HIGH INTENSITY OPERATION AND CONTROL OF BEAM LOSSES IN A CYCLOTRON BASED ACCELERATOR

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Abstract

This paper discusses aspects of high intensity operation in PSI's cyclotron based proton accelerator (HIPA). Major beam loss mechanisms and tuning methods to minimize losses are presented. Concept and optimization of low loss beam extraction from a cyclotron are described. Collimators are used to localize beam losses and activation. Activation levels of accelerator components are shown. Other relevant aspects include the beam trip statistics and grid to beam power conversion efficiency.

INTRODUCTION TO PSI'S HIPA FACILITY

The HIPA facility produces a continuous wave 590 MeV proton beam for the generation of muon beams and neutrons in a spallation target. Acceleration is done in a classical Cockroft-Walton pre-accelerator and, after bunching, in a chain of two isochronous cyclotrons. The cyclotrons are realized as separated sector cyclotrons, employing box resonators at 50.6 MHz for the acceleration of the beam. The facility contains also a source for ultracold neutrons (several 100 neV) which is operated in pulsed mode with a duty factor of 100.

Muons are produced as decay products of pions, which are generated when the high intensity proton beam passes through two rotating graphite targets with thicknesses of 5 mm and 40 mm. The targets are cooled simply by radiation cooling at temperatures up to 1700 K. Muon rates are of the order of $5{\cdot}10^8\,s^{-1}$ per beamline. The significant emittance blowup after the second target requires collimation of 30% of the proton beam intensity, in order to allow the further transport of the beam to the SINQ spallation target. The spallation target consist of lead filled Zircaloy tubes which are packed closely in a target enclosure. This target is cooled by a circuit of heavy water D_2O, which exhibits a neutron capture cross section three orders of magnitude smaller than normal water. The UCN source uses the same type of target, however equipped with a moderator employing frozen deuterium. Ultracold neutrons can be stored with small losses in a closed volume, and so the storage time is dominated by the natural lifetime of the neutrons. The storage volume is filled with freshly generated neutrons roughly every 10 minutes by a proton pulse of 8 seconds.

