Upgrading the PSI Accelerator Facility for High Intensity Operation

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Abstract

In the past the PSI-facility was routinely operated at proton currents of $\sim 250\mu A$ at 600 MeV. In the future 1.5 mA is anticipated for a spallation neutron source. This necessitates the reconstruction of the target stations and an upgrade of the accelerators.

This paper outlines the upgrade program and summarizes the present performance of the accelerators and beam facilities.

1 INTRODUCTION

After the start up in 1974 the accelerator facility of PSI (formerly SIN) has enabled a large number of research groups from Switzerland and from abroad to carry out experiments with pions, muons, protons and light ions. While the experiments in nuclear and particle physics were dominating in the past, the main emphasis is shifted towards the applications of nuclear methods at our facility, a trend that will certainly continue in the future. The main applications are

- Solid state physics using the μSR-facility
- Curative treatment of tumors with pions (BMA) and protons (OPTIS)
- Defect physics and material tests using proton beams at 72MeV and 600 MeV (PIREX)
- Production of radioisotopes, used in PET-experiments and for radiopharmaceutical products.

The PSI-facility is described in [1,2] and sketched in fig. 1. The main accelerator is a ring shaped isochronous cyclotron for 600 MeV protons with a world record performance in beam power. For normal operation the injector 2 cyclotron feeds the main ring with 72 MeV protons. Both stages were built by PSI. The injector 1, a very versatile cyclotron built by Philips Company (NL), is mainly used for nuclear physics experiments and the OPTIS program. It is equipped with a source of polarized protons and deuterons, allowing the acceleration and extraction of proton beams of $10\mu A$ at 72 MeV, again a world wide record. The polarized protons are occasionally injected into the main ring and accelerated to 600 MeV for the production of beams of polarized neutrons.

The 600 MeV protons from the ring are guided onto two consecutive target stations "M" and "E". Behind target "E" the protons are stopped in a high power beam dump. In the future the beam will be refocused and guided on the target of the spallation neutron source (SINQ), which is now under construction [3]. For a full exploitation of this new facility, proton currents $\geq$ 1 mA are required. In the proton channel following the main ring, an electrostatic beam splitter allows to peel off $20\mu A$ from the main beam for the proton areas.

Until the end of 1989 the main ring was routinely operated at beam currents up to $250\mu A$. The maximum current was $370\mu A$, limited by the available RF-power in the ring. This is only a fraction of the potential intensity limit of the main ring, which is estimated to be at 1.5 mA.

