STATUS AND FURTHER DEVELOPMENT OF THE PSI HIGH INTENSITY PROTON FACILITY

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Abstract

The High Intensity Proton Accelerator Facility of the Paul Scherrer Institut is routinely operated at an average beam power of 1.3 MW. Since the last cyclotron conference several highlights have been achieved. The maximum current extracted from the Ring Cyclotron could be increased from 2.2 mA to 2.4 mA during several beam development shifts. Furthermore, the availability of the facility has reached its highest level to date. To even further increase the intensity the beam losses caused by space charge effects have to be reduced to keep the absolute losses at a constant level. This paper gives an overview of the measures taken to increase the beam power while ensuring a high operational reliability. Furthermore, the on-going upgrade program of the RF-system and concepts to compensate for losses caused by space charge effects are presented.

INTRODUCTION

The PSI high intensity proton accelerator facility consists of three accelerators starting with a Cockcroft-Walton type pre-accelerator and a chain of two isochronous sector cyclotrons operated at frequency of 50.6 MHz (Fig. 1). The beam is produced by extracting protons from an Electron Cyclotron Resonance (ECR) source by means of an electrostatic lens system with a voltage of 60 kV. The particles are further accelerated to a kinetic energy of 870 keV by the Cockcroft-Walton pre-accelerator and then vertically injected into the Injector 2 cyclotron. After about 80 turns in Injector 2 the beam is extracted with 72 MeV and then transferred to the Ring cyclotron. The continuous wave beam (CW) is sent to two meson production targets to produce pions and muons used for material research. The targets are realized as rotating carbon wheels of 5 mm (Target-M) and 40 mm (Target-E) thickness respectively [1]. After passing the two targets the beam is collimated and the remaining beam current of 1.55 mA is sent to a spallation target for neutron production. The target installed in the Swiss Spallation Neutron Source (SINQ) consists of a matrix of lead filled Zircaloy tubes. The neutrons produced are moderated in a heavy water tank and are then guided to 13 different user stations. Furthermore, the 590 MeV beam can be kicked towards a pulsed source for the production of ultracold neutrons (UCN) which has successfully been brought into operation in 2010 and is now routinely delivering ultracold neutrons in a pulsed mode mainly for the investigation of the electric dipole moment of the neutron.

OPERATIONAL PERFORMANCE 2012

After almost 40 years of operation, the PSI proton facility has reached its highest availability to date. In 2012 the overall availability of the facility increased from 91.5% in 2011 to 93.5% which corresponds to roughly 30% less outages. Accordingly, the integrated charge delivered to the targets has reached an all-time high (see Table 1). In Fig. 2 the development of the yearly performance of the facility during the past eleven years is shown together with the main reasons causing downtime. Furthermore, in Fig. 3 the outages exceeding 5 minutes of downtime are characterized. It can be noticed that 44% of the downtime in 2012 was caused by failures of the two meson production targets.

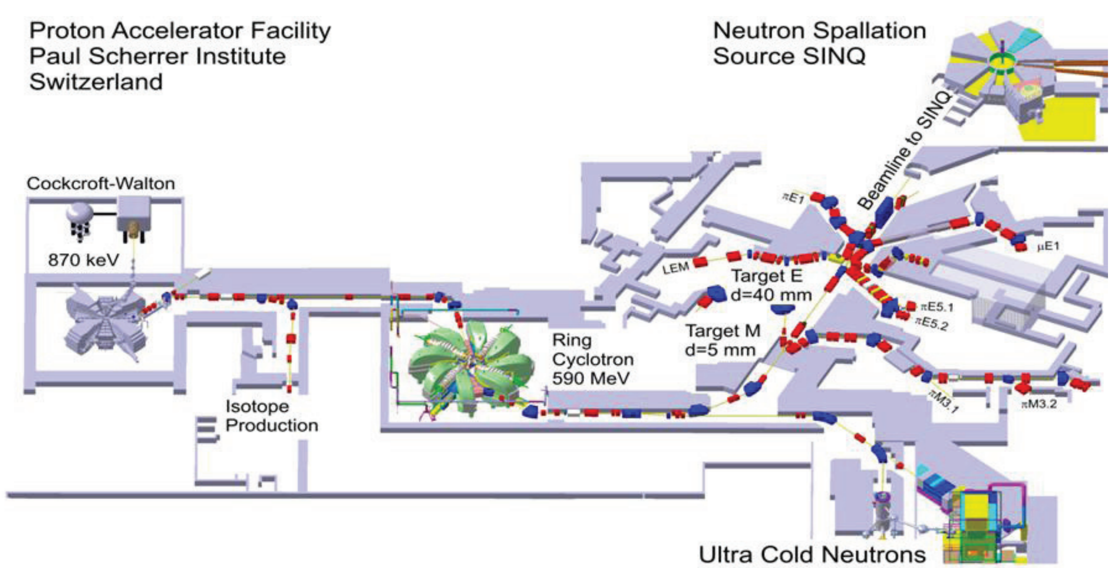

Figure 1: Overview of the PSI high intensity proton accelerator facility confining an area of 120 m × 220 m.

