HIGH POWER OPERATION OF THE PSI-ACCELERATORS

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Abstract:
The PSI-cyclotron facility was upgraded in several steps with the goal to produce 1.5 mA of protons at 590 MeV for the spallation neutron source SINQ, which is near completion. The main subjects of the upgrade of the 590 MeV Ring were the increase of the RF-power, new injection and extraction elements and new diagnostic equipment. The cyclotron is routinely operated at a current level of 1.4 mA, corresponding to a beam power of 0.83 MW. The extraction losses are < 400 nA when the cyclotron is well tuned. The highest beam current reached so far is 1.50 mA. This is near the space charge limit of the 590 MeV Ring cyclotron. Below that limit, the beam losses in the ring are caused by tiny halos accompanying the beam. Repetitive cleaning of the beam with collimators is essential. The origin of these halos is discussed. Based on the experience with the 590 MeV Ring, a cyclotron for 10 MW beam power at 1 GeV is proposed. The main features are 12 sector magnets, 8 accelerating cavities for 1 MV and 2 flat top cavities.

1. Introduction

PSI operates a cyclotron facility for the acceleration of a high intensity proton beam at an energy of 590 MeV for the production of intense beams of pions and muons. The facility is mainly used for research in

- nuclear- and particle physics
- solid state physics using our μSR-facilities
- defect physics and material tests using a proton beam of 10 μA at 590 MeV. This low intensity beam is split from the main beam with an electrostatic beam splitter.
- curative treatment of tumours with nA-proton beams at 200 MeV. These beams are produced by degrading, refocusing and collimating the split beam mentioned above.

The accelerator complex and its evolution during almost two decades has been described previously [1, 2, 3, 4]. Therefore the main features of the facility will only be summarized in brief. The protons are accelerated to the final energy of 590 MeV in two stages. The main stage is an isochronous ring cyclotron with an injection energy of 72 MeV. Its main components are eight sector magnets, four accelerating cavities (50 MHz) and one flat top cavity (150 MHz). The first stage, the injector 2, is also an isochronous ring cyclotron with four sector magnets, two coaxial resonators for the acceleration (50 MHz) and two flat top cavities (150 MHz). A Cockcroft Walton type accelerator with an energy of 0.87 MeV serves as a preinjector.

The 590 MeV protons from the main ring are guided onto two consecutive target stations and then stopped in a high power beam dump. The facility, commissioned in 1974, was originally designed for a proton current of 0.1 mA, but during the following 15 years it was routinely operated at a current level up to 0.25 mA. The maximum current reached was 0.35 mA, limited by the available RF-power in the main ring. This, however, is only a fraction of the beam dynamical intensity limit of the ring, which was estimated to be between 1 and 2 mA.

This promising outlook into a high current future at PSI stimulated the start of many challenging new experiments in particle physics. It also justified the construction of the spallation neutron source SINQ for research in solid state and material physics, planned to be commissionned in early 1996. For a full exploitation of this new facility, proton currents > 1 mA are required. In view of the SINQ an upgrading program for beam currents of 1.5 mA, corresponding to a beam power of almost 1 MW, was started already in the late 70's. The main steps in this upgrade were:

- The original versatile injector cyclotron, made by Philips Company, was replaced by injector 2, a dedicated high current cyclotron for 72 MeV protons. Injector 2 was commissioned in 1985 and has reached 1.5 mA beam current with small extraction losses in 1990. The Philips cyclotron is nowadays used for low energy experiments and for medical applications, but also for the injection of polarized protons into the 590 MeV Ring during a few weeks per year.
- Adaptation of the two target stations (in 1986 and 1990 respectively) to the future megawatt beam and improvements of the secondary beam lines. Additionally, in 1990 a portion of the beam line to the SINQ was installed. With a 60 mm graphite target this beam line can only transport 60% of the protons. The rest is absorbed by collimators and the target.

- The 590 MeV Ring was upgraded in several steps during the annual shut down periods between 1990 and 1994. The main items of this upgrade program are described briefly in the following chapter.

2. Upgrading Program for the 590 MeV Ring

The 590 MeV Ring cyclotron is schematically presented in fig.1. The four accelerating cavities (50 MHz) are rectangular boxes made of aluminium. They provide a sinusoidal voltage distribution in the radial direction with a peak voltage of 730 kV (in 1995). A flat top cavity operating at 150 MHz is superimposed to the accelerating voltage such that the resulting voltage is flattened over a phase range of about 30 degrees. The flat top scheme is very effective in reducing the energy spread of the beam in the cyclotron, thus giving narrower beams at extraction radius and thus improving the extraction[5]. The resulting accelerating voltage leads to a turn separation of 24 mm at injection and 7 mm at extraction. The final energy is reached after 217 revolutions.

