OPERATION OF THE HIGH INTENSITY PROTON BEAM FACILITY AT PSI

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Abstract

The cyclotron based high power proton accelerator facility at PSI drives a neutron spallation source and two Meson production targets with a proton beam at 590 MeV kinetic energy. This paper concentrates on the operational and technical aspects specific to acceleration and transport of a high power beam. Furthermore a summary on upgrade plans to increase the beam power from presently 1.2 MW to 1.8 MW will be given.

INTRODUCTION TO THE FACILITY

The facility at PSI provides a continuous proton beam at an energy of 590 MeV with a current of 2 mA during regular production runs, and a maximum current of 2.2 mA for limited run periods. The continuous beam acceleration is possible by the employment of a Cockroft Walton accelerator which supplies a DC accelerating voltage of 810 kV and a chain of two isochronous cyclotrons. The Injector II cyclotron accelerates the beam to 72 MeV kinetic energy. It is equipped with four sector magnets, two accelerating resonators operated at 50 MHz and two third harmonic resonators aimed originally at reducing the energy spread in the beam, but nor used for additional acceleration. The Ring Cyclotron accelerates to 590 MeV. It contains eight sector magnets, four resonators and one third harmonic cavity. Behind the Ring Cyclotron the beam is sent onto two solid targets installed in series for the purpose of producing pion and muon beams. The targets are realized as radiation cooled rotating graphite wheels. The pion and muon beams are used to perform scattering experiments on condensed matter as well as particle physics experiments. The scattering of the proton beam at the second graphite target with a thickness of 4 cm leads to a significant emittance blowup of the beam. The scattered beam has to be collimated for further transport. Together with losses from hard scattering events in the target this results in a total reduction of the usable beam current by 30 %. Finally the beam is sent to the neutron spallation source SINQ. Presently the SINQ target consists of a package of tubes made from Zircaloy and filled with lead. The target is cooled by a continuous flow of heavy water, D_2O. In the 72 MeV transport line from the Injector II to the Ring Cyclotron exists the possibility to continuously split a beam current up to 100 μA from the transverse tail of the main beam for the production of radioactive isotopes at a dedicated target station. The beam separation is done with an electrostatic separator and a septum magnet. Another planned experiment which uses the 590 MeV beam will produce ultra-cold neutrons (UCN) [1], i.e. neutrons with energies of 250 neV or below. The key for the successful acceleration of the high power beam lies in the limitation of the beam losses to a relative level in the 10^{-4} range in the cyclotrons and beam transport lines. In the cyclotrons the important losses occur at the extraction element were a deflecting electrode has to be placed between last and second-last turn. To accomplish the desired small beam losses at this extraction element it is important to provide a large beam separation. This is mainly achieved by the highest possible accelerating voltage, respectively by a large energy gain per turn. Not only the radial orbit step is favorably increased with larger energy gain. Also space charge effects which lead to beam blowup are decreased with the total path length in the cyclotron. In the past the accelerating voltage could be considerably increased, essentially by the installation of more powerful amplifiers and resonators. Using the same geometry and magnet arrangement in the Ring Cyclotron the maximum current was raised by more than an order of magnitude (Fig. 1). A layout view of accelerators and beam lines is shown in Fig. 2.

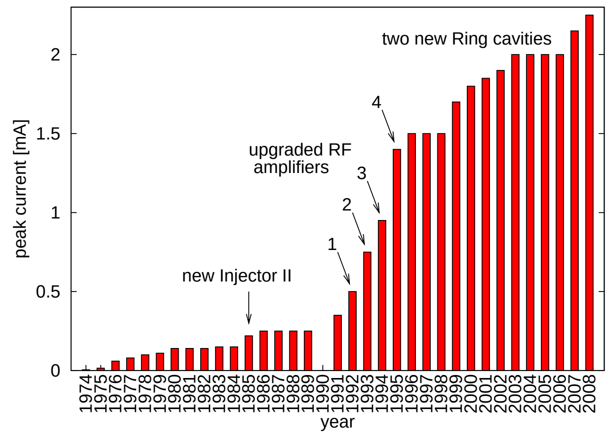

Figure 1: Development of the maximum accelerated beam current in the PSI proton accelerator over time.