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Table 1: Beam Time Statistics for the Proton Facility in 2012 [2]

Target	Total Beam Time	Delivered Charge
Meson Production	4936 h	10.4 Ah
SINQ	4885 h	7.1 Ah
UCN	n.a.	0.06 Ah
Outages > 5 min		205.0 h
Total outages (current < 1 mA)		275.5 h
Overall availability		93.5%

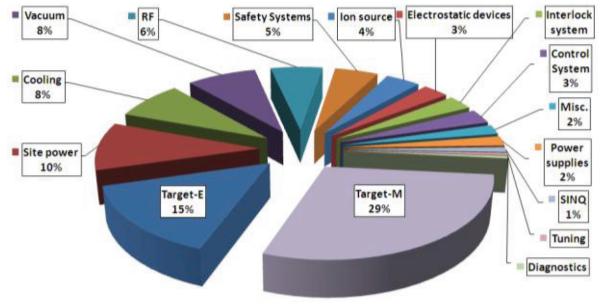

Figure 3: Characterization of the downtime of the proton facility for 2012. Only outages exceeding 5 minutes are taken into account (total 205 hours).

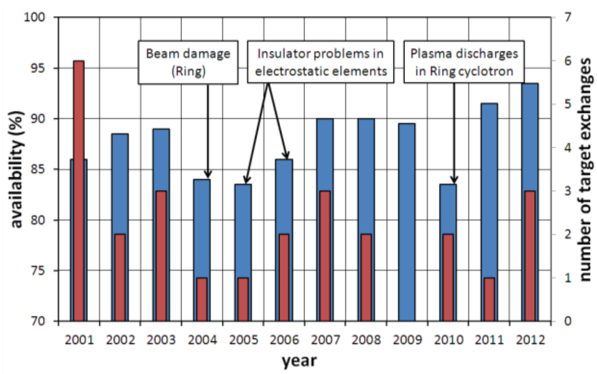

Figure 2: History of the availability of the PSI proton facility (blue) and the number of exchanges of the meson production targets (red) over the last 11 years.

Problems with the targets typically start with an increased torque that approximately two weeks later results in failure of rotation. Though, the deadlock of the thin target (Target-M) occurred with virtually no indication of an increased torque and therefore the replacement could not be performed during a regular planned service period. Since the whole facility performed so well in 2012 this interruption had a significant impact on the overall availability. In both cases the reasons for the failure were ball bearings that are operated in a harsh environment of radiation, vacuum, and high temperature gradients. In fact no oil or grease can be used for lubrication due to the high radiation level around the targets. At the time of failure the targets were in operation for seven (Target-E) and four months (Target-M), respectively. In the past years though, the targets had to be replaced up to six times (see Fig. 2, red bars). Further interruptions were mainly caused by problems with the infrastructure, i.e., cooling and site power. In contrast, the percentage of interruptions caused by the electrostatic elements dropped to a value of only 3%. This is remarkable since these elements caused the comparatively low availability in 2005 and 2006 (Fig. 2). The improvements that led to a now stable operation of these elements are the shielding against RF-influence and the enhanced vacuum in the Ring cyclotron [3]. Furthermore, a redundant beam stopper right opposite to the electrostatic extraction channel in the Ring cyclotron was removed from the vacuum chamber. RF-pickups installed in the vicinity of the extraction channel proved that RF-power decoupled from the cavities was deflected towards the extraction channel by the beam stopper which was causing discharges.

Concluding the operational performance it should also be mentioned that already in the first week of user operation the facility exhibited a rather high availability of more than 85% which is due to the fact that after the shutdown two weeks of beam development were invested to grant stable operation.

