PRODUCTION OF A 1.3 MW PROTON BEAM AT PSI

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Abstract

With an average beam power of 1.3 MW the PSI proton accelerator facility is presently at the worldwide forefront of high intensity accelerators. This talk describes critical aspects and recent improvements related to generation and transport of the high intensity beam in a cyclotron based facility. The installation of new accelerating resonators in the second of two cyclotrons led to a significant improvement in view of beam intensity but also the reliability of the facility. Besides the overall performance and further upgrade plans the discussed topics include: space charge dominated beam dynamics, beam loss handling, activation and specialized technical interlock systems.

FACILITY OVERVIEW

The PSI high intensity proton accelerator generates a proton beam with 590 MeV kinetic energy and presently 1.3 MW average beam power. In practice, the performance is limited by the beam losses at the extraction of the Ring cyclotron. The relative 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 SINQ fits in a rectangle of 120 m × 220 m. The high intensity 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 $5 \cdot 10^8\ s^{-1}$ are achieved [2]. The polarized muons are mainly used for muon spectroscopy experiments. After collimation the remaining beam with roughly 1 MW 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 (D_2O) 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 of the facility.

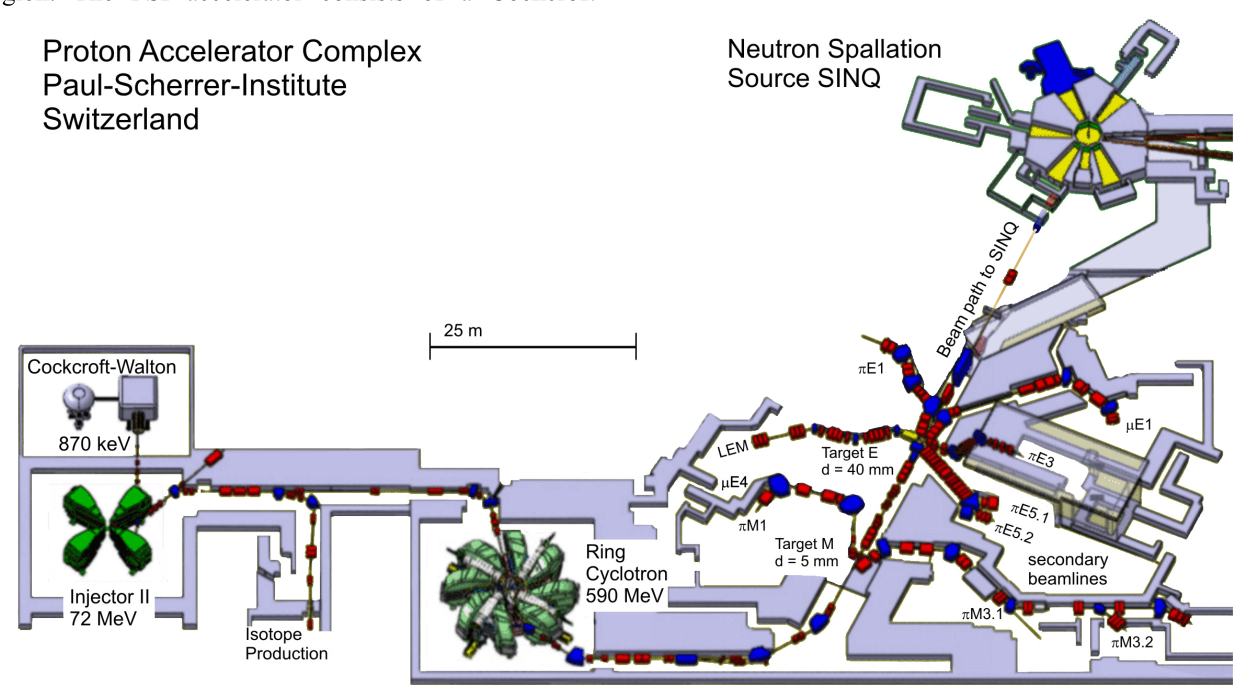

Figure 1: Overview of the PSI high intensity accelerator complex.

SECTOR CYCLOTRONS

In isochronous cyclotrons the revolution time of the particles is kept constant during the course of acceleration. RF frequency and bending field are not cycled and thus the cyclotron is ideally suited for CW acceleration. The particle velocity increases proportional to the orbit radius while the average B-field must be scaled proportional with the relativistic factor γ towards larger radii. In a homogenous bending field the positive slope with radius would lead to a loss of vertical focusing, but sufficient focusing can still be achieved through the introduction of azimuthal field variation (flutter) and spiral shaping of the magnet boundaries [3].