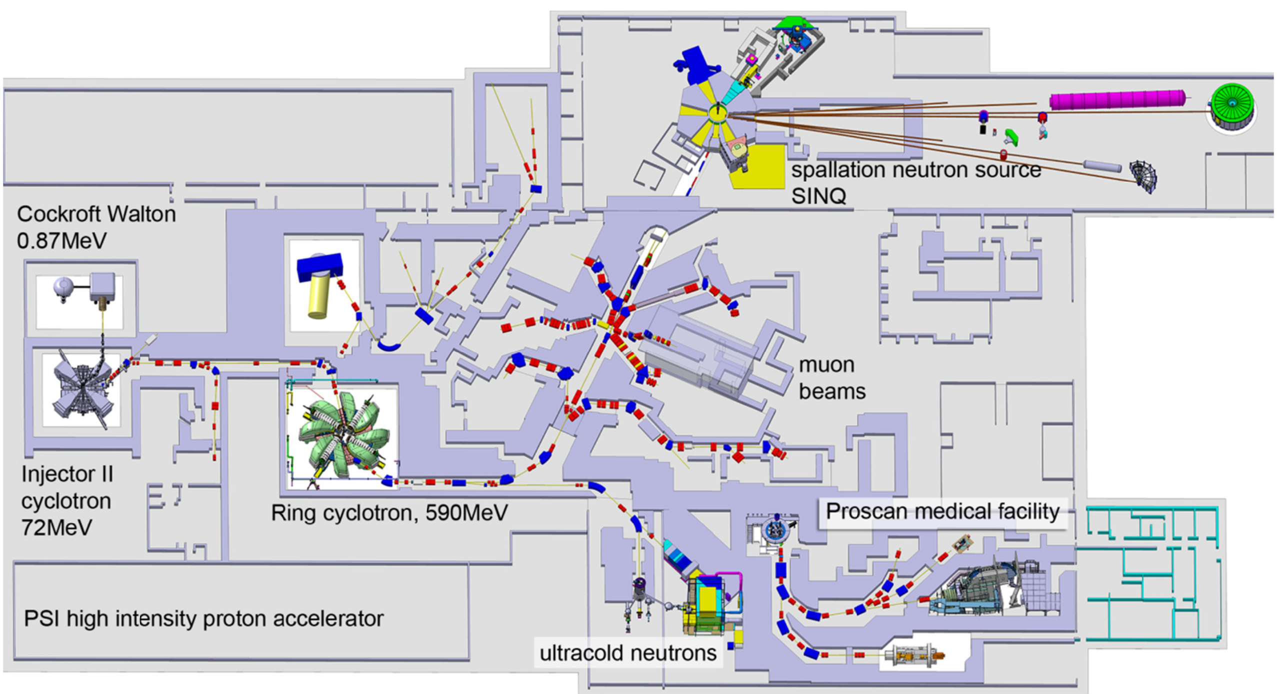

Figure 1: Layout of the PSI high intensity proton accelerator including the two meson production targets (center of image) and the spallation neutron source SINQ with related experimental facilities. The proton therapy facility for cancer treatment was originally connected to HIPA, but uses a separate superconducting cyclotron now.

ISBN 978-3-95450-118-2

The research program at the facility covers a broad range of applications involving neutron scattering, muon spin spectroscopy and few particle physics experiments. Figure 1 shows an overview of the facility.

CYCLOTRONS FOR HIGH INTENSITY BEAMS

Cyclotrons [1][2] are operated in continuous wave mode, which makes them well suited to generate high average beam power. The important issue is the limitation of the beam losses to a level of a few hundred watts. Most critical in this respect is the extraction of the beam from the cyclotron. In principle extraction can be realized in a smart way by accelerating H^- ions and stripping the electrons at the extraction radius. However, this scheme generates significant losses during the acceleration phase since the second electron is only weakly bound to the proton. Thus we accelerate protons in our cyclotrons and extract the beam by placing a thin electrostatic electrode between the last and second last turn in the cyclotron. The deflection of 8 mrad on 920 mm effective length is sufficient to extract the beam using a subsequent magnetic channel. The major loss mechanism in this scheme is scattering of halo protons in the 50 µm tungsten foils of the electrostatic septum. Thus the main effort for reducing losses in the Ring cyclotron concentrates on optimizing the beam separation at the septum and minimizing the production of beam halo. Beam halo is produced by several mechanisms. At PSI longitudinal space charge effects lead to blowup of the energy spread which is transformed into transverse tails due to the action of the bending fields. This effect exhibits strong scaling with the third power of the number of turns in the cyclotron, thus scaling inversely with the third power of the accelerating voltage [3]. Over the history of the facility the major increase in intensity was realized by raising the gap voltages of the cavities, first by installing more RF power, and later with new resonators (Figure 2). As a last step it was possible to achieve a new record of 1.4 MW beam power in 2011 due to a further reduction of beam losses. In the next section these improvements are illustrated.

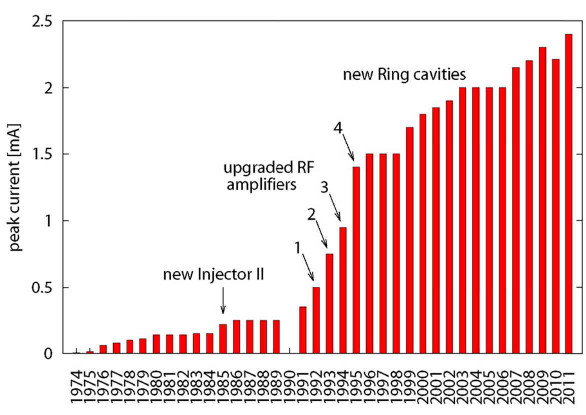

Figure 2: Development of the maximum attainable beam current in the HIPA facility.