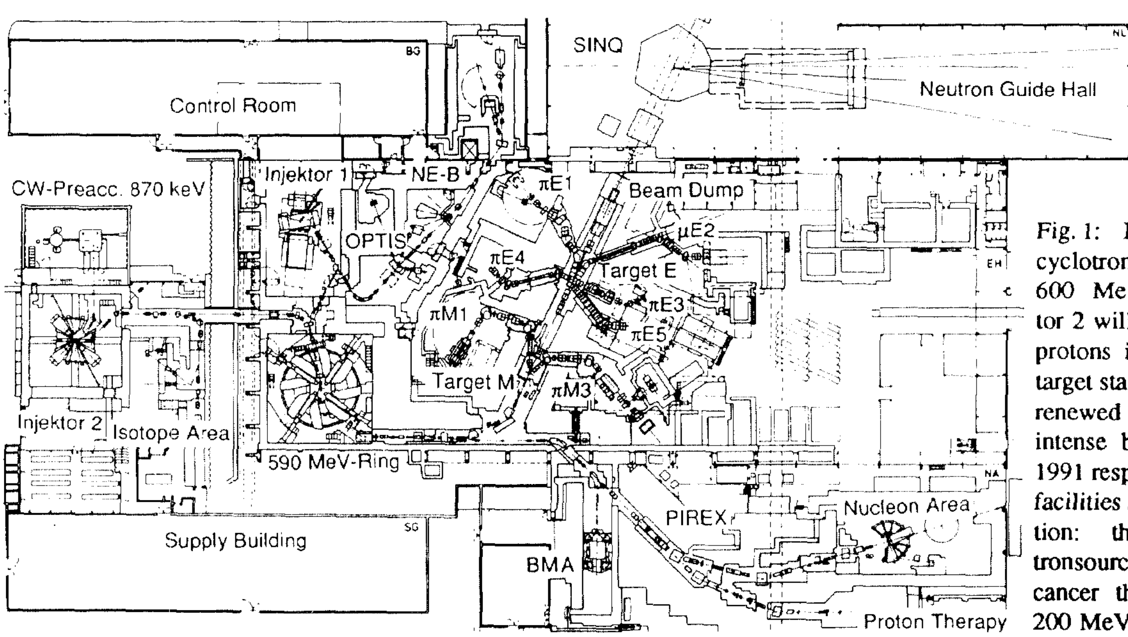

Fig. 1: Layout of the PSI cyclotron facility. The 600 MeV-ring and injector 2 will deliver 1.5 mA of protons in the future. The target stations M and E were renewed and adapted to the intense beam in 1985 and 1991 respectively. Two new facilities are under construction: the spallation neutronsource SINQ and the cancer therapy beam with 200 MeV protons.

Already in the late 70's it was decided to exploit the high current capabilities of the facility and since then the following steps were realized or initiated:

1. Construction of injector 2 (commissioned in 1985)
2. Reconstruction of target "M" in 1985
3. Reconstruction of target "E" and beam dump (Jan. 1990 - June 1991)
4. Upgrade of the 600 MeV-ring (by stages during the annual shutdowns 1990-1994)
5. Construction of the SINQ (commissioning in 1995).

After the completion of the first three steps and a successful start towards step # 4 it is worthwhile to summarize the present performance of the facility.

2 ACCELERATOR UPGRADING PROGRAM

2.1 600 MeV ring-cyclotron

Its main components are 8 separated magnets and four acceleration cavities at 50 MHz, leading to an average energy gain per revolution of 1.7 MeV. A flattop cavity operating at 150 MHz results in separated turns at extraction even for a wide phase width giving an extraction rate close to 100%.

The main items of the ring upgrade are a) the increase of RF-power for the acceleration cavities and b) the replacement of all injection- and extraction elements including their local radiation shield.

Table 1 illustrates the required performance of the RF-systems for 0.25 mA and 1.5 mA respectively. Some of the additional RF-power is needed to increase the cavity voltage by 50%. This increases the energy gain per revolution and drastically raises the space charge limit. At the highest current envisaged, the 50 MHz RF-power needed per cavity amounts to 520 kW! In practice this is achieved with one power amplifier using the Siemens tetrode RS2074. Some problems arise in the flattop-system at high beam currents, because the flattop cavity absorbs power from the beam which might jeopardize phase and amplitude control of the cavity when the absorbed beam power exceeds the wall losses in the cavity. During the shut down 1990 one of the four 50 MHz-cavities was equipped with a new amplifier chain, enabling an increase in energy gain per turn by 10%. During 1991 this new equipment allowed us to deliver beam currents of 0.5 mA through the ring and on target "E" with beam losses in the ring in the order of 0.5μA.

Table 1: RF-power requirement of the ring cavities

proton current	(mA)	0.25	1.5
beam power	(kW)	150	900
50 MHz RF-systems (4)			
- beam load/cavity	(kW)	37	220
- cavity voltage	(kV)	520	730
- power dissip./cavity	(kW)	150	300
- RF-power/cavity	(kW)	187	520
150 MHz flattop system (1)			
- beam power deposited in cavity	(kW)	15	90
- power dissip. in cavity	(kW)	50	100
- Dynamic range of power amplif. (zero to max. current)	(kW)	50 ÷ 35	100 ÷10

The losses occur mainly in the extraction region, where the neutron production and therefore the activation is dominant. They are below the limit which we consider to be tolerable for a safe operation and maintenance of the cyclotron.