Sector cyclotrons are realized in a modular concept, involving the combination of sector shaped magnets and RF resonators forming a ring. As compared to the classical single magnet cyclotron larger flutter can be obtained, which permits to reach energies up to 1 GeV. The modular concept of sector cyclotrons allows the construction of large diameter cyclotrons which is essential for the realization of low loss extraction schemes with electrostatic deflectors. The electrode of the extraction channel is placed in the gap between the last turns. Scattering of halo particles in the material of the electrode presents the major loss mechanism. Sufficient turn separation is important to keep these losses small. The radius increment per turn is estimated as follows:

$$\frac{dR}{dn_t} = \frac{R}{\gamma(\gamma^2-1)}\frac{U_t}{m_0c^2},$$

where U_t/m_0c^2 is the energy gain per turn and rest energy, R the orbit radius and γ the relativistic factor. Thus obtaining a large turn separation is increasingly difficult with higher beam energy, while a large extraction radius is desirable. Secondly it is essential to achieve the highest possible energy gain per turn. In practice the performance of high intensity cyclotrons is limited by extraction losses. The generation of transverse beam tails due to space charge forces counteracts turn separation. The understanding and control of space charge effects is of major importance to minimize the losses.

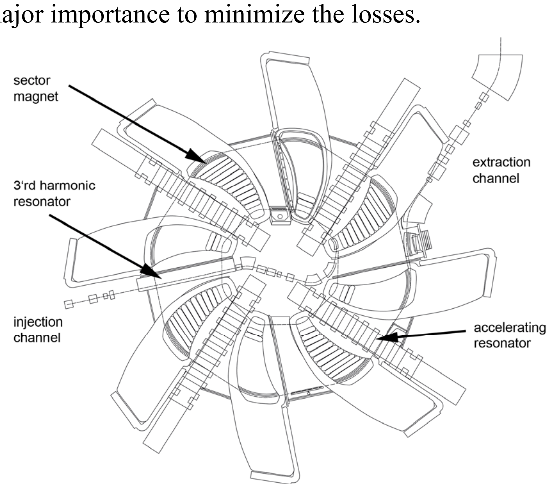

Figure 2: Schematic top view of the PSI Ring cyclotron.

PARAMETERS AND BEAM DYNAMICS

As mentioned before the PSI facility has three acceleration stages. Significant emittance growth occurs in the 40 mm graphite target and results in unavoidable collimation loss in specially shielded collimators. Selected beam parameters along the accelerator chain are shown in table 1, the optics of the high energy transfer line that contains the targets in Fig. 5 (see also [4]).

Table 1: The parameters beam current, kinetic energy, horizontal emittance, relative loss along the accelerator.

	I_{beam} [mA]	E_k [MeV]	$\beta\gamma\varepsilon_x$ [μm rad]	rel. loss
at p-source	25	0.06	0.13	
transfer to Inj II	10	0.87	1.3	
extraction Inj II	2.2	72	2.5	$< 10^{-4}$
transfer to Ring	2.2	72	2.5	$\approx 2\cdot10^{-3}$
extraction Ring	2.2	590	7.5	$\approx 2\cdot10^{-4}$
transfer to SINQ	1.5	572	42	0.3

The maximum attainable beam current is limited by the acceptable radiation level due to beam losses. In the transverse planes space charge force causes a shift of the focusing frequencies that may result in resonant losses. The longitudinal space charge force leads to an increase in energy spread that transforms into transverse beam tails. Such tails are finally causing the mentioned losses and activation at extraction. Within a simplified model involving rotating sectors of uniform charge density, it was shown by Joho [5] that losses caused by longitudinal space charge forces scale with the third power of the number of turns in a cyclotron. Consequently the intensity upgrade path of the facility involved improvements on RF systems and resonators to achieve higher gap voltages. Over the history of the PSI Ring cyclotron the number of turns was reduced from >300 to 188 as of today. In the Ring cyclotron the turns are partially overlapping. For precise prediction of the beam dynamics forces from neighboring bunches must be taken into account [6]. With the tracking code OPAL it is possible to follow ~10^8 macro particles through the acceleration process and to predict the beam pattern at extraction with large dynamic range (Fig. 3).