However, the applied acceleration voltage is not a tuning parameter. In practice it is limited by practical boundary conditions, in case of HIPA by a limitation of the third harmonic flattop cavity. The turn separation can be optimized by tuning and this will be described in somewhat more detail here, since this aspect is of operational nature, which is the theme of this paper.

First we review the scaling relations for the turn separation in cyclotrons. The cyclotron is isochronous which means that the average bending radius R should scale proportional to the velocity v of the beam in order to keep the revolution time constant. In nonrelativistic approximation the radius increment per turn is given by:

$$\Delta R \approx \frac{U_t}{m_0 v^2} R$$

Here U_t is the energy gain per turn and m_0 the rest mass. Since $v \propto R$ we note that the rough scaling of ΔR is inversely proportional to the radius, i.e. towards the extraction radius turns are more densely spaced and clean extraction becomes more difficult. Under the obvious boundary condition that the cyclotron should accelerate to a certain energy, and furthermore taking relativistic relations into account, the turn separation at extraction is given by:

$$\Delta R(\gamma_{extr}) = \frac{U_t}{m_0 c^2} \frac{R_{extr}}{(\gamma_{extr}^2 - 1)\gamma_{extr}}$$

This relation shows that a large cyclotron is advantageous (large extraction radius) for a given extraction energy. Nevertheless conditions become quickly very unfavourable at relativistic energies, i.e. $\gamma_{extr} \gg 1$. In the PSI ring cyclotron a special technique is applied by injecting the beam with a certain deviation from the ideal closed orbit in the radial coordinates. The beam performs betatron oscillations around the ideal orbit and at the extraction point this can be tuned in such way as to maximize the turn separation at the location of the extraction septum. Figure 3 illustrates this method and shows, that the gap can be increased by a factor 3 at maximum.

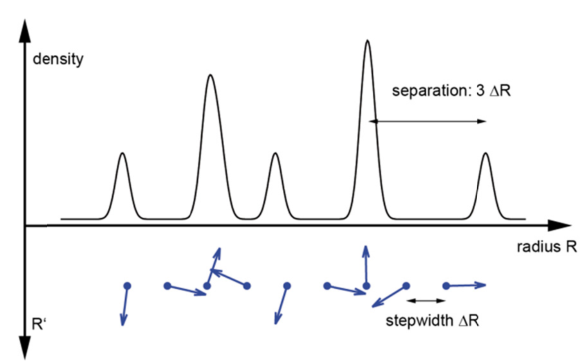

Figure 3: Using eccentric injection, the turn separation at the extraction septum can be maximized. The figure shows radial phase space vectors of the orbit oscillations and the resulting beam density.

ISBN 978-3-95450-118-2

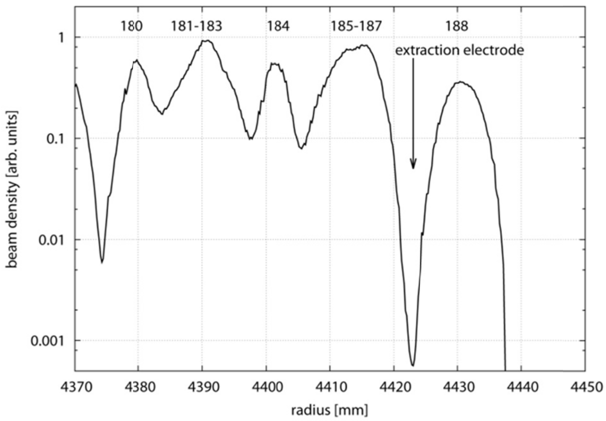

Figure 4: Beam density measured at extraction on a logarithmic scale. The turn numbers are indicated at the peaks.

In comparison Fig. 4 shows a measured extraction profile, illustrating the large dynamic range in particle density. It is worth mentioning that the measured extraction profile was successfully reproduced [4] by numerical simulations using the code OPAL-CYC that includes the treatment of space charge effects. In order to achieve the maximum separation with this method, the exact control of the radial phase advance per turn at the outer radius of the cyclotron is very important. In the Ring cyclotron the betatron tune is declining in the outer region of the magnets from a value around 1.75 towards 1.5. This can be observed nicely in Fig.3, where the phase vector rotates clockwise. If the tune would approach 1.5 too early, around the third last orbit, then this orbit would move closer to the last orbit than the second last orbit, and the full gain of a factor 3 could not be realized.