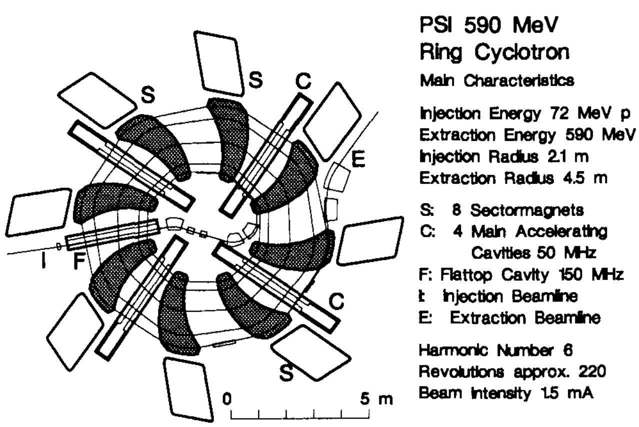

Fig. 1. Layout of the PSI-ring cyclotron

2.1 Upgrade of the RF-system

The importance of the accelerating voltage for the space charge limit in a cyclotron was emphasized by W. Joho[6]. He points out that the longitudinal space charge effects dominate those in the transversal direction, because of the lack of phase focusing in an isochronous cyclotron. The effects of the longitudinal space charge forces can be seen as a vortex motion of the particles in the longitudinal phase space of energy and phase[7,8]. We can distinguish the following two stages which are of importance for the main ring:

1. Particles gaining or loosing energy drift adiabatically to the corresponding equilibrium orbit with larger or smaller radius respectively, thus producing a tilted bunch. This effect can be compensated by operating the flat top system in a „tilt top" mode[6].
2. The Coulomb forces that generate the tilt, however, are not linear and produce a distorted bunch. This effect tends to smear out the turn structure at extraction. An approximation formula used in ref. 6 shows that the resulting intensity limit due to the longitudinal space charge forces is proportional to $1/N^3$, N being the number of turns in the cyclotron.

By converting the revolution number in the above formula into accelerating voltage, we found that for a space charge limit of 1.5 mA the cavity voltage needs to be increased from the original 450 kV to about 730 kV. This means that the RF-power needed to excite one cavity increases from 115 kW to about 300 kW! As an introductory test to the RF-upgrade program, the feasibility of such a demanding operating condition was demonstrated on an existing cavity. It was shown, that the water cooling system and the temperature distribution on the cavity as well as the high voltage behaviour are acceptable.

Table 1. RF-power requirement (typical) of the ring cavities

proton current (mA)	0.25	1.5
total beam power @590 MeV (kW)	147.5	885
50 MHz RF-systems		
-cavity voltage, typical operation (kV)	450	730
-Beam loading/cavity (kW)	36	216
-power dissipation/cavity (kW)	115	300
-RF power / cavity (kW)	151	516
150 MHz flat top system		
-beam power deposited in the cavity (kW)	15	90
-power dissipated in cavity (kW)	50	100
-dynamic range of power amplifier (zero to max. current) (kW)	50÷35	100÷10

Table 1 summarizes the performance of the RF-systems for 0.25 mA and 1.5 mA respectively. It shows that for the highest current envisaged, the beam power per cavity becomes comparable to the dissipative power losses in the cavity walls and the total RF-power per cavity amounts up to 516 kW! Some problems arise in the flat top system at high beam currents, because the flat top cavity absorbs power from the beam. This disturbs the voltage- and phase control circuits of the flat top cavity when the absorbed beam power comes close to or even exceeds the wall losses. The implications of beam loading effects on the design and the operation of RF-systems for high beam power are discussed in ref. 9 and in a separate contribution to this conference[10].

The amplifier chains of the four accelerating cavities and the flat top cavity were all refurbished and equipped with new power amplifiers. The new amplifier systems were implemented in the facility in five steps between 1990 and 1995 during the annual shut downs. This resulted in a stepwise increase of the energy gain per turn by about 10% and a corresponding decrease in revolution number from 347 (in 1989, prior to the upgrade) to 301, 267, 239 and 217 respectively.

As a further step in the upgrade of the RF-system we plan to replace the existing aluminium cavities by new copper cavities with a geometry optimized for a high shunt impedance. We consider a peak voltage of 1 MV @50 MHz with wall losses of 500 kW as a realistic goal. A 1:3 - model cavity is near completion. The new cavities could be used either to push the space charge limit of the ring further up or to save electric power.

