EXPERIENCE WITH THE HIGH CURRENT OPERATION OF THE PSI CYCLOTRON FACILITY

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ABSTRACT

The PSI two stage accelerator facility is at present being upgraded to higher beam intensities. In view of the spallation neutron source under construction, beam currents of about 1.5 mA at an energy of 590 MeV are anticipated. The status of the upgrading program is summarized and operational experience with increased beam intensities is reported. At the 72 MeV injection energy the design goal could be reached. Making use of strong bunching a stable beam of 1.5 mA could be extracted from the 'Injector 2' cyclotron. The behaviour of strongly bunched beams and the effect of space charge forces are discussed. In the partially upgraded 590 MeV Ring cyclotron and at the reconstructed target station and beam dump area, the beam intensity could be increased to 0.5 mA, at present limited by the available RF-power. Beam loss, beam quality and possible limits are discussed.

1. INTRODUCTION

The cyclotron facility at PSI (Paul Scherrer Institute) is one of the three existing meson factories in the world. A high current proton beam at an energy of 590 MeV is used for the production of intense secondary beams of pions and muons. The main accelerator is a separated sector 'Ring cyclotron' specially designed for the acceleration of high intensity beams with a 72 MeV cyclotron as injector. Until 1985 the facility was operated with beam intensities up to 200 μA using the Philips cyclotron as injector and is now stepwise being upgraded to increase the available beam currents at 590 MeV from the previous level to an expected 1.5 mA. The goal of this upgrade is to provide more intense meson beams for the next generation of precise experiments in medium energy particle physics, especially rare decays, and to produce enough beam power for a spallation neutron source (SINQ) presently under construction at PSI. Several important steps of this upgrade program could be realized in the preceding years:

- 1985: upgrade of the first of the two meson production targets by reconstruction according to design criteria adapted to beam currents of 1.5 mA, to higher beam losses, and hence elevated levels of radiation and activation,
- 1985: start of beam production with Injector 2, a new dedicated injector cyclotron for 72 MeV protons built by PSI and especially designed for high beam intensities,
- 1990: commissioning of a new 500 kW 50 MHz-amplifier designed by PSI as an essential step towards an upgraded RF system capable to deliver the necessary RF power to the Ring cyclotron and installation of the first of four units at the Ring cyclotron,
- 1990/91: reconstruction of the second meson production target station, upgrade of the beam dump area and preparation work for the connection of the future spallation neutron source, again according to design criteria adapted to the anticipated beam intensities.

Details of the upgrading program have been given in earlier publications.[1–3] This publication reports on the present status of the upgrade and on initial operational experience with increased beam intensities from Injector 2 and in the Ring cyclotron. An 18 month shutdown for the reconstruction work in the beam dump area and for installations in view of the upgrade of RF systems in the Ring cyclotron was used to demonstrate the high current capability of Injector 2 and to investigate the behaviour of the beam. Making use of a highly bunched beam the design goal could be reached and a stable beam of 1.5 mA was extracted. In the partially upgraded Ring cyclotron a beam of 500 μA could be accelerated. Separate contributions to this conference deal with investigations on strongly bunched beams in the Injector 2 cyclotron combining simulations and beam tests[4] and with the status of the upgrade of the RF systems to the demand of the high intensity beams.[5]

The problems and limits with the high intensity operation of the cyclotrons at PSI have been summarized in several papers by W.Joho and U.Schryber.[6,7,1] They concluded that the key point is the RF-system and an accelerator design that allows high accelerating voltage and well separated turns. The RF-system has to not only deliver the necessary power to the beam, but also to fulfil high standards in stability under extreme beam loading conditions. The effect of space charge forces have been investigated by S.Adam.[8] The beam current is expected to be an important parameter that affects the setting of components and can have dramatic influence on the beam quality. This then interferes with the goal to keep beam losses at extraction around 0.1%, i.e. 99.9% extraction efficiency, to keep the activation of components at acceptable levels and to protect them from damage.

2. INJECTOR 2

2.1. Design criteria

The new injector cyclotron is built by PSI and is described in detail in ref.9. Its main features are a large orbit radius and good turn separation to allow extraction virtually free of beam loss. This is realized with large separated magnets leaving space for large accelerating structures with a high energy gain. The consequence is operation at a high harmonic number (h=10). The ion source is external and mounted in the dome of an 870 keV Cockcroft-Walton preinjector[10] which is normally operated with an 8 to 10 mA proton beam. The beam is injected axially with two vertical 90° bends.

The final energy of 72 MeV is reached after about 100 revolutions. The turns remain well separated and the turn separation at extraction is still as large as 20 mm. Extraction losses can therefore be kept very low, and restricted to particles travelling far away from the equilibrium orbit as a result of coupling effects, aberrations or space charge forces. Two flattop resonators operating at the third harmonic of the main accelerating RF are installed to reduce the effect of phase width and field errors on the energy spread of the beam.

