THE PSI 2mA BEAM AND FUTURE APPLICATIONS

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Abstract

The performance of the PSI cyclotron facility is described in detail. The facility consists of the 72MeV injector cyclotron and the 590MeV Ringcyclotron. It is used as a powerful driver for the routine production of a 1MW proton beam for SINQ, the spallation neutron source at PSI. In July 2000 a record beam current of 2mA could be extracted form the Ringcyclotron. All aspects relevant to the high intensity operation of the cyclotrons are discussed, such as bunching, beam collimation, beam loss, activation and space charge effects at low energies as well as at the high-energy end. Based on the experience with 1MW beam power the performance is extrapolated to higher beam intensities and some assessments are made on the feasibility of using cyclotrons as possible drivers for the production of e.g. 10MW beam power in view of future applications in transmutation technologies, in the energy amplifier or to generate high flux secondary beams of neutrons, pions or other particles.

1 INTRODUCTION

The PSI accelerator facility was built in 1974 as one of the first meson factories with the goal of reaching a beam intensity of 100µA at an energy of 590MeV. The main stage of the accelerator chain, the PSI Ringcyclotron is a separated sector cyclotron, specially designed for high beam intensities [1]. The concept proved to be successful and an upgrade was undertaken with the goal of reaching a beam current of 1.5mA. In 1985 a new injector cyclotron was commissioned (the Inj.2, also a separated sector cyclotron) [2], in 1990 the pion production targets and the beam dump were reconstructed and in 1991-95 the RF systems of the Ringcyclotron were rebuilt in order to provide the necessary RF power [3]. In the course of the RF upgrade the peak voltage in the four acceleration cavities of the Ringcyclotron was raised from 450kV to 730kV.

Using the first injector cyclotron, the Inj.1 (a standard sector focused cyclotron [4]), a beam current of up to 200µA could be produced, limited by the injector. With the Inj.2 the beam current could easily be raised to 350µA, now limited by the effect of longitudinal space charge forces in the Ringcyclotron. According to a ‘power of three’ law as described by W. Joho in ref [5], this limit is proportional to the third power of the acceleration voltage. Hence with the higher voltages in the cavities of the Ringcyclotron a beam current of 1.5mA could be expected and was indeed reached in 1995. With stronger bunching, better beam matching and other minor improvements the beam loss was further reduced and the beam current for routine operation could be raised to 1.8mA. In a short beam test in June 2000 a maximum beam current of 2mA was accelerated and extracted from the Ringcyclotron. The present paper gives details on some aspects important at high beam intensities.

With the need for stronger neutron sources and upcoming applications in transmutation technologies, the feasibility of cyclotrons to generate 10MW beam power has to be discussed. A tentative layout of a cyclotron facility with a beam current of 10mA at 1GeV has been presented [6]. The extrapolation of the beam performance from 2mA up to 10mA is discussed in this report.

2 ION SOURCE AND PREINJECTOR

For the production of the 1.5 to 2mA beam at PSI the cusp ion source delivers a DC beam current of 8 to 12mA. The preinjector is an 870keV Cockcroft-Walton generator [7]. The ion source is installed on a 60kV platform in its dome. The 870keV beam transport line is of conventional design and considerable deterioration in the beam quality due to space charge forces is observed. An important aspect in the 6-dimensional matching of the phase space of the beam to the injector cyclotron, Inj.2, is strong bunching. The corresponding double gap buncher was installed at a distance of 6.6m from the injection point on the first turn of the Inj.2, but it was moved to 4.9m in 1998. It is operated at a peak voltage of 7.2kV.

For a future 10MW facility 5 times more beam current would be needed, i.e. 50 to 60mA. Several sources have been developed that deliver beam currents up to 100mA. The corresponding beam power and the importance of extremely high beam stability make a future preinjector challenging, but not impossible.

3 SPACE CHARGE COMPENSATED BUNCHING

As mentioned above, strong bunching is an important factor for optimal beam matching on the first turn of the Inj.2 cyclotron but the corresponding high buncher voltage introduces undesirable energy spread in the time focus on the injection point. However, with a proper combination of the buncher voltage and the DC beam current, the space charge forces can be employed to reduce this energy spread, as proposed by Stetson and Adam [8]. The space charge forces in the time focus act accelerating for the slow particles ahead of the bunch, but decelerate the fast particles in the tail, thus reducing the

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energy spread. Making use of this braking action, the effect of the space charge forces can be turned around to be beneficial for the further beam transport. An example of this space charge dominated bunching or space charge compensated bunching is shown in figure 1. The relation between energy and phase in the hot spot of a bunched beam is plotted for the two cases 0mA (no space charge) and 12mA beam current as calculated using SPUNCH, a code written by R.Baartman [9] based on a simple model. With increasing beam current the bunching factor (i.e. the ratio between the peak intensity in the hot spot and the DC beam current) is obviously reduced by the space charge effect, but more beam is contained in the indicated phase space area that is accepted by the cyclotron.