2.2 Injection- and extraction elements

The injection and extraction devices, the electrostatic inflector channel (EIC), the electrostatic extractor channel (EEC), and the Panofsky-type dipole / quadrupole magnetic channel (FM) were redesigned mainly with the aim to facilitate their handling and servicing in view of the increased activation levels expected from the higher beam losses.

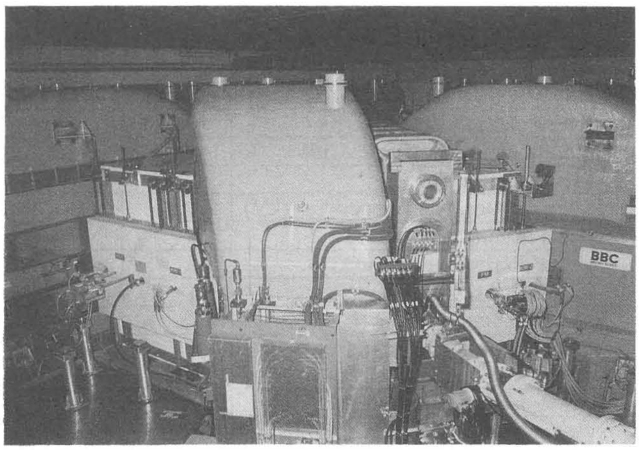

Fig. 2. View of the beam extraction region of the PSI-ring cyclotron. From left to right follows the electrostatic extraction channel, a sector magnet, a 50 MHz accelerating cavity and the Panofsky-type magnetic channel. Concrete blocks and motor driven shielding ports protect the service personnel from radiation.

The electrostatic devices follow basically the old EEC design[11,12]. They consist of an aluminium cathode at high voltage, indirectly cooled through BeO insulators, and a thin septum made of Tungsten strips (with 2% ThO_2), 0.05 mm thick, 4 mm wide and spaced 2 mm apart. The strips are individually tensioned to about 5 kg/mm^2 in order to reduce thermal deformations of the septum. Common features to all three devices are:

- The installation and removal from the accelerators and its transport to the service and storage areas is done using massive shielding boxes with remote handling features. For each device a stand-by unit is available.
- The quick removal of the channel itself from the rest of the device. This is the part where the failure will most likely occur. The channel is equipped to accept remote handling tools for removal and service.
- Use of high radiation resistant materials, particularly vacuum metal seals.

Furthermore, after these devices have been installed in the 590 MeV Ring, they are covered behind motor driven shielding ports (see fig. 2).

2.3 Diagnostic system

For the operation of high intensity cyclotrons it is essential to have diagnostic equipment able to measure the beam at full intensity. The traditional design of beam probes with stopping blocks and thick fingers[13] cannot be used any more. At our beam power the probes have to be transparent to the beam as far as possible. In cases where continuous monitoring is necessary, nonintercepting probes are used[14].

The new radial probes designed for the 590 MeV Ring cover the whole accelerating range from injection to extraction. They have either one or three carbon wires of 33 μm diameter. In the three-wire probe one wire is vertically oriented, whereas the other two are arranged crosswise under 45 degrees with respect to the vertical wire. This allows measurement of horizontal and vertical position and also the shape of the beam. The mass of intercepting material is so low, that measurements can be made at full intensity and without producing disturbing beam losses.

To exploit the probe signals a new CAMAC based front end electronic unit has been developed. It includes a fast logarithmic current-to-voltage converter with a high dynamic range[15], permitting measurement of low and high intensity beams.

2.4 Control system

To cope with the increase in beam intensity and also to replace old and obsolete equipment, the control system had to be upgraded. A solution with a distributed and message based system was chosen.

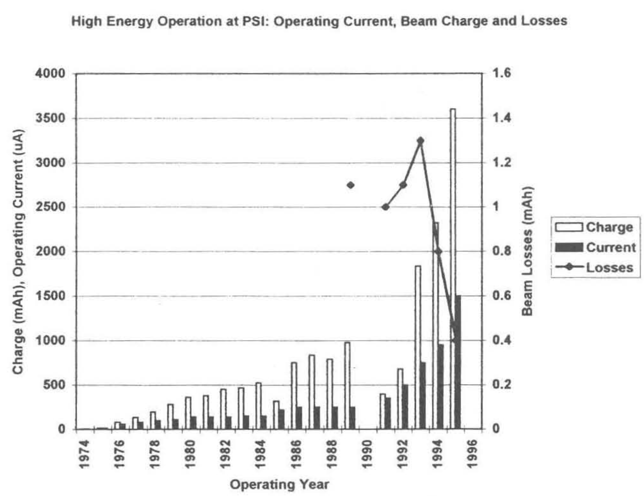

Fig. 3. High energy operation at PSI from 1974 to 1995. The integrated beam current through the 590 MeV Ring, the beam current during routine operation and the integrated extraction losses are shown. The data from 1995 are extrapolated.