2.2. Commissioning to beam currents above 1 mA

Since commissioning of the Injector 2 cyclotron in 1985 several attempts to extract beam currents above 1mA were undertaken. In all cases a degradation of the beam with increasing beam current was observed. The following cases were investigated:

- Injection of an unbunched beam with 8 to 10 mA beam current. Above 0.8 mA the phase width of the beam exceeded the acceptance of the cyclotron of ± 20 deg.
- Injection of a weakly bunched beam. This resulted in a reduced phase width but introduced additional energy dispersion into the centre region that could not be properly matched to the corresponding equilibrium orbit.
- Use of a more intense beam from the ion source. A beam current of up to 16 mA could be transported and injected into the cyclotron, but the handling in the injection beam line was very difficult and the gain from the correspondingly reduced phase width was cancelled by drastically increased beam losses at extraction, probably due to a degradation of beam quality introduced by space charge forces in the injection beam line.
- Pulsed beams. Extraction in a 1 out of 3 pulsed mode was expected to be a fair test of space charge effects, since the charge in the individual bunches remains unchanged, while problems related to high beam power, as operation of RF systems close to power limits, stability of RF systems and excessive beam loss at collimators and in the extraction system could be avoided.
- The highest beam currents could be extracted making use of strongly bunched beams, improved collimation in the centre region and with a special effort to match the vertical dispersion at the injection into the cyclotron.

The result of these experiments is summarized in fig. 1. Two probes that scan the beam over several turns before extraction were used to get a quick estimate of the beam quality at this point. The width of the beam averaged over the last turns before extraction for well optimized cases is plotted as a function of the beam current. In all cases the width of the beam increases steadily with increasing beam current. Several facts make the average width of the beam depend upon beam intensity. Since the beam intensity is adjusted by the position of a phase defining collimator on the first orbit, the phase space volume occupied by the beam grows at low intensities first radially, and then in phase. Finally, at higher beam currents space charge forces add to the energy dispersion in the beam.

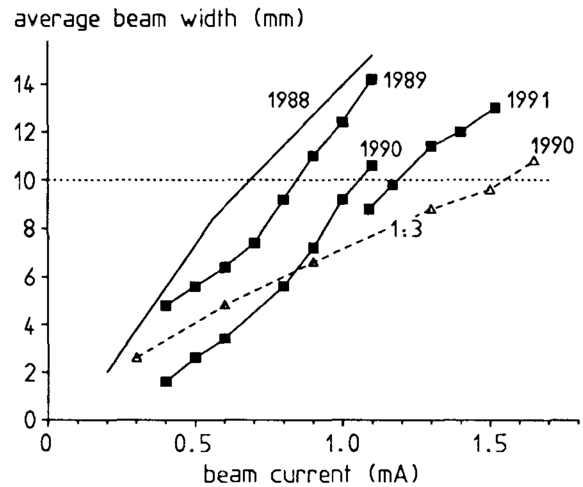

Fig. 1. Average width of the beam on the last turns before extraction from Injector 2 as a function of the beam current. It shows the degradation of the beam quality observed in several experiments to accelerate elevated beam currents. Best results were found making use of strongly bunched beams (1990/91). Beams with widths below 10 mm can be accelerated in the 590 MeV Ring cyclotron without excessive losses.

2.3. Longitudinal space charge forces

Theoretical investigations on the effect of space charge forces in the PSI cyclotron have been performed by S. Adam and W. Joho.[8,6,7] Their results are summarized in fig. 2. In an isochronous cyclotron the longitudinal space charge effects dominate. They manifest themselves threefold, in a tilt or rotation of the bunch in phase and radius, in a deformation of the bunch, and a vortex motion of the particles.[11-13] Leading particles gain additional energy and drift adiabatically to the corresponding equilibrium orbit with larger radius, thus producing the tilt. The forces that generate the tilt, however, are not linear with the phase of individual particles in the bunch, but depend on the shape of the distribution function and lead to the typical 'butchers hook' deformation of the bunch as shown in fig. 2a. Due to the coupling of radial and longitudinal motion, finally, the radial deplacement of the particles and radial space charge forces introduce a longitudinal motion as well. This generates the vortex motion or in extreme cases the spiraling of the bunch as shown in fig. 2b.

The tilt of the bunch in phase against radius can be compensated by detuning of the phase between the flattop and the accelerating resonators. A change of 1 degree in the flattop phase produces an energy variation of .034% per degree phase width in the beam. An example of this compensating effect is given in fig. 3 for the case of a 1 mA beam extracted from Injector 2.

In order to observe the deformation of the bunch in phase and radius a system to measure the time structure of the beam with high radial resolution has been installed on the last turn in the Injector 2 cyclotron. The predicted deformation of the bunch in phase and radius and its vortex motion is barely observed in the measured time structure. An example is given in fig. 4a, but in most cases the resolution of the measuring system is not sufficient and the structure disappears in the general degradation of the beam. This is particularly the case with strongly bunched beams in which the phase width of the beam is reduced to just a few degrees.

