UPGRADE OF THE PSI CYCLOTRON FACILITY TO 1.8 MW

M. Seidel, P.A. Schmelzbach

Paul Scherrer Insititute, CH-5232 Villigen PSI, Switzerland

Abstract

The cyclotron based proton accelerator facility at PSI is regularly operated with beam currents close to 2mA at a kinetic energy of 590MeV. The present efforts in developing the facility are directed towards a further increase of the beam power from 1.2MW to 1.8MW. This is achieved by the continued installation of new high gradient resonators in the Ring cyclotron as well as in the injector cyclotron, permitting to increase the turn separation which results in lower relative beam losses. Supporting measures include the installation of harmonic buncher systems for both cyclotrons. The paper discusses technical and beam dynamical aspects of this improvement program.

INTRODUCTION TO THE FACILITY AND IT’S UTILIZATION

The PSI facility produces a high power proton beam for the generation of intense pion and muon beams as well as to drive the neutron spallation source SINQ. The beam with a final kinetic energy of 590 MeV is accelerated by a Cockroft-Walton pre-accelerator and a chain of two cyclotrons. With a current of nearly 2 mA in CW operation the beam power amounts to 1.2 MW. The beam passes then consecutively through two Meson production targets, realized as radiation cooled, rotating graphite wheels with 0.5 cm and 4 cm thickness. Because of scattering in the targets about 30% of the protons have to be collimated to obtain a beam small enough for the further transport to the spallation target in the SINQ neutron source. The spallation target consists of lead filled Zircaloy tubes which are cooled by heavy water D_2O to minimize the absorption of the generated neutrons.

The experimental applications are related to the fields of condensed matter research and particle physics. All instruments are intensively used over roughly 9 months per year. In fact it is not possible to satisfy all requests for experimental time. The number of users has continuously grown over the last years. Table 1 gives some statistical numbers on the utilization of the different experimental areas. For comparison PSI’s synchrotron radiation facility, the SLS is included in the table. For all applications it is desirable to raise the flux of secondary particles either to reduce the duration of measurements or to increase their precision. Continuous efforts are undertaken to raise the beam current. For the operation of the facility the most important aspect is the control of the beam losses and the limitation of component activation. Per year the facility is typically operated for ~5000h and the availability is in the range of 85-90%. The legal obligations for the operation of the facility require the provision of an elaborate infrastructure, especially in the field of radiation safety.

Table1: Statistical figures on the utilization of the PSI high power proton facility and the Swiss Light Source [1].

user statistics 2006	SLS photons	SINQ neutr.	SμS muons	LTP particle physics
beamlines/instr.	11	12	6	10
experiments	653	260	135	10
users involved	934	259	95	133