The correct tuning of this orbit pattern can be verified using a radial probe, as shown in Fig. 4. However, in practice the optimization of amplitude and angle of this injection mismatch is done by the operators empirically.

SETUP AND LOSS TUNING IN HIPA

Indeed the strategies for general setup of the accelerator and loss tuning are distinct. During a general setup the beam can be stopped at two intermediate beam dumps, one at low energy in the Injector II cyclotron, and one at high energy. In this way the accelerator can be set up in steps and potential problems can be easily associated with the corresponding section. Diagnostic systems as wire scanners or radial beam probes in the cyclotrons are used to verify optical beam properties against models and to apply corrections when appropriate. The radial field shape in the cyclotrons must be tuned very precisely to ensure the condition of isochronicity during the course of acceleration. The phase relationship between RF and beam is measured using phase probes at different radii. The field shape is then tweaked using trim coil circuits. The Ring cyclotron is equipped with 15 of such circuits. Radial beam position and correct injection into the cyclotron is measured using radially moving probes. With tilted wires these probes can also give information on the vertical beam position. In the transport lines we use inductive beam position monitors in connection with orbit feedback loops to center the beam. Due to current dependent space charge effects the optimizations are current dependent, and settings must be found that allow ramping of the beam current with acceptable losses at all currents on the ramp. Using such systematic strategies, based on models, one can reach beam currents representing a large fraction of the design current. However, to reach the full current with low losses one relies on empirical tuning. The problem is that subtle changes in the beam distribution at larger transverse amplitudes contribute significantly to the losses at extraction. However, the change in the distribution is too small to be measured using standard diagnostics, nor can effects be clearly associated with certain sections of the accelerator. For example one notes a significant impact from small changes in the ion source, e.g. the hydrogen gas flow, onto the losses observed at extraction of the Ring cyclotron. Thus for practical operation at high intensity the operators are continuously tuning certain parameters, e.g. injection angle and position, with the only goal to minimize the beam loss measurements around the cyclotron and in the extraction line.

In recent years several improvements were implemented at HIPA. A new ECR ion source with lower emittance was commissioned. Several power supplies that induced residual 50 Hz ripple from the grid were identified and improved. In the Ring cyclotron plates that hold trim coils were bent inwards, presumably as a result of RF induced heating. The exchange of these plates increased the vertical aperture. These improvements resulted in lower losses as illustrated in Fig. 5. The low losses allowed achieving a new intensity record of 2.4 mA, while the standard operating current remains at 2.2 mA.

Once extracted from the Ring cyclotron, the 590 MeV beam is used to generate muons in two graphite targets. The second target with 40 mm thickness leads to an emittance blowup of more than a factor 5 [5]. Roughly 10 % of the protons undergo inelastic reactions in the target material. Another 20 % of the beam must be collimated behind the target to allow a safe and low loss beam transport to the SINQ spallation target. The losses from scattering are localized in a few copper collimators. These collimators receive a significant continuous power load resulting in high temperatures, but also very high radiation doses. During an inspection in a hot cell, a secondary dose rate of 500 Sv/h was measured at one of the collimators. Despite of the high dose which the material received, no degradation or swelling was optically visible [6].