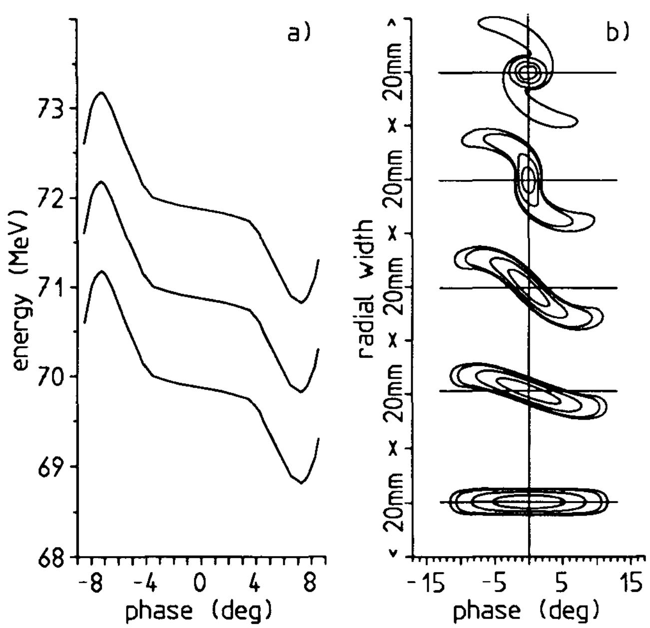

Fig. 2 Calculated deformation of the bunches under the influence of longitudinal space charge forces taken from ref. 8. The left side (a) shows the tilt of the bunch in energy vs. phase on the last turns of Injector 2 at a beam current of 1 mA within 30 deg at injection. The phase width is reduced by phase compression during acceleration. The effect of stronger space charge forces result in a vortex motion as shown on the right side (b) for the case of a 3 MeV beam with a current of 1.5 mA within 20 deg coasting over eight revolutions, every second turn is shown.

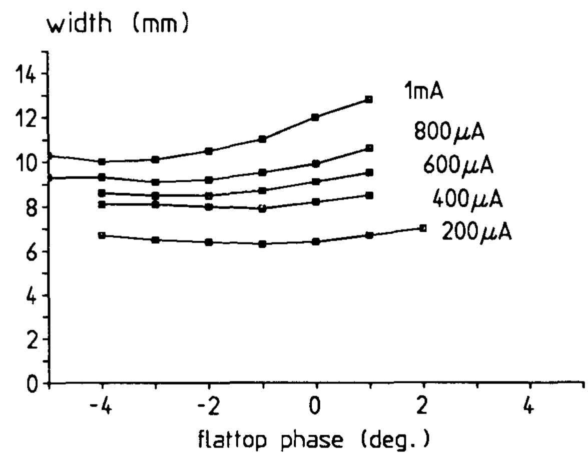

Fig. 3. Dependence of the average beam width at extraction from Injector 2 on beam intensity and flattop phase. It demonstrates that an enegy spread builds up. It is introduced by longitudinal space charge forces and is proportional to the beam current. This effect can be partially compensated by adjustment of the flattop phase.

2.4. Strongly bunched beams

Investigations on the properties and behaviour of strongly bunched beams in the injection beamline and on the first few orbits of the Injector 2 cyclotron are presented in detail in a separate contribution to this conference.[4] The results can be summarized as follows. With beam currents of several mA at the injection energy of 870 keV, the debunching effect of space charge forces can not be neglected. The action of these forces, however, can be very favorable if the beam current is adjusted such that the debunching from the space charge forces compensates the energy modulation introduced by the buncher. A prerequisite for the compensation is a beam transport with minimal dispersion. Because Injector 2 works with axial injection, the debunching would otherwise result in a distortion of the beam in the vertical phase space. The beam is expected to be bunched into about 14 degrees phase width with a bunching factor around 3. In additiion the calculation showed that the beam enters over a phase range of about 40 degrees on the same radius into the cyclotron and that the phase acceptance is extended to late particles too far out in phase. To remove these phase tails from the beam an additional cleaning collimator was added in the calculations and installed in the cyclotron a quarter of a turn behind the phase defining collimator. According to the calculations 43% of the incoming dc beam would be accepted on the first orbit, but 8% would have to be cut off in the cleaning collimator and 35% would be accelerated within a phase range of ± 20 degrees and within 4 mm radial spread, which would be a perfect beam for a cyclotron equipped with a flattop system. Space charge effects in the cyclotron could not be taken into account in these calculations. Table 1 gives selected results from the calculations.

The data show the improvement of the beam quality by the cleaning collimator. This allows to accept more beam by repositioning of the phase defining collimator.

Table 1: Calculated effect of the buncher and the cleaning collimator on the beam injected into the Injector 2 for the case of a 10 mA dc beam.

buncher voltage	0 kV	4 kV	7 kV
without cleaning collimator			
average width	5 mm	11 mm	13 mm
phase range	42 deg	52 deg	38 deg
acceptable beam	1.0 mA	1.9 mA	1.1 mA
with cleaning collimator			
average width	4 mm	4 mm	4 mm
phase range	42 deg	44 deg	36 deg
acceptable beam	1.1 mA	2.0 mA	3.5 mA

It was difficult to predict how such a beam would be affected by the longitudinal space charge forces in the cyclotron. Since the vortex motion in the plane defined by phase and radius increases with the third power of the inverse phase width, the limit of the "spiraling instability" predicted by S.Adam[8)] would certainly be crossed. Experiments with such a beam in the cyclotron gave good results and did not show the drastic increase of the energy spread expected from space charge simulations. Several observations give evidence of a "soliton-like", well compacted beam in radius and phase, and with no visible structure or filamentation within the resolution of the available beam diagnostic systems.