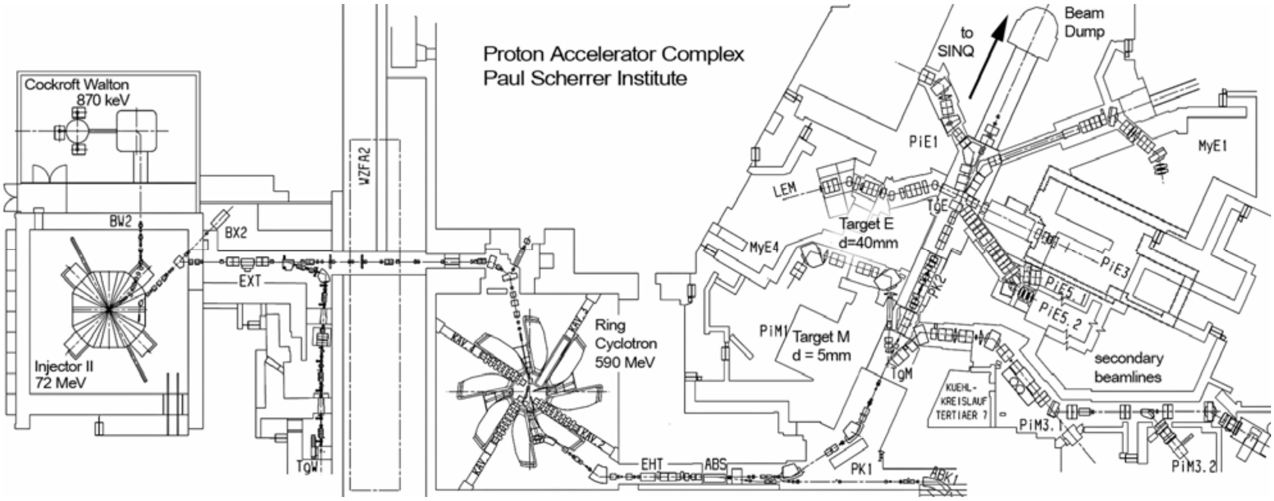

Fig.1: The PSI Proton accelerator complex showing the Cockroft-Walton pre-accelerator, the Injector II, the Ring Cyclotron, the Meson production targets with attached secondary beamlines and the transport channel to SINQ.

UPGRADE PHILOSOPHY

Already in the past the facility has been continuously upgraded and improved. Fig. 2 shows a statistics on the yearly beam charge achieved and the number of operating hours which reflect the reliability of the facility. In 1990 the target E station was rebuild.

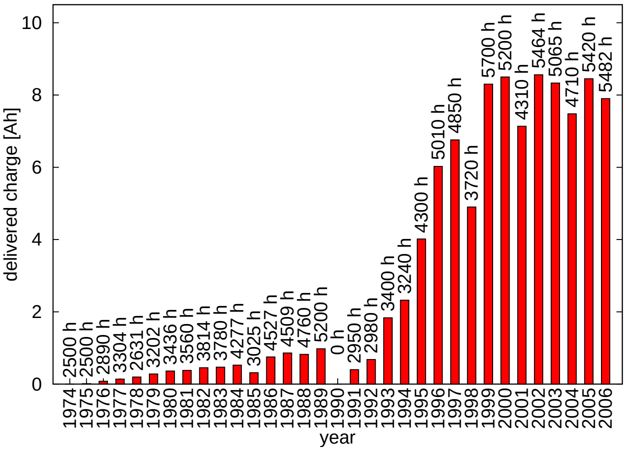

Fig. 2: The delivered charge per year in the PSI proton accelerator. The number of operating hours is indicated above each column for the corresponding year.

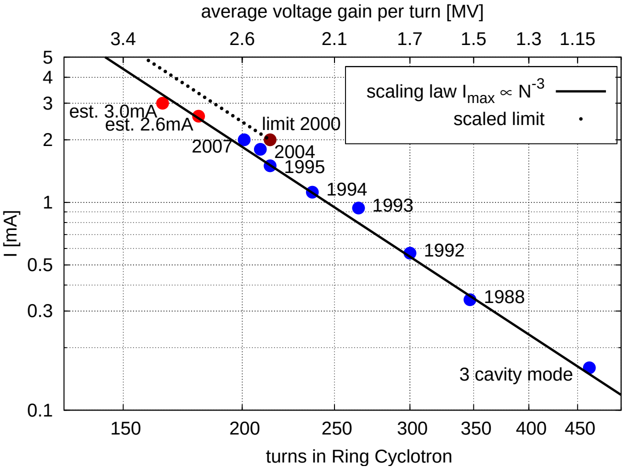

Fig. 3: Development of turn numbers and beam current in the Ring Cyclotron. The point in 2000 was obtained by running at the acceptable limit of losses, while standard operation leaves some room to manoeuvre. Estimated turn numbers for the increased currents are indicated.

Despite the increases in beam current the uncontrolled beam losses in the cyclotrons and transport lines have to be kept constant to maintain the activation at acceptable levels. In other words, the relative losses have to be reduced in the same proportion as the beam current is increased. Presently the typical relative beam losses in the Ring Cyclotron amount to $2 \cdot 10^{-4}$. A key property for small beam losses is a low particle density between last and second last turn in the cyclotrons at the location of the electrostatic extraction element. With a given ring geometry the turn separation is increased by a higher energy gain per turn, which is especially important on the outer turns. This can be achieved by upgrading the RF system and/or installation of improved resonators. With the higher energy gain the number of turns is reduced. During the operation history of the Ring Cyclotron the number of turns has been reduced considerably (Fig. 3).