The old PDP 11/44 16 bit computers are replaced by VME-RISC machines with CAMAC interfaces. These serve now as front end computers providing access to the accelerator devices. This access is done via standardized communication systems on ETHERNET. All the application software is executed on workstations. The same workstations are also used as the operator interface using X-windows[16].

3. High Intensity Operation in 1995

3.1 Performance of the facility

The performance of the accelerators for the period 1974 to 1995 is shown in fig. 3. Since the beginning of the upgrade program in 1990 the beam current during routine operation could be raised from 0.25 mA to 1.4 mA, while the average extraction losses in the 590 MeV Ring were reduced by almost a factor of three. The highest current registered so far is 1.50 mA with extraction losses of about 0.8 μA.

It should be mentioned, however, that for the user of the facility the stability of the beam as well as its availability are of similar importance as the beam intensity. For the PSI-facility, the availability (determined over periods of one week) is usually between 80% and 92% at a beam current of 1.2 mA.

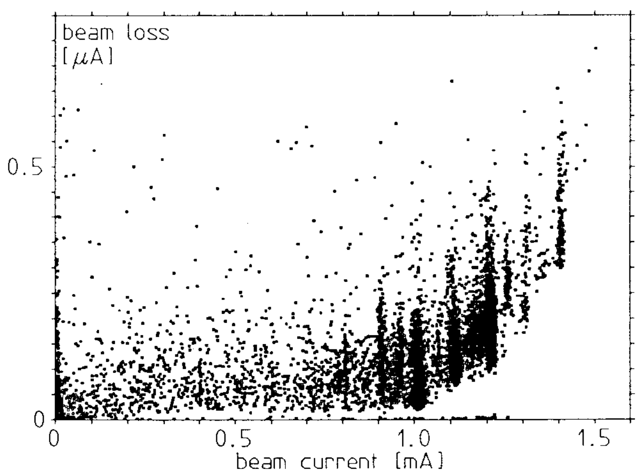

Fig. 4. Extraction losses in the ring cyclotron during routine operation in 1995. The individual data points are extracted from a periodic logging system. The losses are monitored by ionization chambers installed near the extraction devices.

For the protection of the accelerator components and in order to keep the activation tolerable, the beam losses are continuously monitored with a system of ionization chambers, installed at selected locations around the 590 MeV Ring and along the beam lines. A rough calibration is done by stopping a beam of <1 μA in specific locations and by measuring the response of the ionization chambers, which leads to an accuracy of about ± 20%. Fig. 4 shows the extraction losses in the ring cyclotron during routine operation in 1995. The individual data points are extracted from an automatic logging system which collects periodically (every 15 min.) all relevant information from the facility. From the fact that the data points are widely scattered, it becomes evident that the losses are influenced by many different factors: the quality of a setting, the actual technical condition of the equipment and last but not least, the human factors, like skill and motivation of the operators.

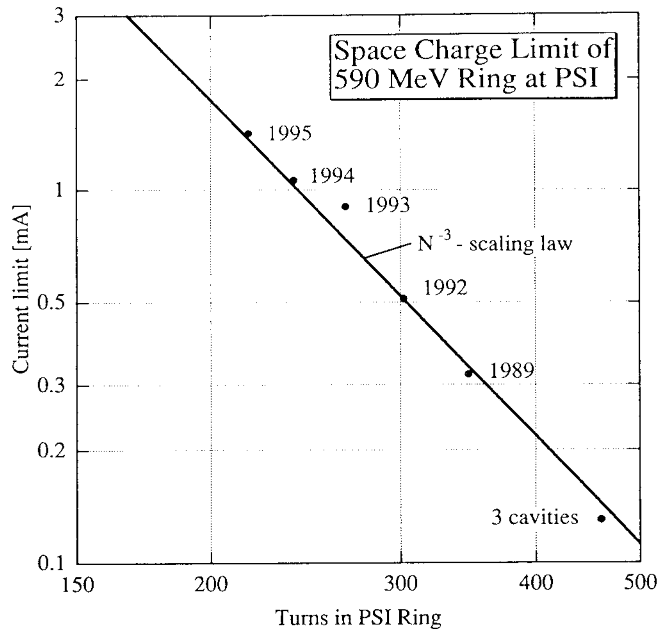

Fig. 5. Space charge limit of the 590 MeV Ring before and during the four steps of the ring upgrade. Each year the voltage of one cavity was increased from ≈450 kV to 730 kV each year. There is a good agreement between the registered maximum beam current vs. the turn number N in the cyclotron and the N^{-3}-scaling law. The operating point with 3 cavities stands for the fall-back mode of former years, used when one of the four cavities failed.

