TOWARDS THE 2 MW CYCLOTRON AND LATEST DEVELOPMENTS AT PSI

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Abstract

PSI operates a cyclotron based high intensity proton accelerator routinely at an average beam power of 1.3MW. With this power the facility is at the worldwide forefront of high intensity proton accelerators. An upgrade program is under way to ensure high operational reliability and push the intensity to even higher levels. The beam current is practically limited by losses at extraction and the resulting activation of accelerator components. Further intensity upgrades are only possible if the relative losses can be lowered in proportion, thus keeping absolute losses at a constant level. The basic upgrade path involves the reduction of space charge induced extraction losses by implementing improved RF systems and resonators in both cyclotrons. The paper describes the ongoing upgrade program, achievements that were realized since the last cyclotron conference and several operational experiences and difficulties that were observed during routine operation.

INTRODUCTION TO THE PSI FACILITY

The PSI high intensity proton accelerator generates a high power proton beam with 590 MeV kinetic energy. At full energy the relative beam losses have to be kept within the lower 10-4 range to avoid excessive activation of accelerator components in the extraction region. The PSI accelerator consists of a Cockcroft-Walton pre-accelerator and a chain of two isochronous cyclotrons, the Injector II and the Ring cyclotron. The beam is produced in continuous wave (CW) mode at a frequency of 50.6 MHz. The whole facility including the experimental areas fits in a rectangle of 120 m × 220 m. The proton beam is used to produce pions and muons by interaction with two graphite targets that are realized as rotating wheels [1]. The targets have thicknesses of 5 mm and 40 mm. Pions decay into muons that are transported in large aperture transfer lines to the experiments. Muon beam intensities up to 5·108 s-1 are achieved [2]. After collimation behind the meson production targets the remaining proton beam with roughly 1MW is then used to produce neutrons in a spallation target. The actual target consists of a matrix of lead filled Zircaloy tubes. The neutrons are moderated in volumes filled with heavy water (D2O) surrounding the target, and then transported to the 13 instruments installed in the Swiss Spallation Neutron Source (SINQ) facility. In 2010 a pulsed source for ultracold neutrons (UCN) will be brought into operation as well. The research themes at PSI cover a broad range of applications involving neutron scattering, muon spin spectroscopy and few particle physics experiments. Fig. 1 shows an overview.