The extrapolation to the case of a future 10mA cyclotron is shown in figure 2. The amount of beam contained in the accepted phase space area and the energy spread is plotted for two cases: i) the typical case of the PSI Inj.2 with the buncher located 6.6m upstream of the cyclotron and a DC beam current of 8mA and ii) the case of a prospective 10mA cyclotron with a buncher distance of 3m and 50mA DC beam current. If the buncher is moved closer to the cyclotron, a higher buncher voltage is needed and the compensation of the energy spread shifts to a higher DC beam current. In case ii) about five times more beam would be contained in the same phase space area as in the PSI Inj.2.

4 INJ.2, BEAM MATCHING AND SPACE CHARGE EFFECTS

The special features of a beam bunch of equal dimensions in radial and longitudinal direction have already been noted by Chabert [10] in 1981 and analytically analysed by Chasman [11] in 1984 but, to our knowledge, the PSI Inj.2 is still the first and only cyclotron that is operated in this regime. Under space charge dominated conditions in a cyclotron, such a circular bunch is a stable configuration with favourable conditions [10,11,12,13], especially at high beam intensities. The bunch remains circular due to the strong radial-longitudinal coupling and space charge forces can, therefore, not distort it. The beam profile is compact and does not have long tails. Since it remains circular and of equal size through the whole acceleration process, the bunch has an extremely narrow phase width at extraction. In the case of Inj.2 the phase width is about 2º [14]. A flattop system is, therefore, not useful in this cyclotron.

In order to operate Inj.2 in this regime the beam has to be longitudinally matched. At 2mA the beam has a width of about 15mm and hence it has to be injected with a bunch length of 15mm. With operation in 10th harmonic and with an average orbit radius of 406mm at injection, this corresponds to a phase width of about 20º, which can be achieved with the buncher mentioned above. It was

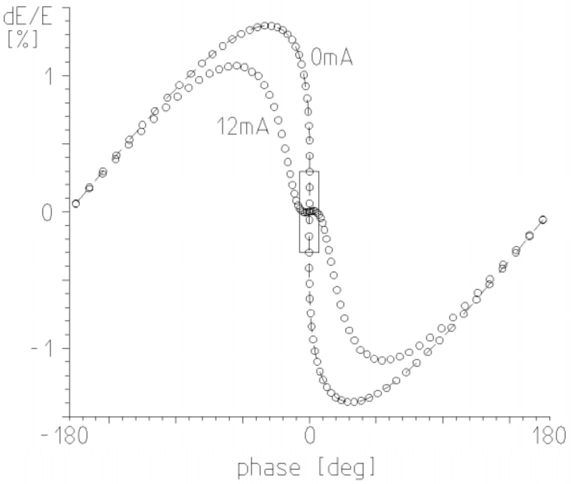

Figure 1: Influence of the DC beam current on the relation between energy spread and phase in the hot spot of a bunched beam. In the case of a space charge dominated beam, the energy spread is reduced and more beam is contained in the indicated acceptance area of the cyclotron (each dot corresponds to 5º initial phase).

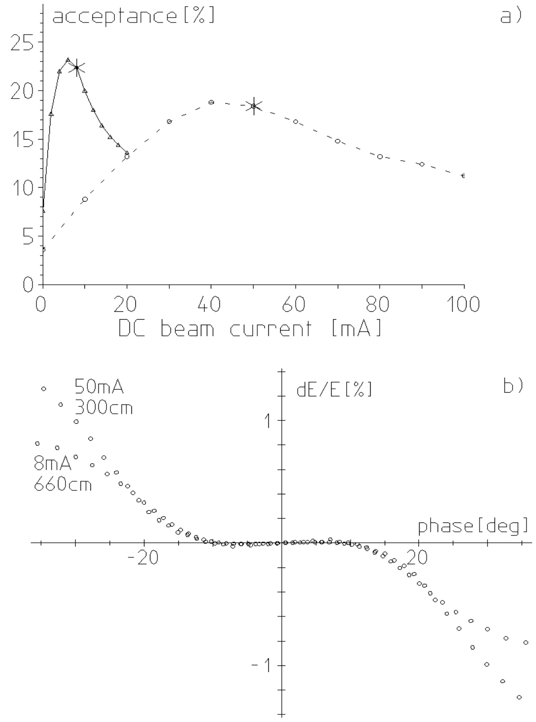

Figure 2: Comparison of space charge dominated bunching for two cases: the PSI Inj.2 with a distance of 6.6m between buncher and cyclotron (solid line) and a tentative injector for a future 10MW cyclotron facility with a reduced distance of 3m (dashed line). The lower plot shows the calculated relation between phase and energy and the upper plot the amount of beam within an acceptance area of 24˚ phase width and 0.6% energy spread. The working points for 1.8mA and 10mA extracted beam current for the two cases are specially marked.