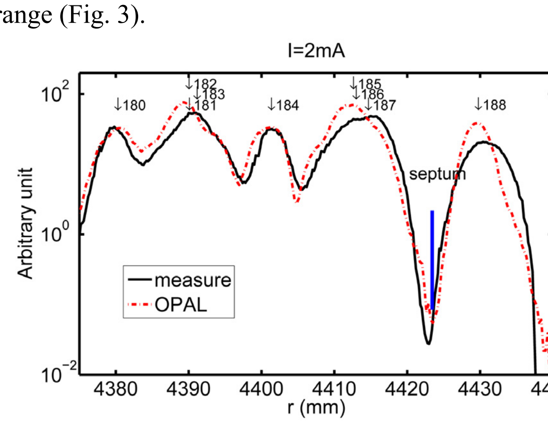

Figure 3: Radial beam profile with indicated turn numbers at extraction. The density is minimized at the location of the extraction electrode.

For very short and transversally separated bunches a different regime can be entered that results in the formation of a compact and stable circular bunch shape. In this case complete coupling between the longitudinal and radial degrees of freedom is established [7, 8]. At PSI this operating regime is observed in the Injector II cyclotron. The profiles in Fig. 4 are measured by detecting protons scattered at a vertically oriented wire probe, placed at varying horizontal positions. The distribution of such events is recorded as a function of time [9]. In 2009 a new 10th harmonic buncher cavity [10] was installed in the 72 MeV transport line, in-between Injector II and Ring cyclotron. The new re-buncher should permit the injection of much shorter bunches, and thus it is expected that the circular beam regime can be reached in the Ring cyclotron as well.

OPERATIONAL EXPERIENCE AND SPECIFIC EXPERTISE

A comprehensive and fast run permit system (RPS) prevents damage or excessive activation of components and proved to be of utmost importance for practical operation of the high intensity facility. With typical beam sizes it takes between 10 ms and 100 ms to melt stainless steel with a mis-steered beam. The interlock system detects such losses within 100 µs and it is set up redundantly. Roughly 1500 signals are monitored within the RPS, occupying 150 CAMAC and VME crates. Loss measurements from 110 ionization chambers and 180 collimators and segmented aperture foils are used to verify the correct loss pattern in the accelerator. The beam is stopped when a value exceeds a certain limit, but also when it falls significantly below the normal value. The limit values at which the RPS stops the beam are adjusted dynamically with the beam current. When the loss conditions are exceeded only moderately, the system intervenes with some time delay to give the operator a chance to adjust parameters. Further interlock-relevant parameters include beam transmission measurements, magnet/cavity parameters, component temperatures, and a system that directly monitors the peak current density in front of the spallation target [11]. The fast ramp up of the beam current in the 72 MeV transfer line is facilitated by orbit feedback based on 120 inductive BPM's. Phase probes in the cyclotrons allow adjusting main field and trimcoils. 190 wire monitors/radial probes, harps and fluorescence monitors are used to monitor the beam profiles [12].

As described before the highest beam loss occurs in the extraction beamline. Residual dose rates reach 10 mSv/h in this area, while average levels in the Ring cyclotron are around 1 mSv/h or less (Fig. 6). An ultimate and most relevant measure for the activation levels in the accelerator is given by the radiation dose, the service personnel receives during the 4 month shutdown work per year. In 2010 186 persons were involved in these service activities and they received a collective dose of 47 mSv. Over the history of the PSI accelerator there is no correlation visible between the personnel dose and the yearly integrated beam charge [13].

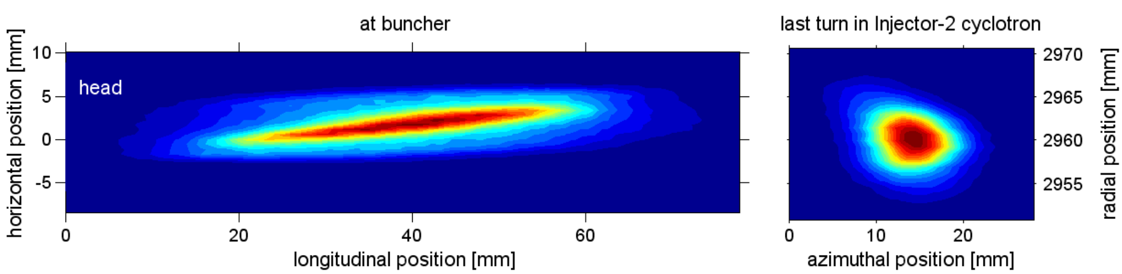

Figure 4: Particle density for a current of 2.2 mA at 72 MeV, measured at the exit of the PSI Injector II cyclotron (right) and after an additional drift length of ~20 m. The strong blowup in a comparably short drift space demonstrates the strong focusing effect of the circular beam regime within the Injector II cyclotron.