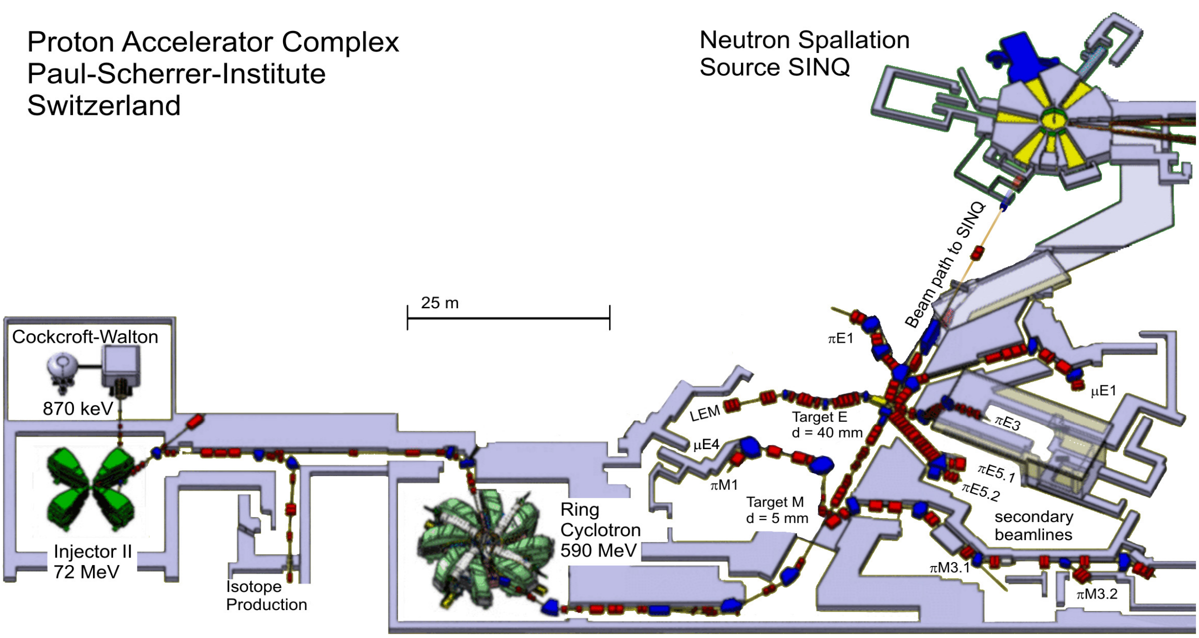

Figure 1: Overview of the PSI accelerator complex.

RECENT PERFORMANCE IMPROVEMENTS AND DEVELOPMENTS

Ring Resonators and Double Seals

The original aluminium resonators in the Ring cyclotron were successively replaced by newly designed copper resonators. The first resonator was installed already in 2004, and for some time the cyclotron was operated with both types of resonators in parallel. The new setup with all four resonators in place was completed in 2008. The new resonators can be operated at higher gap voltages, which allows reducing the number of turns in the cyclotron. In fact, because of longitudinal space charge effects the beam losses scale inversely proportional to the third power of the number of turns [3][4]. Thanks to this improvement and a new operational license a standard current of 2.2 mA, corresponding to 1.3 MW beam power, was reached in 2009. The losses at 2 mA were reduced by a factor ~2 (Fig. 2). The resonators are now operated at a voltage of 850 kV and the specification leaves room for further increases slightly beyond 1 MV. At present the limitation is given by the third harmonic resonator whose voltage cannot be raised in proportion. Because of smaller ohmic losses in the 4 copper resonators roughly 600 kW of wall plug power are saved. The efficiency of the RF system for converting wall plug power to beam power amounts to 0.32. It is obtained by multiplying the efficiencies 0.9 for AC/DC conversion, 0.64 for DC/RF conversion and 0.55 for RF to beam power. A review of resonator and RF development at PSI is given in these proceedings [5].

Together with the resonators a new type of inflatable seals was installed in the Ring cyclotron [6]. The design of these seals is critical since they need to have a relatively long length of 2.5 m. The new design incorporates two O-ring seals with an intermittent evacuated volume that also serves testing puposes (Fig. 3). After the installation practically no vacuum leaks were observed, whereas such problems occurred rather often with the old seals.

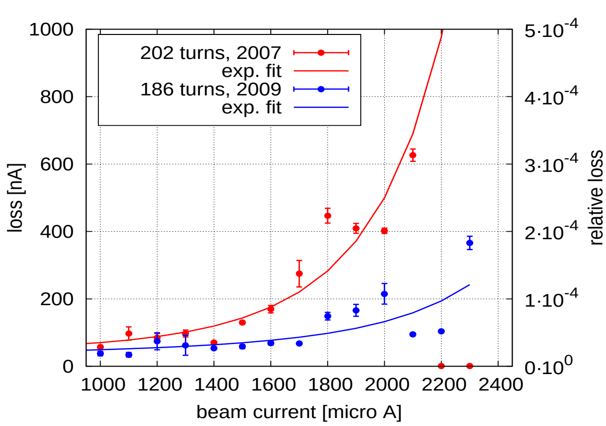

Figure 2: Loss currents under optimal conditions as a function of beam current. The turn reduction due to higher gap voltages led to a significant reduction.

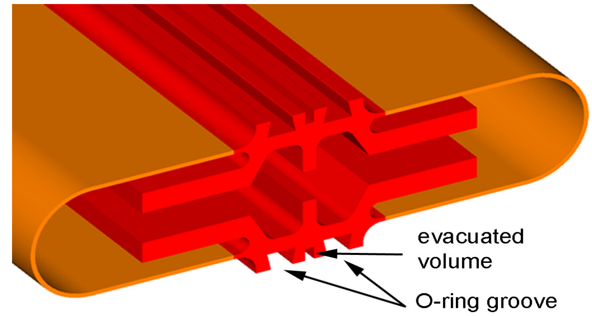

Figure 3: CAD model of the new inflatable seals that are in use to connect resonators and neighboured chambers.