The maximum current through the ring cyclotron is defined in a pragmatic way as the beam current which leads to relative extraction losses of $5*10^{-4}$ during routine operation. This is below a level of 1 to 2 μA, which we consider to be tolerable for safe operation and maintenance of the cyclotron. Fig. 5 shows the maximum beam current for the different steps of the upgrade program. They are in good agreement with the N^{-3}-scaling law mentioned above, which suggests that the current limit is indeed governed by the longitudinal space charge forces.

The beam losses at injection into the main ring are almost negligible when the beam from injector 2 is well collimated. Collimation is very difficult, since every cleaning edge represents a new source of scattered protons. Therefore it must be done in several steps, mainly inside the injector 2 but also along the 72 MeV beam line. Collimation in the center of injector 2 is also important in order to keep its extraction losses tolerable. While this collimation in the center region results in a diffuse halo of scattered particles, reproducible satellites can be observed in the 72 MeV beam line, if the injector 2 cyclotron is operated close to its limits. Fig. 6 shows horizontal and vertical beam profiles in a dispersive location, suitable to cut beam components with different energies. From this figure we conclude that:

- the beam satellites appear in the horizontal direction only
- the fractional intensity in the tails is of the order of 10^{-3} of the main beam
- the energy difference between satellites and main beam corresponds to the energy gain per turn in the injector 2 at extraction. This indicates that the satellites result from the extraction mechanism in injector 2. The electrostatic septum is located in the region where the tails between the last internal revolution and the extracted beam overlap. Particles in the tails are extracted one revolution too early or too late with respect to the normal beam.

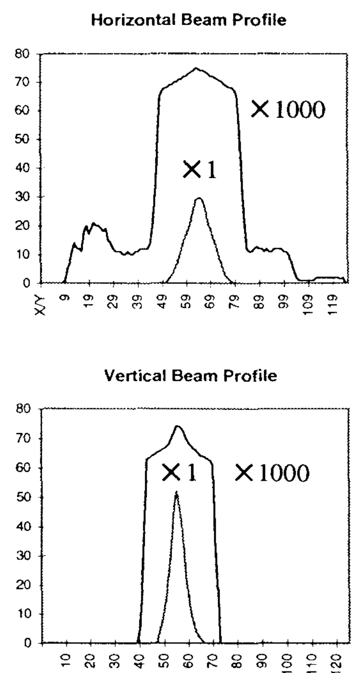

Fig. 6. High intensity beam profiles in the injection beam line (72 MeV). Satellites appear in the horizontal direction only. They become visible when the profile is magnified electronically by a factor 1000. The dashed lines represent the real beam profiles.

The injector 2 is described in ref. 3 and some high intensity aspects are discussed in ref. 17. The center region is shown in fig. 7. A 10 mA DC-beam @ 870 keV from a Cockcroft Walton preaccelerator is axially injected. The main features of the beam preparation are a 1^{st} harmonic buncher in combination with careful collimation of the beam in phase and both lateral directions[18]. A proper combination of buncher location, buncher voltage and intensity of the DC-beam results in a time focus with a minimum energy spread at the high power collimator KIP2.