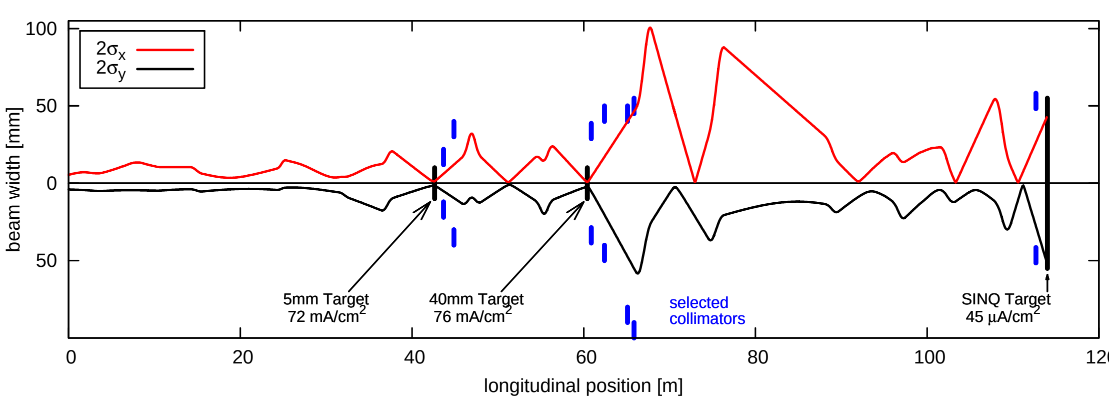

Figure 5: Horizontal and vertical beam envelopes in the transfer line from Ring cyclotron to SINQ. The two meson production targets and the SINQ spallation target are indicated with current densities. Selected collimators are shown.

Naturally the aspect of radiation safety plays an important role for the operation of a high intensity accelerator. A dedicated radiation safety group with 10 specialists takes responsibility for all related aspects. In total ~1300 employees at PSI are radiologically monitored, but only ~180 of them are directly involved with service at the accelerator. The whole facility is monitored with a grid of 100 TLD/CR39 dosimeters and 16 remote controlled radiation detectors.

Over the recent years the average availability of the PSI proton accelerator, defined as delivered beam time divided by scheduled beam time, has reached a level of 90%. Major statistical contributions to the downtime are vacuum leaks and failures of the electrostatic devices. These devices are critical since their insulators suffer from metallic deposits, originating from sputtering processes. Short (30 sec) beam interruptions occur at a rate of 20 to 50 per day. The frequency of such beam trips has some potential impact on the lifetime of targets due to thermal cycling, although in practice fatigue failures were never observed. Typical causes for beam trips are RF trips, high voltage breakdown of electrostatic devices and bursts of the loss rates, caused by beam jitter.

The operation of a high intensity proton beam facility requires specific tools and installations such as mobile shielding flasks for targets, a dedicated hot cell for service of activated components or the ability to perform analytics of radioactive materials. To predict radiation fields or generally the effects of beam interaction with material, numerical modelling is performed in many areas. In particular the following areas are covered using the numerical codes given in brackets: particle transport and neutronics (MARS/MCNPX), material activation and qualification of radioactive waste (PWWMBS/ MCNPX), layout of shielding (MCNPX/ATTILA), cooling and thermo-hydraulics (ANSYS/CFD-ACE).

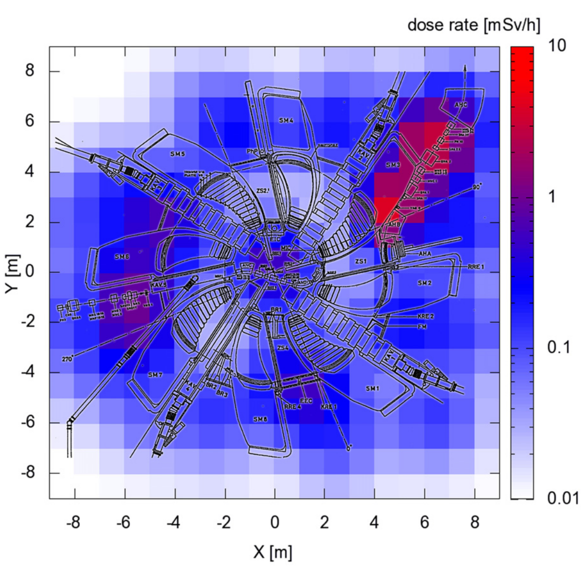

Figure 6: Map of residual dose rates in the Ring cyclotron. The map is interpolated from ~30 data points.