2.2 Injector 2 cyclotron

The injector 2 is also a ring cyclotron, with four sector magnets, two 50 MHz acceleration systems and two 150 MHz flattop cavities. A Cockcroft-Walton type accelerator serves as a preinjector delivering 8 mA of protons (dc) at an energy of 870 keV. A buncher is installed to produce peak currents up to 40 mA in the injector 2. Due to the high RF-voltage the number of revolutions is small (around 100). This results in a large turn separation of 1.8 cm at extraction and minimum extraction losses. The space charge effects are reduced as well.

During 1991 the injector 2 has reached its design goal. A 1.5 mA beam (110 kW beam power) was successfully extracted. The extraction losses were 1.3μA, corresponding to an extraction efficiency of 99.9%!

In injector 2 the beam width at extraction (averaged over 5 revolutions) is used as a simple criterion for the horizontal beam quality and energy spread. A large beam width results in high beam losses and jeopardizes the extraction of high beam currents. Figure 2 shows the improvement of the beam width versus the beam current from 1988 to 1991. Also shown is the original acceptance limit of the 600 MeV-ring. This limit will be raised in steps until 1994 as a result of the increase in cavity voltage which is part of the ring upgrading program.

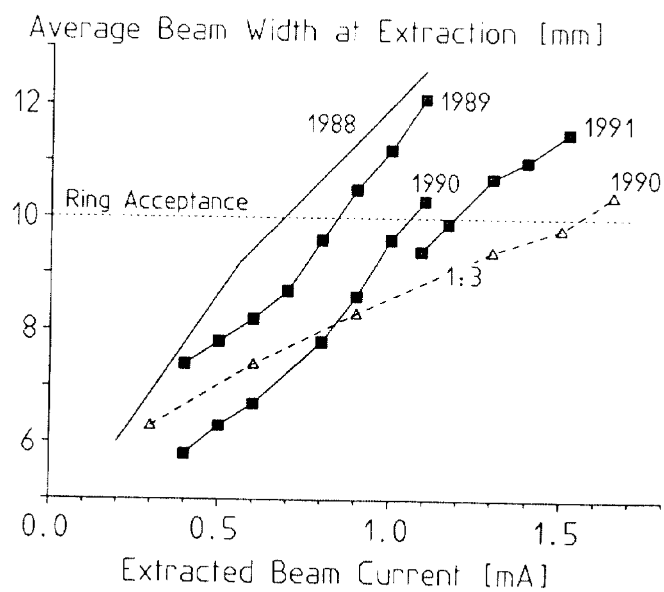

Fig. 2: Beam width at extraction of injector 2 as a function of beam current. The dotted line shows the acceptance of the 600 MeV-ring cyclotron prior to the upgrading program. The dashed line shows the results from pulsed beam experiments, where 2 out of 3 micropulses were suppressed.

2.3 *Upgrading of the Beam Facilities*

During the years 1985-1991 an extensive upgrading program has been carried out with the following aims:

- Adaptation of targets and beam dump to the megawatt beam in the future (thermal load, shielding, handling of components)
- Installation of the first section of the proton beam transport system to the spallation neutron source.
- Improvement of the secondary beam lines and installation of the new high acceptance, low energy beam line πE5.

In order to achieve these goals, a new mechanical design of the target station and of the beam dump has been applied. The main features are:

- All the elements and their local shieldings are mounted on support stands which are precisely positioned on ground plates, allowing a self-centering installation of the elements. Except for the support stands and some positioning pins there are no additional fastenings. All elements can thus be installed and removed exclusively in the vertical direction with the crane. There is no need for local mechanical work on the highly activated components.
- The connection between beam pipes and target vacuum chambers are made by means of inflatable all metal elements which do not require any clamping.
- All the power-, cooling- and signal connections are brought through the local shielding to a working platform 2.5 m above the proton beam axis, where a low dose rate is expected after the beam is turned off.
- The rotating carbon targets, beam monitors, beam collimators and elements of the beam dump are designed as vertical insertion devices. They can be removed into remotely controlled shielded containers.