Space charge effects

Space charge effects play an important role for the loss generation in cyclotrons. By combining several simple arguments it was shown by W. Joho [2] that losses caused by longitudinal space charge forces scale as the third power with the turn number in cyclotrons. The practical relevance of this rule can be seen in Fig. 3. Since the absolute losses have been kept constant, the typical current of the Ring Cyclotron scales inversely with the third power of the turn number. The strong space charge effects which occur with very short bunches result in a new operating regime [3], where the particles in the core of the bunch basically rotate around the bunch centre, in this way forming a stable circular bunch shape throughout the acceleration process. Fig. 4 illustrates qualitatively the behaviour of individual protons that move in the field of a rigid spherical bunch with a superimposed outer magnetic field in vertical orientation. The model neglects focusing forces and relativistic effects. The coordinate system is moving with the bunch and the integration time corresponds to 50 turns in the Ring Cyclotron. As was shown already in 1984 by Chasman et al. [4], the particles in regions with strong space charge forces move on cloverleaf trajectories around the bunch centre. Though the Coulomb force is repulsive, the particles are bound.

A stable round beam was first observed in PSI's Injector 2 cyclotron and there is hope that a similar operating regime can be established in the Ring Cyclotron. The required short bunch length is achieved by employing a 10'th harmonic buncher at 500 MHz which significantly compresses the bunch at injection. Space charge simulations using multiparticle codes and detailed field maps of the Ring Cyclotron are discussed by A. Adelmann at this conference [5].

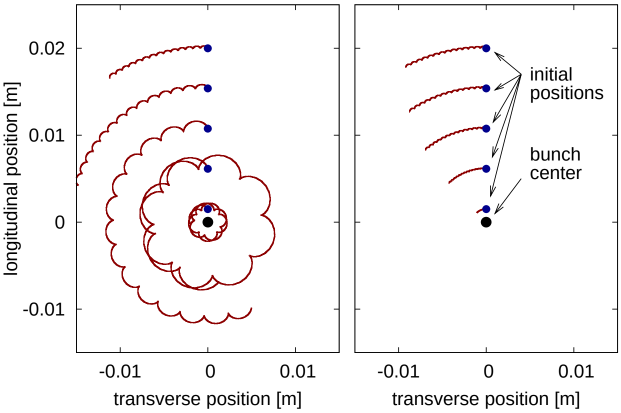

Fig. 4: Motion of protons in the field of a rigid circular bunch and a constant outer magnetic field. The rms bunch-radius is 0.7 cm in the left picture and 1.6 cm in the right one.

COMPONENTS OF THE UPGRADE PROGRAM

ECR Ion Source

The presently used source to generate the proton beam is a multi-cusp ion source. It uses electrically heated filaments to generate the plasma. The filaments have to be exchanged roughly every two weeks and this causes a downtime of about two hours per exchange. A new compact microwave source is under development and was tested with promising results. The magnetic field is generated by an arrangement of permanent magnets. Besides the better reliability further advantages of the new source are smaller beam emittance and better stability. A detailed description of the new source is presented at this conference [6]. Further improvements are planned for the Cockroft-Walton pre-accelerator where a new stabilizing system for the high-voltage generation will be installed.

Harmonic Bunchers at 870 keV and 72 MeV

Proton source and Cockroft-Walton pre-accelerator generate a continuous beam. In the transport line to the Injector 2 a 50MHz buncher cavity impresses a velocity modulation on the beam which leads to a bunching process at the entrance of the injector. Equilibrium between bunching and space charge repulsion results in a very small energy spread at the injection point, which is desirable for the formation of short, round bunches during the acceleration process. The nonlinear behavior of the sinusoidal buncher voltage at larger deviations from the ideal phase leads to imperfect bunching, i.e. a fraction of the beam cannot be captured in the cyclotron. This is improved by applying a second buncher voltage at the third harmonic of the fundamental 50 MHz frequency. The ratio of the two amplitudes is chosen such as to maximize the linear part of the resulting sum voltage curve. A 3'rd harmonic buncher was installed in the 870 keV transport line in the shutdown 2006. As expected the capture efficiency could be significantly increased, resulting in a maximum extracted current of 2.7 mA. Details on this buncher system are presented at this conference [7].

Table 2: Parameters of the buncher systems. The 10'th harmonic buncher is not yet installed.