ECR Proton Source

In 2010 a new ECR proton source [7][8] was brought into operation. While the old source was electrically heated with filaments that had to be replaced every two weeks, the new source employs the ECR principle and does not require regular service. At the time of writing the source was continuously in operation for 3.5 months. With RF powers between 390 W and 600 W the generated proton current is in the range of 12 mA to 18 mA. The rms beam emittance was measured to be 4.2 mm mrad and is supposedly smaller than the one of the old source. Nevertheless it took a long time to retune the accelerator in 2010 for operation at similar loss levels as with the old source in 2009. One hypothesis is that slight beam optical mismatch of source and injector II cyclotron have led to these difficulties.

10^th^ Harmonic Buncher

The 500 MHz "superbuncher" was installed delayed in fall of 2009. The buncher is situated in the 72 MeV transfer line between injector and Ring cyclotron with the goal to generate a short bunch length at injection and to establish the circular beam scheme also in the Ring cyclotron [4]. For further reduction of the turn number in the Ring the function of the buncher is critical since the voltage of the existing flattop resonator cannot be raised further. With empirical tuning of amplitude and phase a positive effect on the losses was observed at low currents of ~200 µA. At higher currents only increasing losses were observed. It is suspected that a better relative phase control for the three phases of buncher, injector and Ring cyclotron is needed. Furthermore it might be necessary to readjust the transverse optics when the buncher is operated. Because of many technical and performance problems in 2010 it was not possible to study the effect of the buncher in more detail.

OPERATIONAL EXPERIENCE

Beam Currents and Losses in 2009/10

As mentioned the turn number reduction in the Ring cyclotron of 2008 has lead in principle to a significant reduction of the losses. However, the optimal setup is fragile and minor technical problems can already result in a strong increase of the losses and limitations of the beam current. During start-up in 2009 such problems were caused by a misaligned vertical collimator that covers the complete radius in the Ring cyclotron. The tighter vertical aperture caused enhanced scattering of the beam tails (Fig. 5). The collimator is realised as a pair of graphite sheets and was probably deformed because of heating due to stray RF waves. The original purpose of the fixed collimator was to provide a passive protection system in case of beam mis-steering. Since the loss-monitor based interlock system has been significantly improved over the years it was decided that the collimator could be safely removed. Afterwards it was easily possible to accelerate 2.2 mA. During tests a peak current of 2.3 mA was achieved without problems (Fig. 4).

In 2010 the start-up was suffering from plasma effects that were generated in the Ring cyclotron as a result of excessive stray RF amplitudes [9]. Sputtering effects caused thin coatings on the insulator surfaces of the electrostatic extraction element and it had to be replaced. But also after this problem was overcome, the facility suffered from enhanced losses at the Ring extraction which limited the maximum current to 2.0 mA till the beginning of August. Enhanced energy and beam position jitter at 50 Hz disturbed the operation. This problem was resolved as described in the next section. After careful retuning and cycling of the dipole magnets in the Injector II cyclotron the losses were finally reduced to an acceptable level and operation at 2.2 mA was resumed. It is now believed that improper optical matching of the beamline from the source to the injector cyclotron has caused the enhanced beam tails and the resulting losses. Remarkably, when the enhanced losses were present it was not possible to directly measure an enhanced emittance or detect signs of beam tails. These profile measurements were done using beam tomography methods [10] with 5 wire scanners in the horizontal plane of the 72 MeV transport line. The problems observed in 2010 demonstrate how difficult it actually is to tune the accelerator to optimum loss conditions. Many efforts are also invested to accurately simulate the beam dynamics of the high intensity beams in cyclotrons [11].