HIGH POWER BEAM PRODUCTION AND UPGRADE PATH FOR CYCLOTRONS

For the production of a high power beam it is most important to limit the beam losses to a level that results in acceptable activation and dose rates in the accelerator. The long term experience at PSI shows that losses of 200-400 nA per location, i.e. relative losses in the order of 10^{-4} are still acceptable. In the Ring Cyclotron such beam losses are primarily generated at the extraction element, which is realized as an electrostatic element, employing

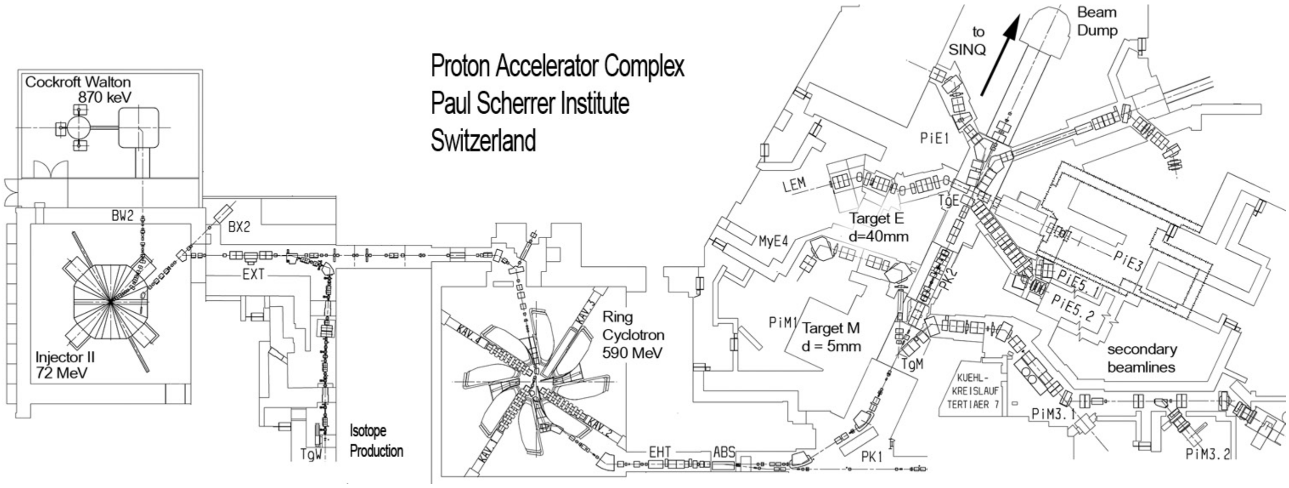

Figure 2: Overview of the PSI high intensity proton accelerator

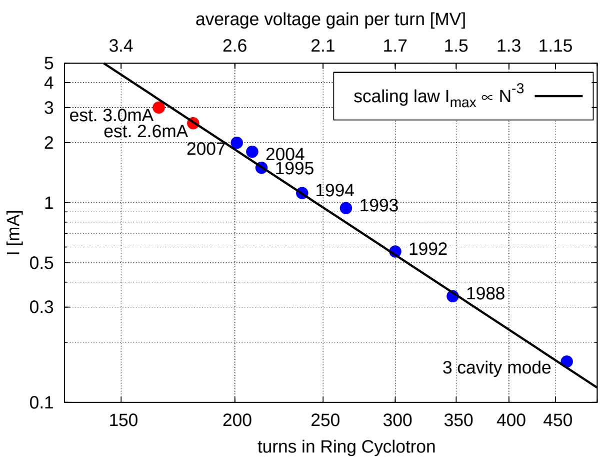

Figure 3: Development of the Ring Cyclotron beam intensity as a function of the turn number.

thin tungsten foils as electrode. The deflecting electrode is inserted between last and second last turn. The beam dynamics in the cyclotron is dominated by longitudinal space charge effects. The beam developes an enlarged energy spread which is translated into radial tails caused by the bending fields. Such radial tails may be scattered in the electrode of the extraction element and cause the undesired activation of components in the extraction region of the cyclotron. Based on simple arguments it can be shown that the described extraction losses scale with the third power of the number of acceleration turns in the cyclotron [2]. This means, under the constraint of constant losses the maximum current can be raised proportional to the inverse cubed turn number. Over the history of the PSI cyclotron the development of the beam current indeed followed this law (Fig. 3). The desired faster acceleration process is achieved by increasing the accelerating voltages in the resonators.

Another important aspect for high power beam production ist to ensure the integrity of the accelerator in the presence of a MW beam. For a typical beam dimension of 1-3 mm a mis-steered beam will melt steel in a short time of 10-100 ms. The accelerator is equipped with redundant interlock systems, capable to diagnose a beam loss and switch the beam off within a few ms.

OPERATIONAL ASPECTS

Reliability

The PSI accelerator has a long history and some components date back to the 1970'th. A continuous effort with significant investments has been undertaken in the past years to replace many old components as vacuum pumps, diagnostic devices, magnets and even RF resonators. As a result the reliability of the accelerator, defined as the ratio of realised uptime and scheduled uptime, approaches a number of 90 %. Another aspect of the reliability improvement program is to minimize the risk of long interruptions which may be caused by the damage of outstanding single elements as complicated vacuum chambers or magnets. Although considerable investments are necessary, such elements are rebuild as spares, or at least plans for their replacement are worked out.