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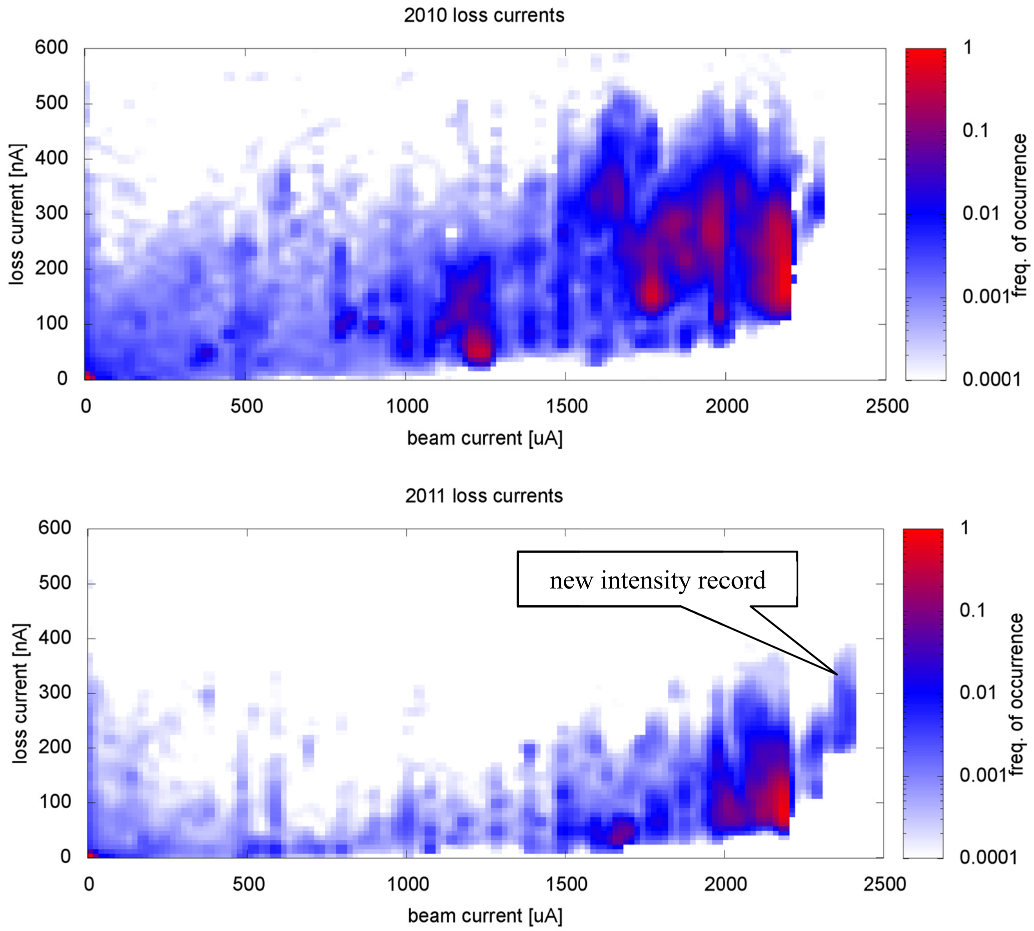

Figure 5: Beam losses as a function of beam current for the years 2010 and 2011. The color code corresponds to the frequency of operation at a certain combination of loss current and beam current. Note the logarithmic scale of the color code.

OPERATIONAL EXPERIENCE AND STATISTICS

Power consumption and efficient utilization of electrical power is an important aspect for a high intensity accelerator facility. The facility, including all experimental equipment, consumes 10 MW electrical power. Out of that 4.3 MW are consumed by the RF system, while the beam power is finally 1.3 MW. At zero beam current the facility still consumes 8 MW of grid power, only 2 MW scale with the beam current. Thus it is cost effective to run the accelerator at a high beam current, giving a high rate of secondary particles that results in higher throughput at the experiments, while the yearly operation time could be limited. Indeed the total operation time per year was reduced over the years, while the total delivered charge was increased (Tab. 1). The overall efficiency of the RF system, from grid to beam is 32 %. This number is a product of the individual efficiencies for AC/DC conversion (0.9), generation of RF from DC electrical power (0.64) and transfer of RF power to the beam in a copper cavity (0.55).