	Fundamental	3'rd harm.	10'th harm.
E_k [MeV]	0.87	0.87	72
f_0 [MHz]	50.6	151.8	506
U_{nom} [kV]	8.5	1.2	218
P_{nom} [kW]	0.125	0.022	10
P_{max} [kW]	0.3	0.05	30

Another buncher which operates at the 10'th harmonic of the Ring Cyclotron RF frequency will be installed in the 72 MeV transport line [8]. As discussed in the last section, this will result in a much shorter bunch in the cyclotron, which should lead to a self stabilization of the bunch shape. This superbuncher has to generate relatively high voltages. Parameters of all buncher devices are shown in table 2. A CAD drawing of the 500 MHz buncher is shown in Fig. 5.

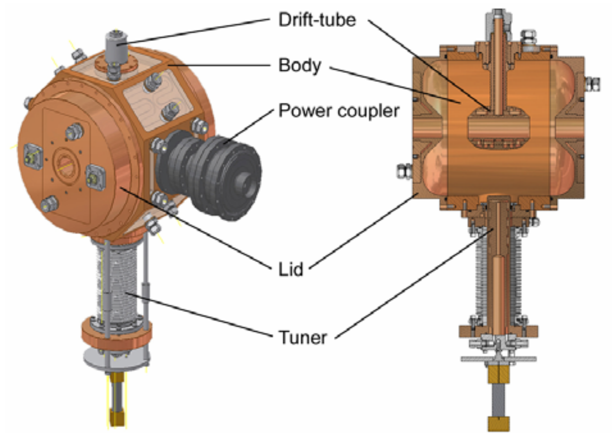

Fig. 5: 500 MHz drift tube cavity with two gaps, to be utilized as 10'th harmonic buncher for improved injection into the Ring Cyclotron.

New Resonators for both Cyclotrons

As discussed above the major upgrade path for the facility consists in reducing the losses by applying a larger energy gain per turn. New resonators will be designed and installed in the Injector 2 cyclotron. Presently the injector cyclotron is equipped with two 50 MHz accelerating resonators and two 150 MHz third harmonic flattop resonators. Because of the short injected bunch length and strong space charge effects the bunches stay in a compact round form throughout the acceleration process and the two flattop resonators are not needed anymore. This opens the opportunity to replace them by two additional accelerating resonators. The new resonators will be made from aluminum. Because of the specific injector geometry they exhibit a sector shape and the mechanical tolerances, especially with respect to the vacuum sealing surfaces which are tilted against each other, are very tight. Consequently the allowed deformations resulting from the atmospheric pressure are small as well. The resonators will be manufactured at an industrial company. Delivery of the first resonator is planned for 2009.

In the Ring Cyclotron the existing four aluminium resonators are to be replaced by new ones with a copper surface on the inner side and a steel structure for mechanical stability [9]. Two of the new resonators are already installed and operated with excellent performance since 2006. They achieved a gap voltage of 1.4 MV on a test bench and in the Ring Cyclotron they are now routinely operated at 830 kV. Because of the higher conductivity of copper the RF-quality factor is higher and at the same operating voltage as for the aluminium resonators roughly 300 kW of dissipated power can be saved. Further improvements over the old resonators include better vacuum sealing surfaces resulting in smaller leak rates, and better RF couplers which give faster conditioning times and less dark current.

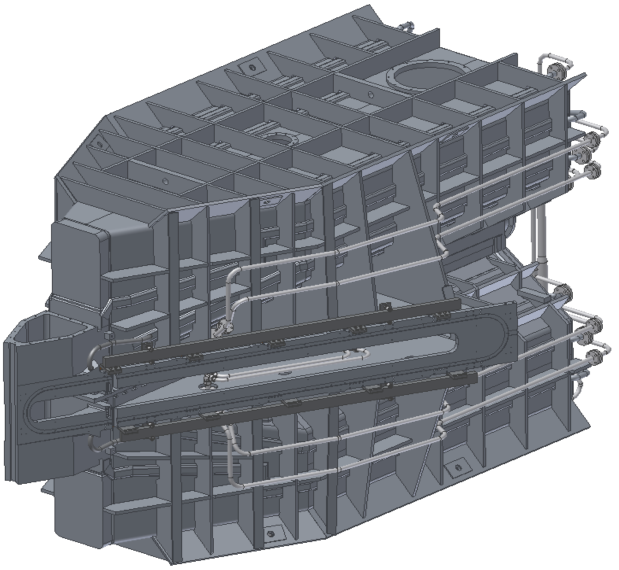

Fig. 6: Design of the new 50MHz resonator for the injector cyclotron.