2.5. Observations with the 1.5 mA beam

As seen in fig. 1, injection of a strongly bunched beam gave the best beam quality at the extraction energy of 72 MeV. After tuning to minimize beam losses measured by ionization monitors and on collimators in the extraction system, the current could be raised to more than 1.5 mA. The extraction rate was around 99.9%, the measured beam losses 1.3 μA. The beam was stable and could be kept at this level over days. Some of the results are given in fig. 4c, fig. 5 and in table 4. The orbits are slightly off centre by a coherent betatron oscillation of 2 mm to improve turn separation at the electrostatic and electromagnetic deflectors. Beam collimation in the centre region was important as predicted from the buncher and centre region calculations.[4)] With a dc beam current of 8.0 mA in the injection beam line, 3.0 mA were accepted into the first orbit, but only half of it could be used for acceleration. 600 μA were cut away in the vertical slit, 800 μA in the cleaning collimator and 100 μA in the slit on the fourth turn. The percentage of the beam cut off by the cleaning collimator agrees well with the 25% predicted.[4)] The fact that the beam is improved by cutting with the vertical slit, however, was not expected. It gives evidence that

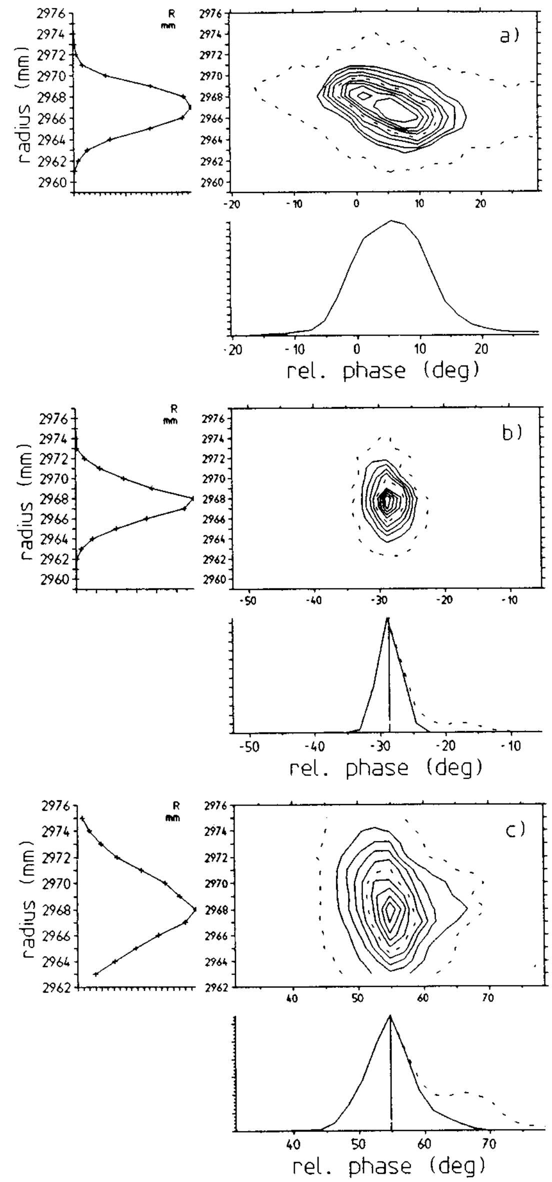

Fig. 4. Improvement in the longitudinal phase space of the beam on the last turn before extraction from Injector 2: a) a 300 μA beam in 1989 before optimization of bunching, b) typical production run at 360 μA using a strongly bunched beam with proper dispersion matching and with a cleaning collimator added 90 deg behind the phase defining collimator, c) the 1.5 mA beam extracted in 1991. Shown are the intensity distribution (1%, 10%,....90%) projected onto the plane defined by radius and phase as well as the radial and longitudinal profiles. The measurement is made with a time of flight analysis of protons scattered from a thin carbon fibre as a function of its radial position. The dashed lines in the phase profile show the raw data before application of a correction for pileup in the photomultiplier at elevated beam intensity.

vertical distortion from the debunching described above either makes beam quality worse or is used to improve the phase cut.