1999	2000	2001	2002	2003	2004	2005	2006	2007
89	86	88	82	91	88	84	88	90

Table 1: Reliability in percent over the last years.

During the normal operation many short interruptions occur that are not connected to failures of devices. Often a short high voltage breakdown in the electrostatic injection or extraction elements causes such short beam trips. Another cause are trips of the RF system. A statistics on the occurance of interruptions as a function of their duration is shown in Fig. 4.

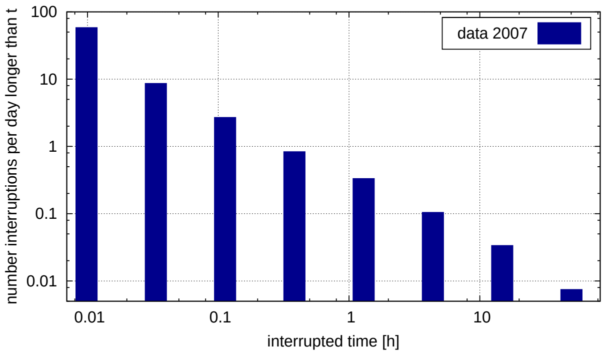

Figure 4: Statistics on the number of interruptions per day with a duration longer than the time shown on the abscissa.

Operation Schedule

For many years a one week operational schedule was implemented at PSI. Every week one day was reserved for service work and machine development (MD). In 2007 a three week schedule was set up with the idea to minimize start up time. This decision was supported by the high reliability of the accelerator which required less interventions and repair work. Within this schedule the production run is interrupted every three weeks for $2\frac{2}{3}$ days (8 shifts) or $3\frac{1}{3}$ days (10 shifts) in an interleaving scheme. This schedule provides a higher flexibility since the non-production time can be used for MD and training of the operators, but also for relatively long repair and maintenance tasks in case such measures are necessary. As the yearly schedule is considered, the facility is typically operated from April to December, and the first three months are used for extended maintenance and installation of new components.

With the high reliability of the facility certain operational tasks occur rarely. An example is the complete setup from scratch, as it is required after a power outage. In this context we found it very important to train the operators to deal with such situations, and we have established a training program for standard tasks. The overall performance of the facility has benefited from this program, although some operating time has to be spent for the training.

Diagnostics and Interlock Systems

A mis-steered beam is capable to melt a steel vacuum chamber within a few milliseconds [4]. At some locations with high activation levels such failures can have severe consequences since repair or exchange of the damaged components would be very difficult and time consuming. The PSI facility has a rather sophisticated interlock system to recognize failure situations quickly and switch the beam off. Ionization chambers which measure the losses in the vicinity of the beampipe are used as the most important tool to recognize uncontrolled beam losses. These 110 chambers are also used to optimize the settings of the accelerator. Another important system is given by 80 collimators and slits, which are electrically isolated from ground and provide a signal directly proportional to the loss current from beam tails. Current monitors are used in pairs to measure the transition of accelerator sections. This is especially important in the context of the of the 4 cm Meson production target, where the transition ratio should be $70\,\%$, and a higher transition indicates beam bypassing the target. The unscattered beam exhibits a much higher density which cannot be accepted by the SINQ spallation target. There are even more interlock systems installed including for example monitoring of the magnet currents or the activation levels in the cooling water circuits. The run permission system processes roughly 1500 signals and it contains 150 electronic racks distributed over the facility.

ACTIVATION AND AIXILIARY SYSTEMS

For a high intensity accelerator as the PSI facility the typical limitation is given by the beam losses and the resulting activation of accelerator components. The ultimate measure of this aspect are the dose numbers the service personnel of the accelarators receives during the typical maintenance works. In the facility one has to distinguish areas which are designed for continuous high beam loss as the target areas, and other areas as the cyclotrons or transport lines where the loss should be as low as possible to allow for serviceability. At the Meson production targets a fraction of $30\,\%$ of the beam has to be collimated. The components in this region are optimized for high lifetime and the beamline is appropriately shielded by 2 m steel and 4 m concrete shielding. Critical components as the targets and the water cooled absorbers can be removed from above through “chimneys” with the help of special exchange flasks. The beam pipe itself cannot be removed and exhibits activation levels up to $10-100$ Sv/h.

The Ring Cyclotron needs frequent access by service personnel. At the extraction channel it exhibits its peak activation of $\approx\, 9$ mSv/h. The majority of the area shows levels between 0.1 and 1 mSv/h. Fig. 5 illustrates this by a rough mapping of dose rate measurements in the Ring Cyclotron bunker. An example for the personnel dose typical for maintenance work is the shutdown 2008 which extended over three months. The activities involved 188 colleagues and they received a collective dose of 57 mSv. The highest individual dose was 2.6 mSv. The legal limit is 20 mSv per year and another internal goal is not to exceed a value of 5 mSv for the yearly shutdown alone. The shutdown work usually dominates the yearly dose. Over the past years the beam current was significantly increased, but this is not reflected in the personnel dose recorded, which stayed practically constant over this period of time [5].

