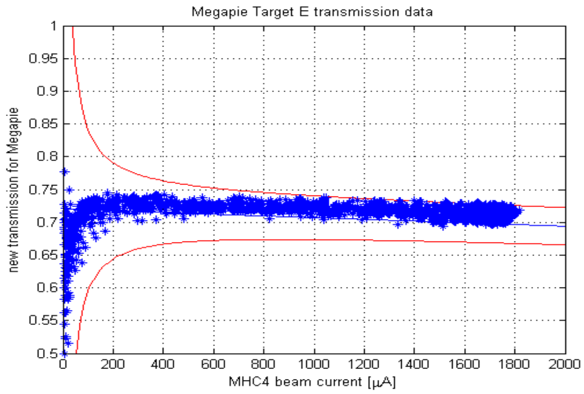

Fig.5: Validity window for the Target E transmission.

III. MANAGING ACTIVATION

Obviously activation of components is a critical issue for the operation of a high power facility in CW mode. One has to distinguish regions where beam losses are unavoidable as targets or the beam dump, and regions where losses can be tuned to a minimum to allow for servicing of the installations. At the Meson production target E the beam is strongly scattered and a fraction of roughly 30% has to be collimated constantly. In this region the estimated activation levels reach 100 Sv/h. The beamline is shielded in two stages. The primary shielding consists of roughly 2 m steel. Above the steel shielding auxiliary components like vacuum pumps, water cooling and electrical installations are located. Another level of concrete shielding is installed above this "service level" (Fig.6). Critical components in the beamline are introduced through chimney-like vacuum chambers from the service level. In this way the critical components, for example the targets, are still accessible and can be exchanged. The graphite wheel of target E exhibits typical activation levels in the range 1-10 Sv/h. Its exchange is a routine operation with a specifically designed shielded exchange flask. To accomplish the exchange the device is connected to the corresponding chimney on the service level and the target including its fixtures is pulled up into the flask. The closed flask can be safely transported to a storage area, or the PSI owned hot cell, were further steps can be taken.

The components in the cyclotrons are much less activated. The typical levels reach up to a few mSv/h. On the other hand servicing of the by far more complex installations in the cyclotrons requires human activities directly at the components. To minimize the radiation dose for the employees the procedures for standard service work are strongly optimized. Temporary shielding walls are used as well as specially manufactured shielding boxes for the exchange and transport of special components like the electrostatic injection and ejection elements. A top view map of the approximate activation levels in the ring cyclotron is shown in Fig. 7. The major area exhibits dose rates below 1 mSv/h, whereas a few components, namely the electrostatic devices and the ejection channel have more than 5 mSv/h. In the last two decades the yearly integrated beam current has been raised by more than an order of magnitude. In the long term statistics of the employees radiation dose monitoring there is no correlation with the beam current visible (Fig. 8 and [2]). In the last years our ability to predict activation levels, based on the irradiation history and numerical simulation tools has been drastically improved [3]. These tools become more and more important for the professional disposal of radioactive material. The legal regulations require to determine or to predict the inventory of radioactive isotopes in the material intended for disposal. Since the analytical determination of small contaminations is typically very difficult, the prediction via benchmarked simulations is often the only way to fulfill these requirements.

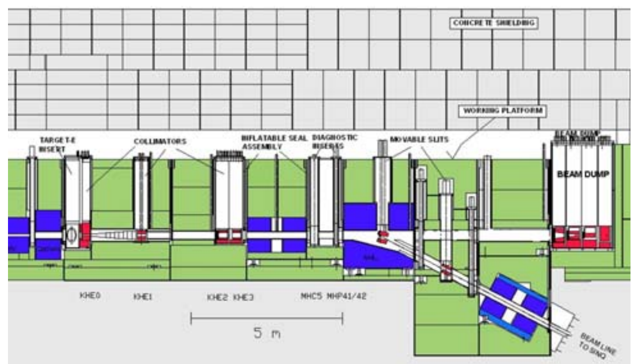

Fig. 6: Side view of the target E installation showing the primary steel shielding below the service level (green), the chimney installations and the concrete shielding above (grey).