The phase width of the beam remains uncertain. The time structure measurement (fig. 4), based on a time of flight analysis of protons scattered from a thin carbon fibre (30 μm) in function of the radial position of the fibre, gave a phase width of 16 deg (full width for 96% of the beam) at 1.5 mA. This is in accordance with the width of 11 deg expected for a bunching factor of 3 for a perfectly cut square distribution, if the phase compression by a factor of 2 is accounted for. On the other hand, the buncher calculations predict a phase width of only a few degrees which is supported by the results of several experiments described below. The small phase width demonstrates in any case that the bunching and the phase cut were indeed very effective. It was, however, a surprise that the influence of longitudinal space charge forces did obviously not destroy the beam. As shown in fig. 1, the radial width of the beam did only moderately increase with beam current and as seen in fig. 4c and in fig. 5 the phase space volume remained compact. The phase width and the radial width of the beam were observed to grow roughly by the same amount and in parallel and it seems that the vortex motion in the plane defined by radius and phase keeps the beam together and leads to a compact

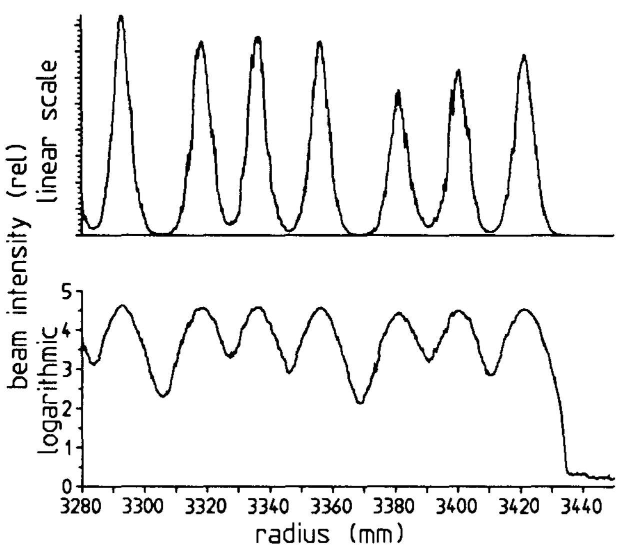

Fig. 5. Beam profile of the last seven turns in the Injector 2 cyclotron measured at a beam current of 1.5 mA. In order to see space charge induced broadening of the beam such measurements must be made at full beam current. Only a probe equipped with a thin Carbon wire (about 50 microns diameter) can withstand the high power density of this beam. The profiles are also shown in a logarithmic scale to give information on beam losses to be expected from beam tails or from the halo of particles extending into the valleys between the orbits.

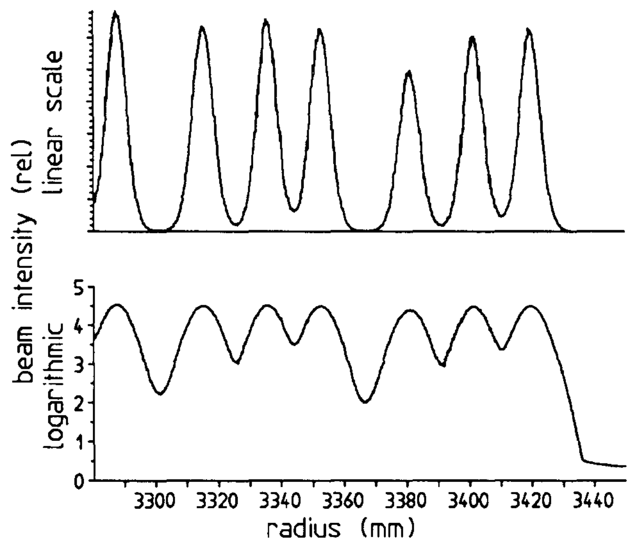

Fig. 6. The same measurement as in fig. 5 for the case of 1.3 mA extracted with the flattop resonators turned off. Despite space charge forces and the fact that acceleration is no longer independent on phase, the turns remain separated and compact.

ball of charges growing with increasing beam current, a situation already predicted in early publications on space charge effects in cyclotrons.[12] Recently, several experiments with the flattop resonators turned off also gave surprising results which support this interpretation. A beam of up to 1.3 mA could be extracted in this mode with still well separated, compact turns (fig. 6) while a phase width above 10 deg should result in a complete overlap of the turns. Similar inconsistencies are observed if the magnetic field setting is varied or if the flattop resonators are used to introduce a phase dependent acceleration. Further investigations are necessary to understand the combined effects of vortex motion and phase compression on the beam during acceleration.

3. RING CYCLOTRON

3.1. The Upgrade program in the Ring cyclotron

The 590 MeV Ring cyclotron was designed two decades ago by PSI (formerly SIN) according to identical design criteria as later copied for Injector 2: a large structure with separated magnets and hence operation in a high harmonic number (h=6). This gives enough room for injection and extraction elements and for four powerful acceleration cavities with a high energy gain of about 2 MeV/turn. The Ring cyclotron is also equipped with a flattop cavity operated at the third harmonic of the accelerating voltage. The turn separation at extraction is 4.5 mm for a well centered beam, but it is generally expanded to about 8 mm by off-centre injection, in order to achieve full extraction. The original design goal was a beam current of 100 to 300 μA, but the first