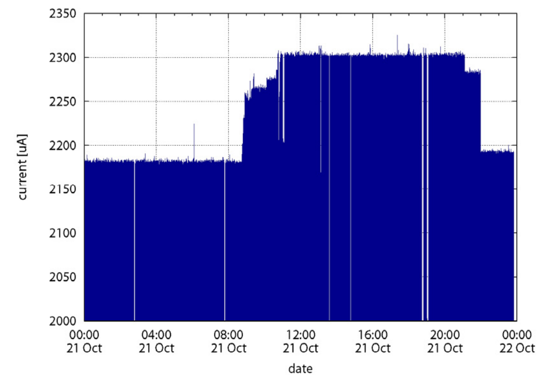

Figure 4: Example of stable operation beyond the standard current at 2.3 mA (1.36 MW) in 2009.

50 Hz Jitter Impairing the Performance of the Accelerator

After the installation of the new ECR source an enhanced 50 Hz beam jitter was observed. In the 590 MeV beamline to the meson production targets the horizontal position jitter was as large as 2 mm, corresponding to more than one rms beam width. Only little jitter was present in the vertical plane. The jitter was traced back to an energy modulation of the beam caused by 200 V peak to peak jitter of the 810 kV accelerating voltage in the Cockcroft Walton accelerator (CW). However, finally it turned out the primary reason was a beam current modulation in the proton source, whose magnitude exceeded the voltage stabilization capabilities of the CW power supply. The RF generator of the source is a filament heated magnetron. Replacement of the Magnetron power supply with a better stabilized one and an improved regulation of the CW voltage resolved the problem and led to a reduction of the jitter amplitude by a factor 3. There is still significant 50 Hz jitter present, caused by other sources. Further improvements are necessary to reduce these disturbing effects.

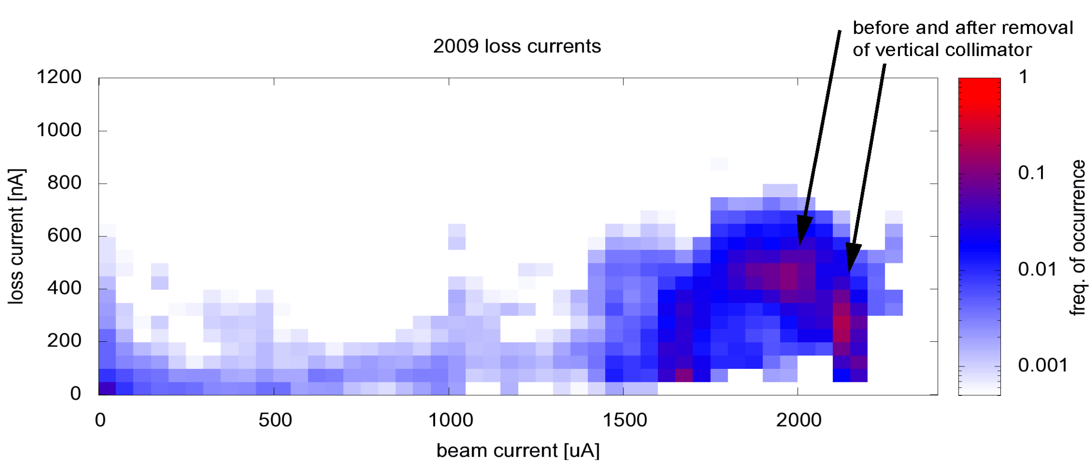

Figure 5: Distribution of extraction losses as a function of current. The colour code corresponds to the frequency of operation at the particular working point. Loss monitors were calibrated by provoking total loss of a small test current.

Beam Trip Statistics

Beam trips interrupt the user experiments and cause thermal cycles for the targets which may lead to a reduction of their lifetime. Also in view of potential ADS applications of cyclotron based high intensity accelerators the demonstration of a good trip performance is of interest. Most of the short term interruptions in the cyclotron are caused by high voltage trips of the electrostatic elements which deflect the injected and extracted beams. Other causes are occasional triggers of the interlock system by spikes in the lossrates, or trips of the RF system. In most cases the system that originated the interruption is automatically reset and the current is ramped up again within 30 seconds.