CYCLOTRON KEY COMPONENTS

In particular magnets, electrostatic elements, resonators and RF systems are key components in the PSI Ring cyclotron. The majority of the total beam power is transferred to the beam through the four 50 MHz resonators. These cavities are designed as box resonators with continuously regulated tuning mechanisms. Major parameters are: $Q_0 = 4{\cdot}10^4$, $f = 50.6$ MHz, $U_{max} = 1.2$ MV. The efficiency of the RF system for transferring electrical wall plug power to beam power amounts to 0.32. This number is obtained by multiplying the efficiencies of subsystems: 0.9 for AC/DC conversion, 0.64 for DC/RF conversion and 0.55 for RF to beam power, where wall losses in the resonators limit the efficiency.

Electrostatic elements are used for injection and extraction of the beam. A thin electrode is realized as a series of 50 µm tungsten stripes and placed in-between two turns in the cyclotron. In this way a good thermal tolerance against temporary energy deposition from mis-steered beam is achieved. The deflection of protons that scatter in the material is minimized. The extraction element has the following parameters: $l_{eff} = 920$ mm, $d_{gap} = 16$ mm, $U_{gap} = 140$ kV, $\theta_{beam} = 8.2$ mrad. In good condition it shows 2-5 high voltage breakdowns per day.

The eight cyclotron magnets with a weight of 250 tons each reach a peak field of 2 Tesla. The detailed field shape is important to fulfil the isochronous condition across the radius. For empirical fine tuning the magnets contain 18 circuits of correction coils.

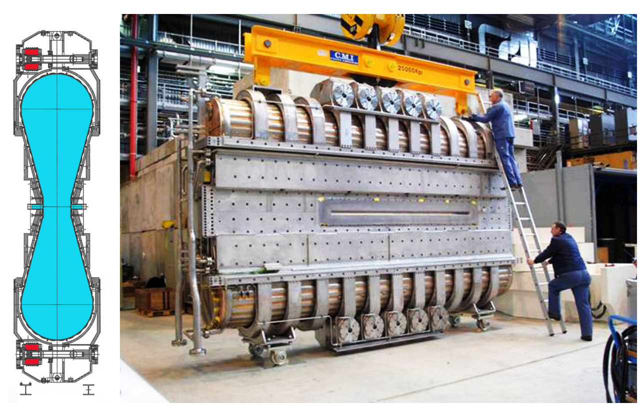

Figure 7**:** Cross section (left) and photograph of the 50 MHz accelerating resonator of the Ring cyclotron.

DEVELOPMENT PLANS AND OUTLOOK

A continuous upgrade and improvement program is being pursued at the PSI high intensity proton accelerator. In the years 2005-2008 four new copper resonators were installed in Ring cyclotron to replace the original aluminium resonators. These resonators deliver higher gap voltages and the resulting reduction of the turn number allowed increasing the beam current to 2.2 mA. Another improvement was achieved in 2007, when the installation of a harmonic buncher at 870 keV led to a strongly improved capture efficiency in the Injector II [14]. This measure also helped to establish the very compact bunch shape as shown in the previous section.

The short bunch length makes it possible to replace the two flat-top resonators in the Injector II cyclotron by new accelerating resonators operating at 50 MHz. 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 [15]. In the 55 m long transport line between Injector II and Ring cyclotron a 10^{th} harmonic (500 MHz) re-buncher [10] has been installed to counteract the space charge blowup. From simulations [16] it is expected that also in the Ring cyclotron the existing 150 MHz flattop resonator can be reduced in voltage when significantly shorter bunches are injected. Commissioning of the buncher is under way. Another improvement is expected from the development of a new ECR proton source with better emittance and reliability [17]. The new source replaces a filament heated source and is brought into operation in 2010. Finally the intensity upgrade requires improving the set of collimators [18] behind target E for acceptance of higher power. The new concepts involve an optimized geometry and more even distribution of the power onto the individual units.

Figure 8: New 50 MHz accelerating resonator for the Injector II cyclotron in the PSI HIPA facility.

In summary the upgrade plans [19] of the PSI facility foresee a stepwise increase of the beam intensity to 3.0 mA. The major ingredients of the upgrade path consist in higher resonator voltages in both cyclotrons and shortening of the bunch length by utilizing a special 10^{th} harmonic buncher cavity. The faster acceleration process permits to increase the beam power at constant absolute losses. The installation of two new resonators in the Injector II cyclotron together with new RF amplifier chains is planned for 2013. The cyclotron concept developed at PSI can be extrapolated to 10 MW beam power [20]. It presents an effective alternative also for industrial high intensity proton beam applications, such as accelerator driven systems.

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