Besides the four accelerator cavities the Ring Cyclotron contains a 150 MHz flattop cavity. Because of amplifier and cooling limitations is not possible to scale the voltage of this resonator proportional to the voltages attainable with the new accelerating resonators. However, from beam dynamics simulations [5] we are confident that the shorter bunches, generated by the 500 MHz buncher, will behave well with a smaller flattop voltage.

Table 3: Parameters of the cyclotron resonators.

	Ring Cyclotron		Injector 2
	old reson.	new reson.	new reson.
U_{max} [MV]	0.75	1.0	0.5
U_{nom} [MV]	0.75	0.9	0.4
P_{wall} [MW]	0.22	0.24	0.044
P_{beam} [MW]	0.26	0.39	0.053
Q_0	32k	45k	28k

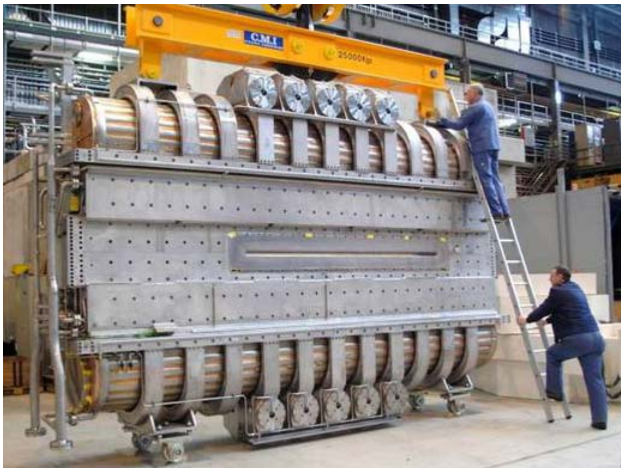

Fig. 7: New copper resonator for the Ring Cyclotron.

Meson Production Targets and SINQ Target

Two Meson production targets made from graphite and with thicknesses of 5 and 40mm are installed in the beam path [10]. The produced Muon and Pion beams are of essential importance for the scientific program of the facility. Thermo-mechanical calculations have shown that both targets can accept a 3 mA beam. The limitation is given by the sublimation rate of carbon atoms from the surface of the graphite wheels, which is strongly temperature dependent. For the thick target the loss of material due to sublimation is expected to become unacceptable just above currents of 3 mA, whereas the thin target could be operated up to 5 mA. A more severe limitation comes from the collimation of the scattered beam. A fraction of 30% of the beam has to be collimated behind the thick target on circular copper collimators (Fig. 8). Above 2.6 mA current the cooling of these absorbers is not sufficient. The upgrade program foresees to replace the absorbers by new ones that allow a more even distribution of the beam losses on the three collimators, together with an improved cooling scheme.