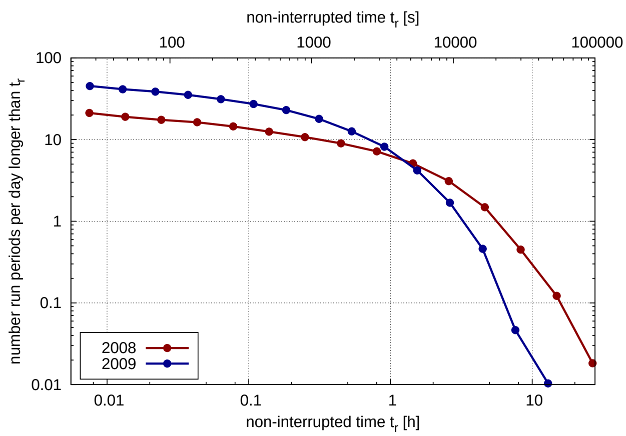

Figure 6: Distribution of durations of non-interrupted run periods in the years 08/09. The differential distribution is integrated from the right. It shows how many runs per day occur with the duration of the abscissa value or longer.

The graph in Fig. 6 shows the number of runs per day with a duration longer than the value read from the abscissa. At the very left end of the graph one can read the total number of runs (and trips) per day. On average 20 to 60 trips per day are observed and the longest un-interrupted runs have a duration of 10..20 hours. In 2009 the accelerator was run at 2.2 mA vs. 2.0 mA in 2008 and the enhanced current could be a reason for the decreased performance. In comparison the desired trip rates of planned ADS systems for transmutation or energy production are in the range 0.1-0.01 d-1 [12], i.e. 2 to 3 orders of magnitude lower.

PLANNED UPGRADE MEASURES

PSI pursues a continued upgrade program with the goal to improve the reliability of the accelerator complex and to raise the beam intensity in steps towards 1.8 MW [13].

New Resonators and RF Systems for the Injector II

The most important upgrade step for the PSI facility is the installation of two new resonators in the Injector II cyclotron. These 50 MHz resonators will replace existing 150 MHz flattop resonators, which are no longer needed because the cyclotron is operated in the circular beam regime [4]. A new resonator type has been designed and two copies are being manufactured at the French company SDMS. Fig. 8 shows a photograph of the first delivered resonator. These cavities are made from aluminium, they exhibit a sector shape and the challenges of the mechanical design lie in a good cooling concept assuring frequency stability. During operation a hydraulic tuning mechanism will regulate the frequency [14].