Table 2: RF power requirements in the Ring cyclotron

proton current	(mA)	0.25	1.5
beam power	(kW)	150	900
50 MHz RF systems			
cavity voltage	(kV)	520	730
beam power per cavity	(kW)	37	220
dissipation per cavity	(kW)	150	300
total power	(kW)	187	520
150 MHz flattop system			
beam power deposited	(kW)	15	90
dissipation in cavity	(kW)	50	100
dynamic range	(kW)	50 - 35	100 - 10

years of routine operation showed that up to 200 μA beam losses were still extremely low. After installation of the flattop cavity, an extraction rate of better than 99.98% could be reported. In a pulsed mode, where two out of three pulses were suppressed, beam losses could be held below the given limits up to beam currents of 250 μA. Based on this, one could expect that in an unpulsed mode it would be possible to extract beam currents up to 750 μA. The intensity, however, was limited by the power that could be deposited in the beam dump and by the power available from the RF systems.

The requirements on the RF systems given by 1.5 mA beam intensity in the Ring cyclotron are summarized in table 2 taken from ref.3. A new 50 MHz power amplifier based on the Siemens Tetrode RS2074 had to be developed by PSI. It delivered a maximum of 850 kW into a resistive load and up to 400 kW into the cavity (300 kW to the walls and 100 kW to the beam). Routine operation is restricted to lower power levels due to problems with the coupling loop (overheating and deposit of sputtered material on ceramic insulators) at increased voltage levels. With one of the RF systems equipped with the new amplifier stage, the power is sufficient for the acceleration of beam currents up to 500 μA. As seen from table 2, a special challenge comes from the decelerating flattop system which was equipped with a new, more powerful 150 MHz amplifier in January 1992. It has to operate at decreasing power with increasing beam intensity, under stringent specifications in phase and amplitude stability. In order to reduce effects from beam loading, the flattop cavity has to be artificially loaded. Even if the power dissipation in the loaded cavity is doubled an extreme dynamic range of 100 to 10 results, if the beam intensity is raised to 1.5 mA. Operational experience and details of the upgrade program on the RF systems are given in a separate contribution to this conference.[5)]

In the years 1992/94 the remaining three 50 MHz RF systems will be equipped with the new amplifier stage. With all RF systems upgraded, the acceleration voltage can be increased and the energy gain be raised from 2.0 to 2.8 MeV per turn. This improves the extraction in two ways. It enhances the turn separation and it diminishes the number of turns which reduces the effect of longitudinal space charge forces. The upgrade program for the Ring cyclotron also includes the replacement of all the injection and extraction elements. The new generation will be equipped with improved local shielding and it will be adapted for easier handling at the higher activation levels to be expected.

3.2. Upgrade of the beam facilities

As with the Ring cyclotron, the original beam facilities were designed for beam currents of up to 200 μA and had to be replaced. The first of the two meson production target stations was rebuilt in 1985. The reconstruction of the second meson production target station, of the beam dump area and the preparation work for the connection of the future spallation neutron source were a major task accomplished in an 18 month shutdown in the years 1990/1991. A special challenge was the dismantling of the old target and beam dump, which had served for 15 years at beam currents of 100 to 200 μA with a total charge of 6.6Ah deposited. 500 t of activated material with a total activity of 10^{15} Bq had to be removed. About two thirds of this material could be reused and the rest was enclosed in concrete boxes and reinstalled as shielding. Local dose rates were as high as 400 Sv/h and the contamination levels were locally a factor 10^4 above tolerance level. Nevertheless incorporation could be avoided and the highest personal dose was about 20 mSv. The total dose received by 200 persons was 470 mSv.

The new beam dump and meson production target station are designed for a beam intensity of up to 2 mA. At the anticipated intensity of 1.5 mA, a beam power of almost 900 kW has to be handled. The beam loss and power balance for this case is summarized in table 3. The design accounts for the fact that one third of the power escapes as radiation of secondary particles and has to be absorbed in water cooled shielding. Therefore the structure is strictly separated into an inner part optimized to handle the thermal problems and an outer mechanical part that is protected from heat and radiation. The inner part is a closed shell of heavy radiation shields around the collimators and the beam dump, all water cooled and generally made out of copper. All sensitive mechanical parts such as vacuum chambers, the seals and the support structures are outside of this shielding and hence protected against heat induced deformations. To ensure easy handling at the activation levels to be expected, all parts are vertically mounted and removable by crane. Their supports are self centering pins without additional fastening, vacuum seals are all metal inflatable elements that do not require any clamping and all the power-, cooling- and signal connections are brought up through the shielding to an accessible platform 2.5 m above the beamline.