Table 1: Operational Parameters Since 2001. The Listed Charge was Delivered on the Meson Production Target E

year	charge [mAh]	op.hour [h]	max.curr [μA]	avail. [%]
2001	7136	4310	1850	88
2002	8560	5464	1900	82
2003	8330	5065	2000	90
2004	7480	4710	2000	88
2005	8450	5420	2000	84
2006	7900	5520	2000	88
2007	8900	5200	2150	90
2008	9200	5264	2200	90
2009	9700	5120	2300	90
2010	8500	5080	2200	83
2011	9600	4952	2400	91

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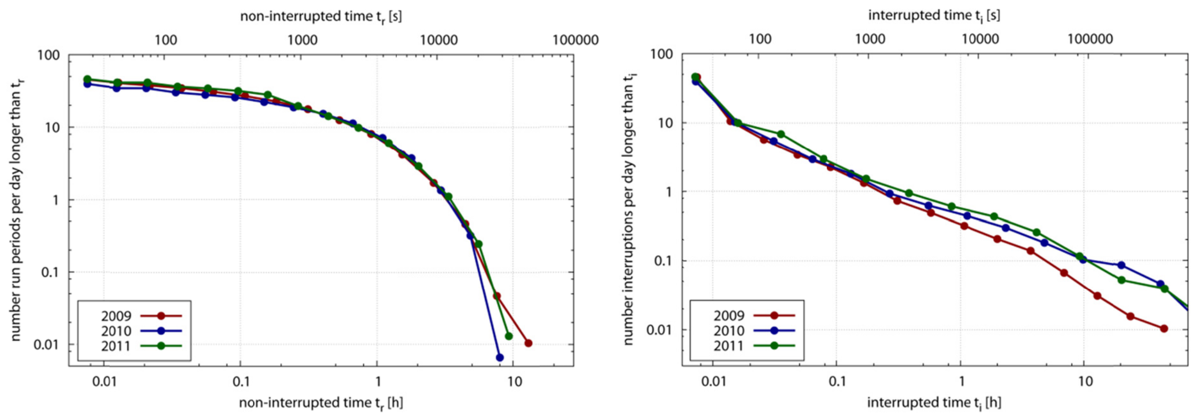

Figure 6: Frequency of uninterrupted run periods per day (left) and interruptions per day (right). The graphs represent histograms that are integrated from long to short time intervals. For example one can read from the left graph that on average 8 uninterrupted run periods per day last longer than one hour.

The absolute beam loss in the extraction region of the cyclotron is in the range of a few hundred watts. In practice that results in peak secondary dose rates of 10 mSv/h at a few locations in the extraction beam line. At the surface of the cyclotron itself dose rates of 1 mSv/h or lower are measured. Using local shielding the typical maintenance operations can be carried out.

The operation of the PSI proton accelerator is characterized by sudden interruptions, with durations ranging from 30 seconds to failures which require repair before restart. Most of the short term interruptions in the PSI-facility are caused by high voltage breakdowns of the electrostatic elements which deflect the injected and extracted beam. Other triggers of the interlock system are intermittent spikes in the loss rates or trips of the RF system. In most cases the system that triggered the interruption is automatically reset and the beam current is ramped up again within 30 seconds. Therefore, the minimum time required for recovery is determined by the ramping procedure even though triggers may only last for a few milliseconds. In order to quantify the trip statistics we have analysed the run periods 2009-2011. Fig. 4 shows integrated histograms for the statistical occurrence of run and interruption periods. At the very left end of each graph the total number of interruptions (right plot) respectively runs (left plot) per day can be extracted. The total trip rate in recent years was around 30/d..40/d. The overall availability of the PSI accelerator is defined as the ratio of delivered and scheduled run time. In recent years the average availability was 90% (Tab. 1) which presents a relatively good performance for a high power proton accelerator. Another discussion of trip rates and failure statistics can be found in [7].

SUMMARY

The PSI high intensity proton accelerator complex is based on a chain of two cyclotrons and produces a beam power of 1.3 MW at a kinetic energy of 590 MeV. The average availability was around 90 % over the recent years. The maximum power is limited by beam losses in the lower 10^{-4} range at the extraction of the Ring cyclotron. While the setup of the accelerator is done in a systematic way, based on beam property measurements and models, the tuning of the losses at the highest beam power is done empirically.

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ISBN 978-3-95450-118-2