Whereas the layout for the secondary beams has not been changed at the target station "M", several changes were made at the target "E": the target length was reduced from 10 to 6 cm of carbon which allows to recover about 60% of the protons for the operation of the SINQ; the two secondary beam lines, collecting pions produced in the forward direction, were converted into two independently operating systems by replacing the old extraction system by two sets of half-quadrupoles, arranged at 8 degrees to the left and right of the proton beam. Starting about 30 cm downstream of target "E", a set of tapered collimators removes the scattered protons. We expect to lose 10% of the protons by absorption in target "E", and 30% by scattering into the collimators. The beam dump, designed for a beam power of 1.2 MW, is used when the SINQ is not in operation. It consists of 4 stacked water cooled copper cylinders 30 cm long and 44 cm in diameter. The first two cylinders have axial bores of 10 and 7 cm respectively. The proton beam is defocused to guarantee an adequate power distribution over the 4 blocks. The high beam losses in the region behind target "E" also require cooling of some of the steel shielding and vacuum chambers.

The main features of the secondary beam lines at target "E" are given in table 2. The basic optical design of the two muon channels and of the πE1 beam has not been changed. However we have removed the entrance windows of the πE1 and πE3 beam lines in order to be able to accept low energy muons ($p_\mu \geq 5$ MeV/c). In addition, the vertical beam line πE3 has been completely re-designed and can now be used for experiments requiring high intensity, low energy pions and muons as well as for the low energy pion spectrometer which requires a high intensity, high resolution dispersed beam. A novel beam line, the πE5 beam, is being installed. It has a very large acceptance of 150 msr and extracts pions and muons in the backward direction. Since its first bending magnet deflects the proton beam, two compensating magnets had to be added upstream in the proton beam line.

Table 2: Pion and Muon Beams Summary

π^+	momentum MeV/c	max. flux at 1 mA	$\delta p/p$ FWHM	spot size cm^2
πE1	120-600	2×10^9 at 300 MeV/c	0.3 %	1.5 × 2
πE3	40-180	8×10^7 at 180 MeV/c	0.1 %	10 × 4 dispersive
πE5	30-120	1.5×10^{10} at 120 MeV/c	2 %	6 × 4
πM1	120-500	2×10^8 at 300 MeV/c	0.1 %	2 × 1.5
πM3	120-500	8×10^8 at 300 MeV/c	0.2 %	1.7 × 2

μ^+	momen. MeV/c	max. flux at 1 mA	$\delta p/p$ FWHM	spot size cm^2	polariz.
μE1	40-125	2×10^8 at 125 MeV/c		3 × 2	75 %
πE4	30-100	4×10^6 at 50 MeV/c		6 × 4	75 %
πE3	5-30	3×10^7 at 28 MeV/c	1 %	2 × 3	> 95 %
πE5	5-30	2×10^8 at 28 MeV/c	2 %	6 × 4	> 95 %
πM3	5-30	4×10^6 at 28 MeV/c	0.4 %	2 × 2	> 95 %

The dismantling of the target station and beam dump after 20 years of operation has been a very challenging task. We had to remove 500 t of activated material with dose rates up to 400 Sv/h. In localized regions the contamination exceeded the allowed value by a factor of 10^4. About 10^{15} Bq were handled during these operations. 300 t of this material could be re-used, while the remaining 200 t were enclosed in concrete boxes and re-installed as shielding. 12000 t of slightly activated concrete and iron shielding were rearranged. The sum of the absorbed doses of the 200 persons involved in the work was kept at the low value of 470 mSv and no incorporation of contamination was monitored. The highest dose received by a single person was 30 mSv.

3 REFERENCES

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