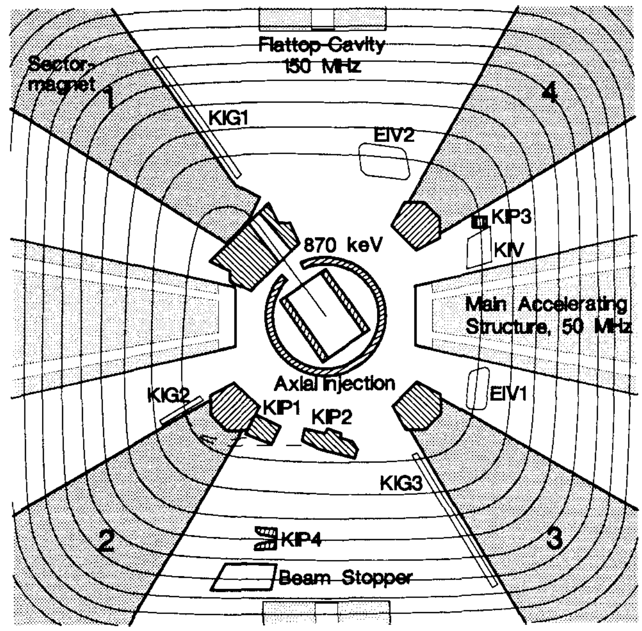

Fig. 7. Sketch of the center region of injector 2. Device names beginning with a „K" represent beam collimators. KIP2 is part of the high power collimator system which selects the phase width of the accelerated beam. Its radial position is variable and KIP2 is therefore used as the „beam current knob" at PSI. KIP1, 2, 3, 4 are radial and KIG 2, 3 and KIV are vertical collimators.

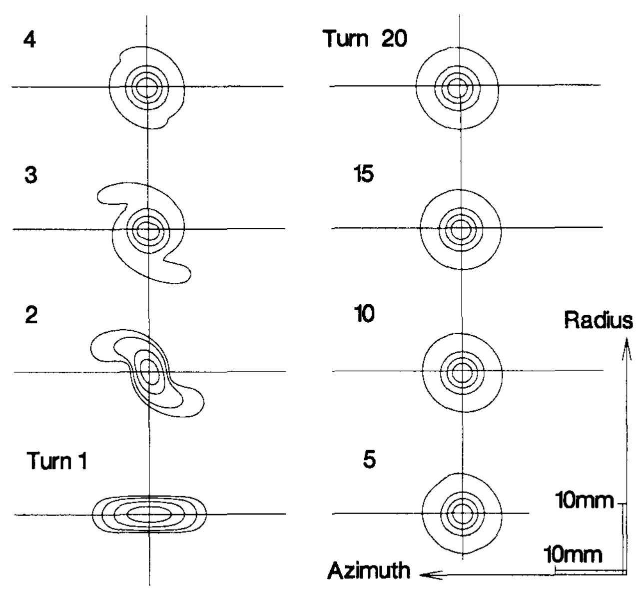

Fig. 8. Simulated deformation of cyclotron beam bunches under the influence of longitudinal space charge forces in injector 2. The case considered here is an accelerated beam of 1.5 mA (average) and an initial phase width of 15 deg. After this space charge „massage" the phase width is reduced to about 5 deg.

This collimator is used to control the beam current by varying its radial position. The minimum energy spread in the time focus is an unexpected benefit from the strong repelling space charge forces in the bunches. In the center of the cyclotron, the beam bunches are severely influenced by longitudinal space charge forces, because the bunches are short and the beam momentum is low. The bunches tilt and deform very quickly as a consequence of the space charge forces (see also section 2.1). Nonlinear effects, which depend strongly on the charge distribution in the bunch and on its curvature, produce a distorted bunch. The coupling of radial and longitudinal motion, finally, results in a vortex motion of the bunch, producing a galaxy shaped charge distribution[7]. This distortion and vortex motion of the bunch results in a deterioration of the beam quality. But since it occurs at low energies, it can be partly cured by collimation in an early stage of the acceleration process.