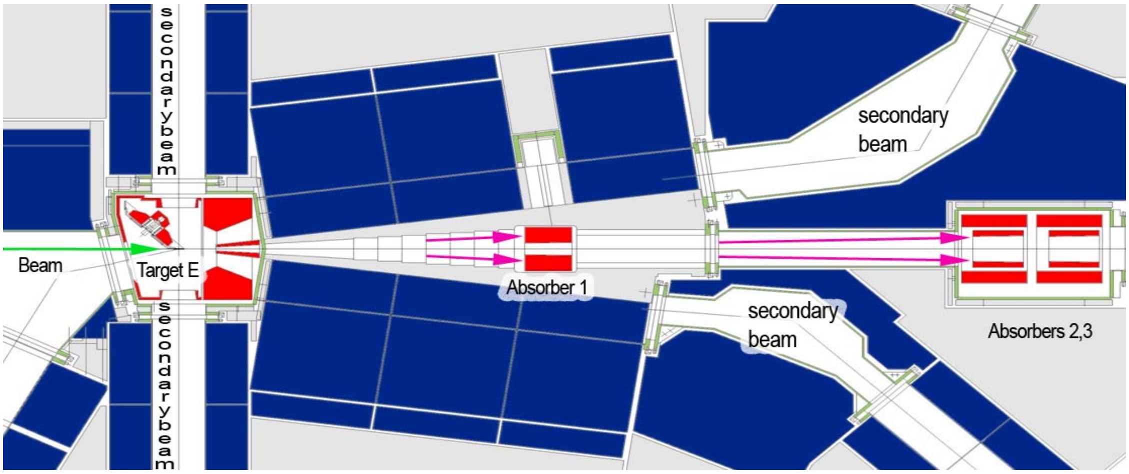

Fig. 8: Top view of the beamline geometry in the vicinity of target E. The absorbers 1,2,3 used for stopping a 30% fraction of scattered beam are indicated. The rotation axis of the target wheel is tilted by 45 deg against the incoming beam.

The beam current density on the SINQ target will be raised from 40 μA/cm^2 to 60 μA/cm^2. The principle cooling scheme for the lead filled Zircalloy tubes using circulating D_2O is still applicable at these parameters. However, the heavy water flow has to be raised. Fine tuning of the exact arrangement pattern of the tubes in the target geometry has to be applied as well.

LEGAL REQUIREMENTS AND AUXILIARY MEASURES

Besides mastering the technical problems considerable efforts are required in the area of complying to legal regulations, licensing of the facility and the provision of the necessary infrastructure for handling radioactive components as well as professional radioactive waste management. The present license for operating the facility allows a maximum current of 2.0 mA during routine operation. In order to obtain the license for the desired 3.0 mA operation we have to demonstrate that the established typical values for the radiation exposure of the PSI personnel as well as the emission of traces of radio nuclides will not be exceeded with the higher current. As discussed above a key element for the upgrade path is to keep the absolute beam losses constant. Since PSI has been following this philosophy also in the past, one can demonstrate with statistical data the absence of any correlation between the average beam current and radiological data as the residual dose rates measured in the vicinity of the accelerator. This also holds for the radiation dose of the personnel, which is archived for every employee. To exemplify we show here local radiation dose measurements in the vicinity of the experimental hall in comparison with the average current development over 12 years (Fig. 9). One major origin of the observed dose measurements is residual radiation emitted from the accelerators in vertical direction and scattered back from the roof or the atmosphere, so called skyshine. In 2006 additional local shielding was installed at the extraction of the Injector 2 cyclotron. This measure reduced the skyshine considerably which is also reflected in Fig. 9.

At locations where beam loss is intended, i.e. at the Meson production targets and the spallation target of SINQ, the residual radiation will simply scale with the beam current. Here we have to ensure by proper shielding that the higher current is acceptable. In fact we are able to demonstrate by extrapolation of the presently observed radiation levels that no additional major investments will be necessary for shielding. In 2006 a liquid metal target [11] was temporarily installed in SINQ and operated for four months with the purpose of performing a pilot experiment. This target led to an increase of the neutron flux by a factor 1.8 as compared to the flux produced by the standard solid target. It gave us the practical proof that the shielding of the SINQ housing as well as that of the neutron guides is sufficient for the 3 mA operation with the standard target.

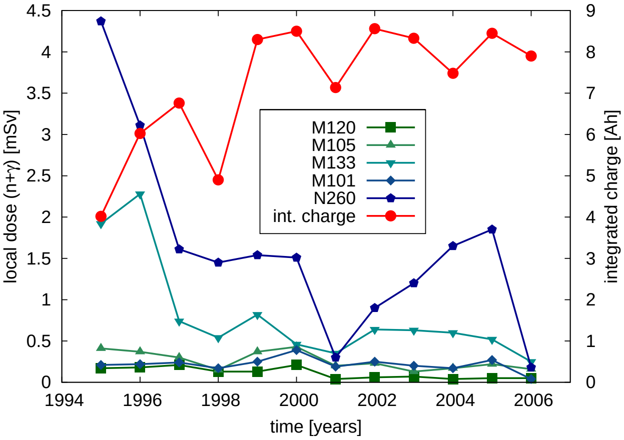

Fig. 9: Selected local neutron-dose and gamma-dose measurements (sum, courtesy [12]), taken at the outer boundary of the building which houses the accelerator complex. The integrated currents for the individual years are shown in comparison.