3.3. Operational experience with a beam of 500 μA

Operation of the facility after the extended reconstruction work could be resumed in June 1991. The beam intensity through the Ring cyclotron and onto the rebuilt pion

Table 3: Beam loss and power balance in the upgraded target station and beam dump

	beam loss	power
incoming beam (1.5 mA, 590 MeV)		885 kW
pion production target (C12, 10gr/cm^2)	18%	45 kW
particle radiation from target		140 kW
primary beam in shaping collimators	22%	145 kW
neutron radiation from shaping coll.		50 kW
primary beam into beam dump	60%	380 kW
neutron radiation from beam dump		125 kW

production target could be continuously increased and a stable beam of 500 μA at 590 MeV was finally reached in December 1991. New protection systems against beam loss and against deviation from full beam transmission were installed and tested. Initially these systems were the source of a large number of false alarms and interruptions in the beam production. The handling of the beam is supported by beam loss monitors (simple air filled ionization chambers) distributed all along the beam line and in the Ring cyclotron and by computer controlled on-line centering of the beam in the transport system.

The beam losses, as measured on collimators of the extractor and in the beam loss monitor system, were around .1% at an extracted beam current of 500 μA, but in further production runs in 1992, the losses could be reduced to about .01% at an extracted beam current of 400 μA (see fig. 7). Data on the beam quality are summarized in table 4 in comparison to values of the beam from Injector 2. Horizontal and vertical emittance areas could be deduced from the width of profiles in the beam transport system. The dispersive resolution, however, was not sufficient to accurately separate the effects of energy spread from the horizontal emittance. The phase width of the 590 MeV beam could not be measured, but was calculated from the result of the time structure measurement in Injector 2 and the known phase compression in the Ring cyclotron. The question of space charge limits is still open. At a beam current of 500 μA, the beam quality seems to deteriorate and beam losses do increase with increasing beam intensity, but higher beam currents or better diagnostics would be needed to clearly attribute these effects to space charge forces. It is expected, however, that at the full beam intensity of 1.5 mA, the space charge forces will manifest themselves very strongly and that the voltage on the cavities has to be increased as indicated in table 2 to reduce their effect. Observed intensity limits from the operation at reduced voltage (e.g. with only three cavities in operation, case b in fig. 7) scale well with the prediction, but the data are too uncertain to allow a positive statement on the limit imposed by space charge forces.

With increasing beam intensity, a detailed analysis of the beam becomes more and more difficult. While beam diagnostic should be done at the full beam current, the use

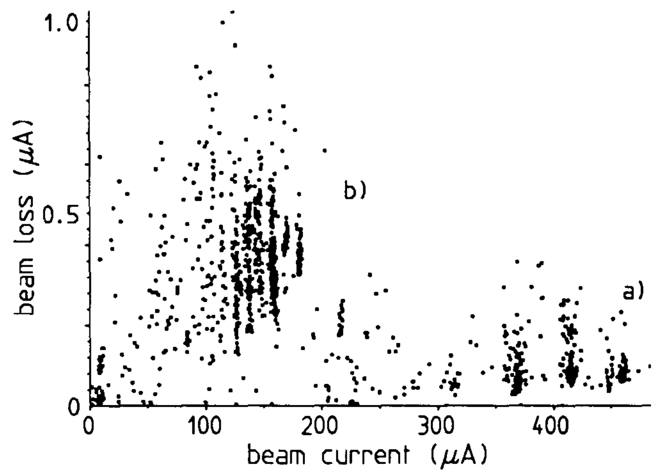

Fig. 7. Beam loss in the Ring cyclotron in correlation to the beam current for a normal production run (a) and for reduced acceleration voltage (b). It demonstrates that beam loss can be kept below 0.1%, if the acceleration voltage is sufficiently high. The beam loss is measured in an air filled ionization chamber. The data are taken by a logging program that reads all cyclotron parameters every 15 minutes and stores them on disc for later analysis.

Table 4: Quality of the beams in the PSI facility

energy (MeV)	beam current (mA)	emitt. area (2σ) horiz. (mm mr)	emitt. area (2σ) vert. (mm mr)	energy spread (%)	phase width (deg)
Cockcroft - Walton preinjector:					
0.87	8.0	8. π	8. π		dc
Injector 2:					
72	0.5	2. π	2. π	0.4	< 12.
	1.5	3. π	3. π	0.6	< 16.
Ring cyclotron:					
590	0.5	1.5 π	1.5 π	~0.2	< 10.

of most of the probes is restricted to low intensities where the properties of the beam are substantially different. Beam profile monitors that can be operated at full current, produce beam spill that exceeds the protection levels. A beam probe that can withstand the full beam is planned, but not yet installed. Under these conditions, new diagnostic methods have to be employed. Two examples are given in fig. 7 and 8. The first is statistical information from a data logging program that reads all cyclotron parameters every 15 minutes and stores the data on disc for later analysis. Apart from error detection, it can be used to find correlations between values and parameters of interest. The second example is a result from a two parameter scan that can be used under operational conditions. This scanning program changes two