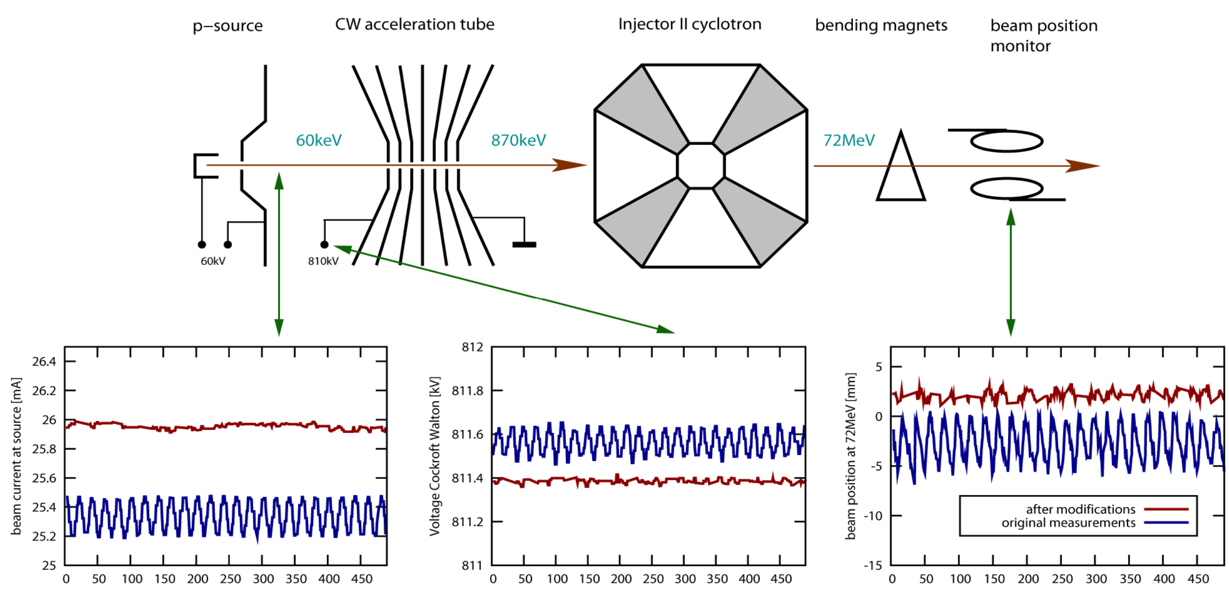

Figure 7: Illustration of the propagation of a initial 50 Hz beam current ripple at the proton source throughout the accelerator. The red curves were recorded after taking the measures described in the text.

Figure 8: The first one of two new resonators for the Injector II, delivered by the French company SDMS.

At present the first delivered resonator is undergoing high power testing at PSI. The resonator was successfully operated at specification level of 100 kW RF power for several days.

New Absorbers at the Meson Production Target

Because of scattering in the 40 mm target, a large fraction of the beam has to be collimated. Roughly 12% of the protons are lost due to nuclear reactions and the debris is absorbed by collimators behind the target. Additional 18% of the beam are collimated because the elastically scattered protons deviate too much from the ideal orbit and could not be transported to the SINQ spallation target. The first two collimators are situated close to the target and exhibit wide opening angles. They absorb secondary particles and thermal radiation. The main collimation is done with two water cooled and segmented copper collimators with a length of 30 cm each. They are installed 4.7 m downstream of the target. At a current of 2.0 mA, this collimator system is estimated to receive a total heat load of ~170 kW, and the peak temperature is calculated to reach ~650 K. After 20 years of operation the first of those collimators has received a high radiation dose. Irradiation damage corresponding to values of 12 to 35 dpa on average were estimated using different computer codes. In order to verify the intactness of the inner surface, the collimator was taken out in the shutdown 2010 and inspected in a hot-cell. Although on parts of the inner surface thin flitters of copper were found, the bulk material seems intact and no signs of swelling were found. A dose rate of ~500 Sv/h was measured on the beam axis close to the entrance into the collimator. In order to reach 3 mA with new absorbers, the deposited power has to be distributed more evenly over the two absorbers. In parallel the aperture of the collimators will be slightly opened without affecting their function to reduce the power deposition. With the help of this measure acceptable peak temperatures are expected. The application of GlidCop as a material with better strength at elevated temperatures would result in a working scheme even without opening the apertures [15]. However, brazing with GlidCop is more difficult and more testing is needed before a decision on the choice of material can be made.

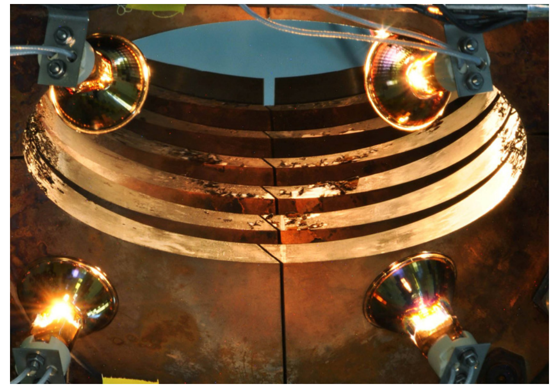

Figure 9: The inner surface of the existing collimator 2 seen from the side of the beam exit and tilted by 90°.

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