RECENT ACHIEVMENTS AND DEVELOPMENTS

During the last Cyclotron conference several important improvements of the facility, e.g., the replacement of the aluminium resonators by copper stainless steel structures and the installation of a new ECR-proton source have been reported on already [4]. It turns out that since 2004 the most important step towards the goal of a 1.8 MW beam was the decrease of the number of turns in the Ring cyclotron. Joho showed in his empirical law that the beam losses in the cyclotron scale with the number of turns to the cube [5, 6]. Following this law the beam current routinely extracted could be increased from 2.0 mA in 2007 to now 2.2 mA. This corresponds to a number of turns in the Ring cyclotron of 202 and 186 respectively whereas the peak voltage of each of the four cavities was increased from 750 kV/p to approximately 850 kV/p. In 2011, for the first time the beam current extracted was raised to 2.4 mA during several beam development shifts for periods of up to 16 hours. As can be seen in Fig. 4 the extraction losses at the extraction of the Ring cyclotron increase by a factor of roughly two from 120 nA to 250 nA. After several hours of tuning the losses could further be reduced to 200 nA which is a factor of two less than in 2007 when the facility was still operated at 2.0 mA with 202 turns in the Ring cyclotron.

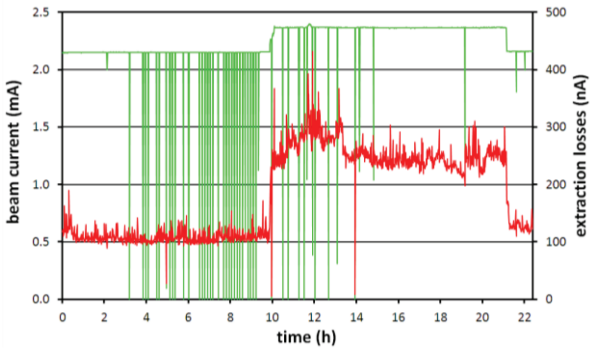

Figure 4: Example of a beam development shift in 2012 when the current extracted (green) was increased from the standard 2.2 mA to 2.4 mA. The extraction losses (red) thereby increase by a factor of roughly 2.

To further increase the beam power it seems obvious to raise the peak voltages of the main resonators in the Ring cyclotron. Though the cavities were designed for a maximum peak voltage of 1.2 MV it is not straight forward to proceed to such high voltages. The third harmonic flat-top cavity installed in the Ring cyclotron is limited to a voltage of 550 kV/p since the tuning and cooling systems are already running close to their limits. An increase of the main resonators' peak voltage would require an increase of the flat-top voltage to keep the phase acceptance of the Ring cyclotron constant. Even if the voltage of the third harmonic cavity could be increased space charge effects cause the proton bunches to expand also longitudinally with increasing beam current. At some current limit the bunch length is expected to exceed the phase acceptance of the Ring cyclotron of 60°. Therefore, within the last two years, focus was put on the commissioning of the 10th harmonic buncher that was installed in fall of 2009. This 500 MHz buncher is located in the 72 MeV transfer beamline between Injector 2 and the Ring Cyclotron. By re-bunching the beam extracted from the injector cyclotron the bunch length is expected to become short enough for the phase acceptance of the Ring cyclotron. In fact it was shown that by tuning the amplitude and the phase of the buncher that the proton bunches could be compressed from to maintain a length of 10 cm (1.5°) at the point of injection of the Ring cyclotron. Due to raising losses mainly generated by space charge induced distortions of the bunches the current extracted from the Ring cyclotron is up to now limited to 1 mA with the buncher voltage switched on. A review on the experimental results with the re-buncher is given in these proceedings [7].

PLANNED UPGRADES

As already reported during the last Cyclotron conference the most important activity is the installation of two new 50 MHz resonators that will replace the 150 MHz flat-top resonators in the Injector 2 cyclotron [4]. Since Injector 2 is operated in the circular beam regime with space charge dominated acceleration, a flat-top system is no longer needed. The manufacturing of the presently used 150 MHz amplifier tubes is discontinued, thus the replacement must be completed within a few years to ensure the long term availability of the facility.

The achievable higher peak voltages will result in less turns in the cyclotron and therefore in lower losses and a better quality of the beam extracted. The two new resonators designed and manufactured in collaboration with the French company SDMS [8] have both been delivered to PSI and are now being tested. The resonators where designed for peak voltages of up to 400 kV/p. First measurements show that a connecting cluster supporting the electrodes of the resonator reaches temperatures of up to 150°C when setting the peak voltage to 400 kV. Since this is above the desired value of 60°C several screws for mounting the electrodes in the centre of one of the resonators melted during the tests and had to be replaced. Presently, the cooling of the connectors is being optimized by improving the thermal contact and, furthermore, existing built-in components like collimators and beam probes are being redesigned to match the new constructional situation given by the resonators. The commissioning of resonator 2 is scheduled for the beginning of 2017 and one year later for resonator 4.

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