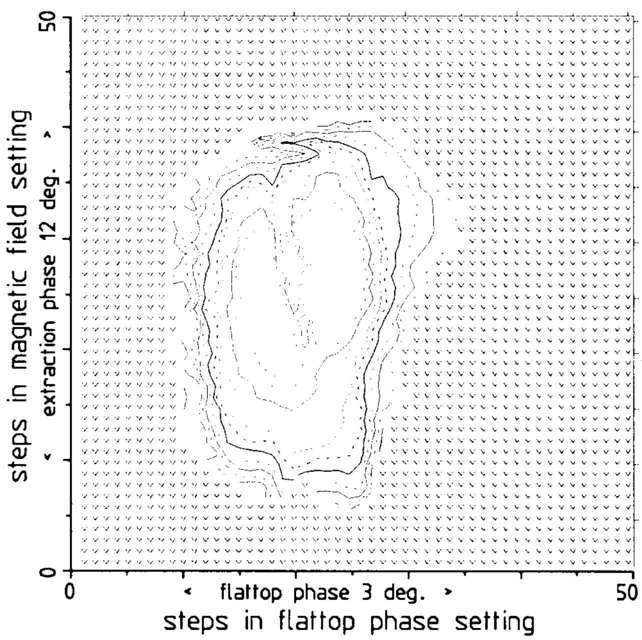

Fig. 8. An example of the complicated structure of the low level beam losses of interest in high current operation, here the beam loss in the Ring cyclotron as a function of the magnetic field setting and of the phase between flattop and accelerating voltage. Shown is the output of an automatic scanning routine, that has been developed to support accelerator tuning under running conditions at high beam currents. It starts from the actual value and automatically avoids the marked region (v) where interlock situations are encountered.

parameters in a specified range, but automatically restricts the range to parameter values where beam loss does not exceed given limits. The value that is recorded in the scan can be any passive parameter related to beam quality. Details on this program are presented in a separate contribution to this conference.[14)]

The setup for a beam with high current and minimal losses proceeds in steps. At first all parameters are adjusted to optimize the beam quality based on measurable properties, partially at low beam intensity. In general, when the beam current is increased also the RF amplifiers have to be adjusted in order to deliver the necessary power with good stability. In a final fine-tuning the beam losses as measured in collimators and in the ionization chambers are minimized. This last step is always based on experience, takes plenty of time (days or even weeks) and does not follow strict recipes. Particles far out in phase space follow other tracks than the main beam, they can have different source points (e.g. collimators) and their phase space coordinates often show strong coupling between horizontal, vertical and longitudinal planes (e.g. aberrations, space charge effects). Once optimized, the beam is very stable and needs little adjustment. Beam losses at extraction do not depend strongly upon magnetic field tuning, but are sensitive to certain parameters in the injector cyclotron like instabilities in the buncher phase, setting of trimcoils in the centre region, ion source parameters and beam position in collimators.

4. ACKNOWLEDGEMENT

This report summarizes the work and effort of a very large number of persons, be it responsible for the design, involved in the upgrade and reconstruction work, or last but not least being patiently engaged in the tuning of the beams. It is absolutely impossible to honor individual contributions to the achievements, but this is a welcome opportunity to express thanks to everybody who has been involved.

5. REFERENCES

1) U. Schryber, "Upgrading the SIN facilities to higher intensities", **Proceedings of the 10th Int. Cycl. Conf.& their Appl.**, East Lansing 1984, p.195
2) W Joho, "Upgrading the PSI cyclotrons for research at high beam intensities", presented at the **Int. Symp. on new trends and facilities in intermediate energy Nucl.Phys.**, Osaka 1991
3) U. Schryber et al., "Upgrading the PSI accelerator facility for high intensity operation", presented at the 3rd **Europ. Acc. Conf**, Berlin, March 1992
4) J. Stetson et al., "The commissioning of PSI Injector2 for high intensity, high quality beams", presented at this conference
5) P. Sigg et al., "Experience with the PSI-cyclotron RF-system under heavy beam loading", presented at this conference
6) W. Joho, "High intensity problems in cyclotrons", **Proceedings of the 9th Int. Conf. on Cycl. & their Appl.**, Caen 1981, p.337 and **Proceedings of the 11th Int. Conf. on Cycl. & their Appl.**, Tokyo 1986, p.31
7) W. Joho "Space charge effects in cyclotrons", presented at the **Int. Acc. School**, Dubna 1988
8) S. Adam, "Calculations of space charge effects in isochronous cyclotrons", **IEEE NS-32** (1985) 2507 and **thesis 7694** ETH Zurich, 1985
9) U. Schryber et al., "Status report on the new Injector at SIN", **Proceedings of the 9th Int. Conf. on Cycl. & their Appl.**, Caen 1981, p.43
10) M. Olivo, **Proceedings of the 11th Int. Conf. on Cycl. & their Appl.**, Tokyo 1986, p.519
11) M. M. Gordon, "The longitudinal space charge effect and energy resolution", **Proceedings of the 5th Int. Conf. on Cycl. & their Appl.**, Oxford 1969, p.305
12) A .Chabert et al., "Beam dynamics in separate sector cyclotrons", **Proceedings of the 7th Int. Conf. on Cycl. & their Appl.**, Zürich 1975, p.245
13) E. Baron et al., "High intensity and space charge problems at GANIL", **Proceedings of the 11th Int. Cycl. Conf. & their Appl.**, Tokyo 1986, p.234
14) S. Adam, "Twodimensional scans with adaptive domain control", presented at this conference