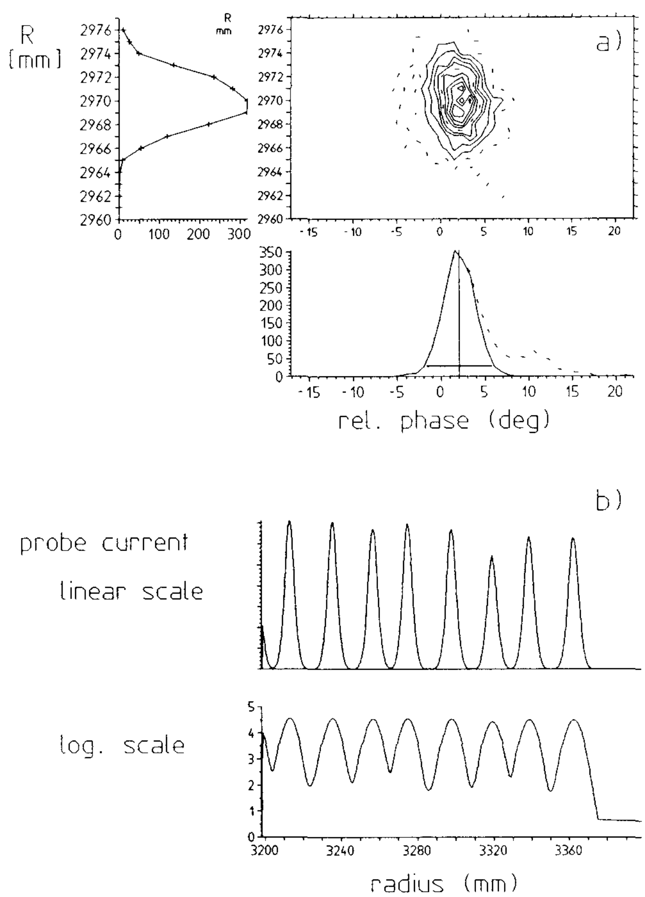

Fig. 9. Measured longitudinal and radial beam profiles of a 72 MeV proton beam in injector 2 at a beam current of 1 mA. a) Projection of the bunch in the plane given by radius and phase in the last turn before extraction (the dotted line indicates raw data before correction of instrumental effects). b) radial turn pattern of the last eight turns before extraction. The profiles are also shown in a logarithmic scale to give information on the beam losses to be expected from beam tails and halos in the valley between the orbits.

One might expect that strong space charge forces generate prohibitive tails. It turns out, however, that the vortex motion and the strong radial and longitudinal coupling results in compact and rather clean beams.

Fig. 8 shows a sequence of simulated beam bunches on different revolutions in injector 2. It suggests that the combined action of space charge forces and coupling in radial and longitudinal direction deforms the injected beam quickly towards a characteristic „eigen-volume", which is a real circular charge distribution in radius and azimuth! This combined action also provides a kind of longitudinal focusing in isochronous cyclotrons as long as the space charge forces remain strong enough. For more details on this surprising fact the reader is referred to the contribution of S. Adam[19] in this conference.

Experience from high beam intensity experiments with the PSI injector 2 demonstrates clearly, that the very strong space charge forces in a strongly bunched beam result in excellent beam conditions (see fig. 9). The width of the beam does increase with beam current, but the longitudinal and radial profiles are indeed clean. Tiny beam tails or diffuse halos from protons scattered by the collimators become visible in the valleys between the turns. This can be seen in the logarithmic representation of the radial turn pattern in fig. 9 b. From the depth of the valley between neighbouring orbits the extraction losses can be predicted.

3.2 Power Conversion Efficiency (PCE)

For future applications of cyclotrons designed for high beam power (1 to 10 MW) the conversion efficiency of electric input power into beam power is an important factor. For a beam power of 1 MW, the overall PCE of the PSI accelerators is 18%. This value includes the power consumption of injector 2, all magnets of the ring cyclotron and the auxiliary equipment of both cyclotron stages (cooling systems, vacuum pumps etc.). The PCE of the ring RF-systems (conversion of line- into RF-power) is 70%. In order to achieve a high PCE it is essential that the cyclotron is operated at its space charge limit.

3.3. Activation and maintenance

After four years of high power operation, the activation of accelerator components is still within tolerable levels for normal hands on maintenace. Only exposed components, such as extraction devices, beam splitters, the 590 MeV targets and their collimators have to be equipped with local shields and installations for remote handling. The annual integrated beam losses are around 1 mAh at extraction from the 590 MeV Ring and about 4 mAh at injection and in the injection beam line (72 MeV).

In 1994 the collective annual dose was 260 mSv for the whole laboratory (about 300 persons) and about 60 mSv for the maintenance of the cyclotron (about 80 persons). This corresponds to the legal annual dose limit of 13 and 3 persons respectively. No increase in the collective annual dose is noticed since the beginning of the high power operation. We are therefore convinced that the PSI-facility will remain maintainable also in the next decade.

4. Concept for a 10 MW-Cyclotron

Based on our experience with the 1.5 mA beam at PSI we propose a cyclotron scheme for the acceleration of a 10 MW beam[20, 21] @ 1 GeV. Such an accelerator could be an economic solution to an „energy amplifier" as proposed by C. Rubbia and his collaborators[22], for future spallation sources and eventually for transmutation. Such an accelerator would have to fulfill the following requirements:

- An accelerator scheme that allows continuous operation with high reliability.
- Beam losses as low as possible to avoid prohibitive activation.
- Efficient conversion of electric input power into beam power.