The yearly shutdown activities start in January, but the facility is switched off before the Christmas holidays. Consequently there are at least two weeks of cooldown time available before critical work begins. To prepare for service work during the production period the beam current is reduced from 2 mA to 1.7 mA on the day before the service at noon, and the beam is switched off 2 hours before the service begins. Because of the nonlinear scaling of the losses with current, the reduction to 1.7 mA gains a factor 2 with respect to the losses (Fig. 6).

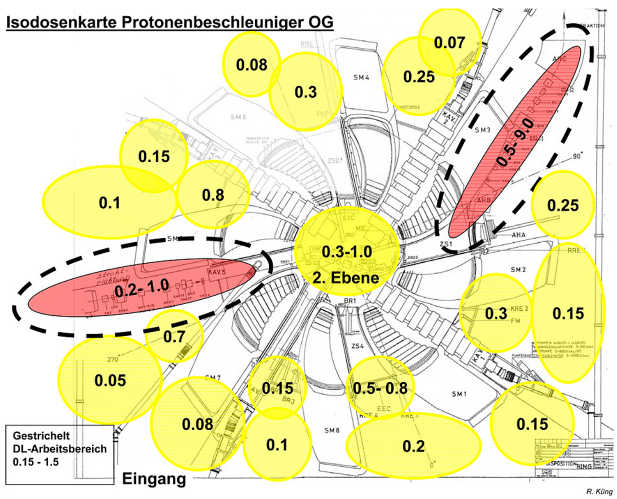

Figure 5: Results of dose rate measurements in mSv/h, in the Ring Cyclotron for a typical service situation (graphics provided by R. Küng, PSI).

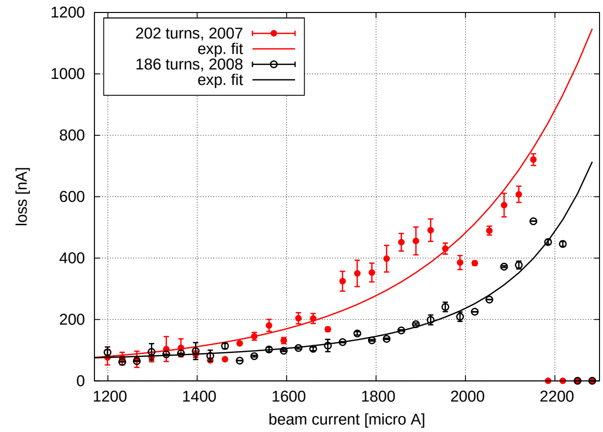

Figure 6: Loss current at the Ring Cyclotron extraction, deduced from ionization chamber rates, as function of beam current for the cases of 202 and 186 turns. The shown data points are taken at optimized situations, i.e. they represent the minimally achieved losses at each current.

The practical operation of a high intensity facility involves the repair, handling and also disposal of activated components and materials. In this context a considerable infrastructure is needed at the institute to deal with such problems. This includes the availability of a hot cell in close vicinity to the facility, for example to investigate used Meson production targets, or to repair electrostatic elements which were in use at the Ring Cyclotron. In the accelerator it might be necessary to measure very high dose rates, or to visually inspect critical components using a radiation hard camera. Another practical example is the chemical analysis of activated dust particles which were found in the vacuum system and the origin of which was in question. For the disposal of activated components the legal regulations require to declare the nuclide inventory of such components. Comprehensive measurements of such nuclide compositions are very difficult and so the legal authorities accept also numerical predicions, computed with benchmarked computer codes. For the planning of specific maintenance tasks in highly activated areas the prediction of radiation levels using simulation codes is valuable as well. At PSI a group of specialized experts is persuing such simulation work. A comparison of predicted and measured activation levels is published at this workshop [7]. In collaboration with other institutes the codes as MCNPX are beeing improved and developed further.

RECENT ACHIEVEMENTS AND OUTLOOK

As mentioned above the most important upgrade path for the PSI cyclotron facility consists in raising the accelerating voltage. The most recent measure in this context was the replacement of four aluminum resonators in the Ring Cyclotron by more powerful copper resonators. The installation of the new resonators was completed in the shutdown 2008 and it permitted in a first step to reduce the number of turns from 202 to 186. The peak gap voltages per resonator were raised from 0.78 MV to 0.85 MV. As a result the beam losses at 2.0 mA were reduced by nearly a factor 2 and a new record current of 2.2 mA was easily achieved. The observed losses as a function of beam current are shown in Fig. 6. After a further upgrade of the injector II cyclotron and the installation of a 10'th harmonic buncher [3], a maximum current of 3 mA is anticipated for 2012.

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