Although the relative beam losses are low in the Ring Cyclotron, the activation levels are not negligible there and may reach several mSv/h at critical locations. Special transportable enclosures, “exchange bottles”, have been designed at PSI to allow exchange and handling of critical components like the injection/extraction elements in the Ring Cyclotron and also the graphite targets and absorbers. On the accelerator site there is a hot cell workshop available which allows working on highly activated components using remotely controlled manipulators. The whole accelerator site of the institute is monitored with a dense grid of passive dosimeters. Furthermore there are many active ionization chambers installed, which continuously monitor the radiation level in experimental areas or in beam line sections. Roughly 1300 employees at PSI are radiologically monitored, although only a fraction of the personnel is directly employed at the proton facility.

Another aspect which becomes more and more important for the operation of the PSI facility is the professional handling and disposal of activated components and radioactive waste [13]. In the last years specialists in the accelerator department have acquired an advanced expertise in this field. With computer tools it is possible to predict the activation of components, for example in a high radiation level area near a target [14]. For the disposal of radioactive waste the Swiss authorities require such calculations to determine or predict the inventory of long-lived radioactive nuclides in the materials, which is generally a nontrivial task. Predictions are computed with validated codes that are benchmarked using measurements of selected nuclides in representative radioactive waste components.

TIME SCHEDULE AND SUMMARY

The proton accelerator facility at PSI will be upgraded in the next years to raise the beam power from presently 1.2 MW to 1.8 MW at a beam energy of 590 MeV. A key component for the upgrade are the new resonators for the Ring Cyclotron with an advanced design and each capable to transfer 400 kW of power to the beam. As compared to linear accelerators the cyclotron concept still presents an effective alternative to generate very high power beams in continuous wave mode.

The upgrade program is progressing as expected and will achieve a major milestone in 2008 when the remaining two of the four new resonators will be installed in the Ring Cyclotron. Two additional resonators for beam acceleration in the Injector 2 are designed and ordered from industry. The installation of these resonators requires also a comprehensive installation of 50 MHz RF systems including a new building. It is planned to increase the current in steps, while optimizing the parameters of the accelerator such that the beam losses can be kept constant at a tolerable level. For currents higher than 2.6 mA it is necessary to rebuild the absorbers which capture the scattered beam behind the 4 cm Meson production target, because of insufficient cooling capacity. The important milestones are given in Table 4. The operation at the full current of 3 mA is expected for 2012.

Table 4: Selected milestones of the upgrade program.

10 / 2007	authorization for short time/experimental operation at 2.2 mA given
12 / 2007	500 MHz (10‘th harmonic) buncher installed
4 / 2008	two new resonators in ring cyclotron installed, legal authorization for 3 mA operation given, new ECR source installed
11 / 2008	new building for injector 2 RF system incl. infrastructure completed
3 / 2009	resonator 2 for injector 2 delivered and controls for RF system installed
3 / 2010	resonator 4 for injector 2 delivered
4 / 2011	operation at 2.6 mA (1.5 MW)
12 / 2011	new collimators at target E installed (power limitation); extension of cooling capacity; improvement of SINQ cooling
4 / 2012	operation at 3.0 mA (1.8 MW)

Besides the beam power upgrade program also the functionality of the facility will we extended in the next years. A new source of ultracold neutrons (UCN) is under construction [15]. This source will also be driven by the 590 MeV beam, but in pulsed operation. The full megawatt beam will be sent to the UCN target for 8 seconds by deflecting it with a fast kicker magnet. Then the normal operation of the SINQ spallation source will continue for ~15min’s before the cycle is repeated. The time period of this operation mode is motivated by the neutron lifetime which dominates the storage time of the generated neutrons.

Another possible extension of the accelerator is a new irradiation facility called LISOR 2, using a split beam of up to 100 μA current at an energy of 72 MeV [16]. Presently irradiation experiments are performed at PSI’s Injector I cyclotron which will be switched off next year.

This report presents a summary of the work done by many colleagues at PSI, mainly in the department Large Facilities, GFA.

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