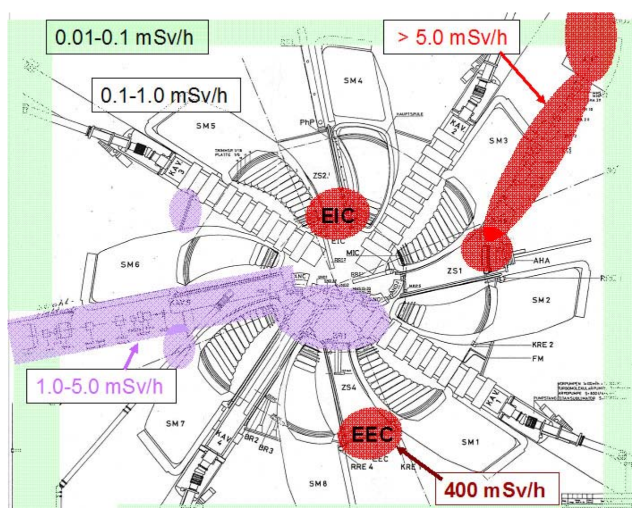

Fig. 7: Isodose map of the main Ring Cyclotron and vacuum chamber of the electrostatic extraction element showing a hot spot of 400 mSv/h.

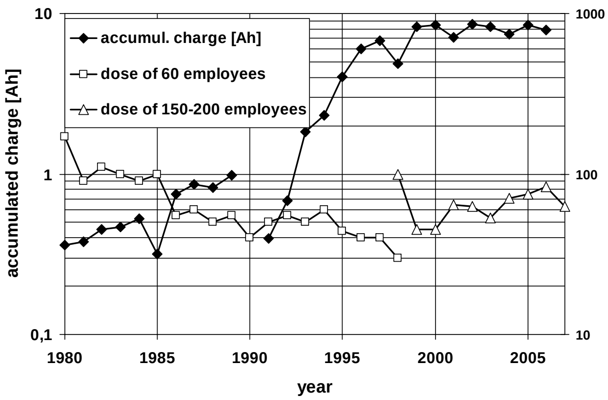

Fig. 8: Integrated beam current and total dose of shutdown personnel, recorded since 1980.

IV. ESSENTIAL OPERATION TOOLS

For the operation of a facility with high beam power it is essential to give the operator the appropriate tools for optimizing the losses, tools for automatic beam centering and regulating.

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 level of the operators may differ and the control system should give them an optimum aid to interpret the many different operating situations that can occur in practice. An automated system for efficient recovery after a beam-off has been implemented, but operator intervention is of course possible at all times during ramping up of the beam.

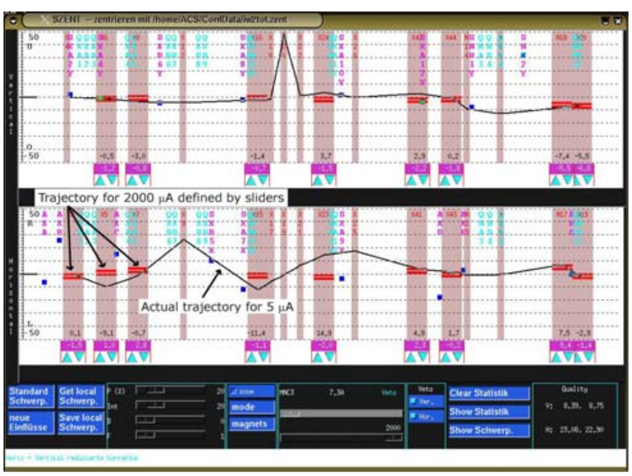

Fig 9: Automated centering utility showing the vertical beam position in the upper part and below the horizontal beam position. The figure shows also the difference between the reference trajectory for 2000 µA and the actual trajectory for 5 µA.

In our facility a major difficulty arises from the fact that during the ramping up of the beam, the beam trajectory is strongly varying (Fig. 9). This is mainly caused by the changing space charge effects [4] as a function of the beam current. The presently installed BPM electronics is practically incapable to operate at beam currents below 5 µA. In some cases we run into a “beam off” condition and the skill of the operator has to compensate for this problem. After the next shutdown however, the conversion to VME electronics will be completed, allowing valid measurements starting already from 100-200 nA [5].

IV. CONCLUSIONS

The PSI facility operates continuously with beam powers above 1 MW. The availability of the accelerator chain is around 90% on average. The most important aspect for operating the facility lies in the limitation of the beam losses to acceptable levels. This is achieved by high accelerating gradients in the cyclotrons which result in a large turn separation at extraction. Furthermore careful tuning of the relevant parameters, the support by excellent diagnostic tools and an efficient control system are important for successful operation. Presently an ambitious upgrade program is under work at PSI with the goal to raise the beam current from 2 to 3 mA. Basic investments for the upgrade program include new accelerator cavities for the Ring Cyclotron, allowing to provide a maximum voltage gain of 1.2 MV per passage and being capable of transferring roughly 400 kW of power to the beam per accelerating cavity. Also the Injector II cyclotron will be equipped with two new resonators. Further important measures consist in the installation of harmonic buncher systems, both for the injector and the Ring Cyclotron.

ACKNOWLEDGMENTS

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