The layout of the cyclotron shown in fig. 10 is based on design criteria, techniques and components which proved to be successful in the PSI-ring cyclotron. Its main components are 12 sector magnets, 8 accelerating cavities and 2 flat top cavities. The high cavity voltage of 1 MeV would result in a turn number of about 140 in the cyclotron and a space charge limit of 10 mA. If properly designed, the high power cyclotron could have a power conversion efficiency of 40 to 50%.

The exact value of the injection energy is still open and should be optimised together with the injector cyclotron and the preinjector.

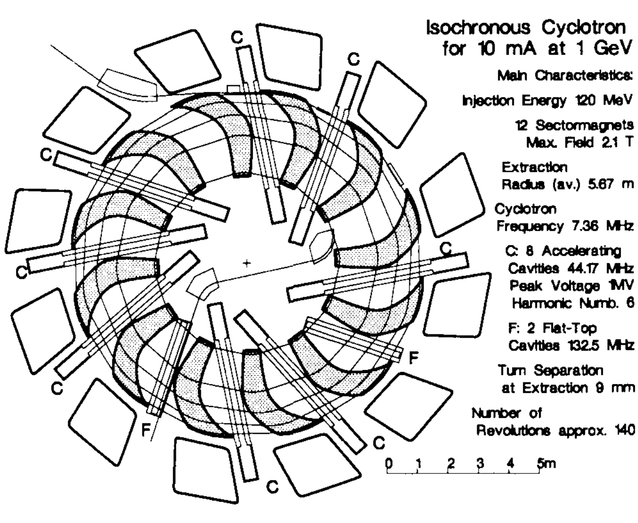

Fig. 10. Layout of the proposed high power 1 GeV cyclotron

5. Acknowledgments

The authors express their appreciation to all the colleagues at PSI who are involved in the upgrade of our facility. We would also like to thank our team of operators for their persisting effort to achieve the ambitious goal of operation: to produce a stable megawatt beam with tolerable losses.

6. References

1. Blaser, J.P. and Willax, H. A., Proc. 9th Int. Conf. on High Energy Acc., Stanford, 1974, p. 643
2. Joho, W. und Brunner, A., Kerntechnik Jahrg. 17, 1975, No. 8, p. 345
3. Schryber, U., Proc. 10th Int. Conf. on Cyclotrons and their Applications, East Lansing, 1984, p. 195
4. Schryber, U., et al. 3rd Europ. Part. Acc. Conf., Berlin, 1992, p. 173
5. Adam, S., et al., Proc. of the Part. Acc. Conf., Washington DC, IEEE NS-28, #3, 1981, p. 2721.
6. Joho, W., 9th Int. Conf. on Cyclotrons and their Applications, Caen, 1981, p. 337
7. Adam, S., Thesis ETH Zürich, Nr. 7694, 1985
8. Adam, S., IEEE Trans. NS 32, 1985, p. 2507
9. Sigg, P., K. et al., Proc. of the 13th. Int. Conf. on Cyclotrons and their Applications, Vancouver, 1992, p. 534.
10. Sigg, P. K. „High Beam Power RF Systems for Cyclotrons", this conference.
11. Olivo, M., Proc. of the 7th Int. Conf. on Cyclotrons and their Applications, 1975, p. 292
12. Olivo, M., and H. W. Reist, Proc. of the European Particle Accelerator Conf.,1988, p. 1300
13. Rezzonico, L., Proc. of the 11th. Int. Conf. on Cyclotrons and their Applications, Tokyo, 1986, p. 457.
14. Rezzonico, L., Proc. of the 12th. Int. Conf. on Cyclotrons and their Applications, Berlin, 1989, p. 313
15. Rezzonico, L. et al., AIP Conference Proc. 333, Vancouver, 1994, p. 398
16. Blumer, T. et al., Nucl. Instr. and Meth. in Phys. Res., Vol. A 352, 1995, p.170
17. Stammbach T. et al., Proc. of the 13th. Int. Conf. on Cyclotrons and their Applications, Vancouver, 1992, p. 28
18. Stetson, J. et al. Proc. of the 13th. Int. Conf. on Cyclotrons and their Applications, Vancouver, 1992, p. 36.
19. Adam, S. „Space Charge Effects in Cyclotrons - From simulations to Insights", this conference.
20. Stammbach, T. et al., Proc. Int. Conf. on Accelerator-Driven Transmutation Technologies and Applications, Las Vegas, 1994 (to be published).
21. Stammbach, T. et al., „The Feasibility of High Power Cyclotrons", presented at the 4th Europ. Conf on Acc. in Appl. Res. and Techn., Zürich, 1995.
22. Carminati, F. et al, CERN Report, 1993, CERN/AT/93-47