found to be important that the buncher phase is well stabilized and that the beam is not dispersive at the injection point. If this is fulfilled and a hot spot of high charge density develops, the typical features of a circular beam bunch appear. Even a slightly mismatched beam is captured into the matched circular beam bunch by the space charge forces themselves, as shown by Adam and Koscielniak [15] using beam simulation. It is, however, rather important to collimate the beam in the centre region of the cyclotron in order to remove particles that are, due to mismatch and non linear terms in both the geometry and the space charge forces, far outside of the bunch, especially in the longitudinal and vertical directions.

The centre region of the Inj.2 is shown in figure 7 of ref. [16]. The phase selection of the strongly bunched beam is done in the phase-defining collimator on the 1st turn (KIP1 & KIP2). Vertical and radial cleaning is done with several collimators on the 1st to 5th turn. With 1.8mA accelerated beam in Inj.2, the typical beam currents are as follows: 12mA DC proton beam from the ion source, 1.2mA are lost in collimators along the 870keV injection beam line. One third of the remaining 10.8mA is accepted through the phase defining slits KIP1 & KIP2 (2.4mA & 4.8mA). The first set of radial and vertical collimators on the 1st turn each cut about 0.6mA away, essentially cleaning out phase tails, and the cleaning slits on the following turns remove about 0.3mA radial and 0.3mA vertical beam tails. Only about 50% of the beam in the hotspot on the 1st turn is accepted through the collimation system. In order to improve the longitudinal matching and the capture rate the buncher has been moved closer to the injection point in 1998, from previously 6.6m to 4.9m upstream of the injection point.

The Inj.2 cyclotron has well separated turns up to the extraction radius, where the turn separation amounts to 20mm and is only slightly enhanced by a weak coherent betatron oscillation of 2 to 3mm. The resulting separation corresponds to about 6σ of the beam profile of a 1.8mA beam. The width of the profile depends on the beam intensity as shown in figure 3. The beam loss at extraction is correspondingly low and the extraction rate amounts to about 99.98% averaged over one year routine operation at 1.5 to 1.8mA beam intensity. The solid line in figure 3 shows an increase of the beam width proportional to the cubic root of the beam current.

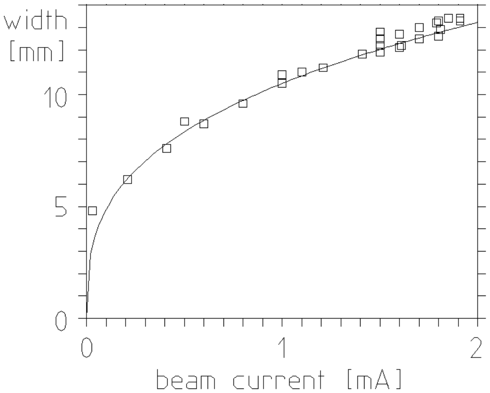

Figure 3: Beam size at extraction from Inj.2. The width of the beam profile (4σ) in function of the extracted beam current averaged over the last seven turns is shown.

The extrapolation to the case of a 10MW facility is straightforward. With an extraction energy of 120MeV the injector cyclotron would be larger, but it could be operated in the same regime. Space charge forces keep the beam together and do not impose a limit. The beam size is expected to increase with beam current, but with four instead of two resonators enough energy gain per turn can be provided in order to assure separated orbits. Admittedly, the collimation of 10 times more beam power at the injection point would be a difficult technological challenge, but with the buncher moved to 3m upstream of the injection point better longitudinal matching, a higher capture rate and a cleaner beam can be expected. A code to perform full six dimensional simulations is being developed [17] in order to optimise the injection process and improve the capture rate even further.

5 BEAM TRANSPORT LINE BETWEEN INJ.2 AND RING

Due to the layout at PSI the beam transport line between Inj.2 and the Ringcyclotron is about 58m long. It allows for matching the beam in five dimensions: in the horizontal and vertical planes and in energy dispersion. A rebuncher (or debuncher), however, is not installed. Since space charge effects in the Ringcyclotron depend strongly on the phase width, such a device could be expected to reduce distortions to the beam at high beam intensities.

Along the transfer line and at injection into the Ringcyclotron some beam loss is observed originating from the Inj.2. In order to reduce activation further downstream, a cleaning slit is installed in the energy dispersive part of the beam line and used to cut off about 2μA of the beam on each side in the horizontal direction. The slits are made out of carbon, which has predominantly short-lived activity. A 1m thick concrete local shielding avoids high neutron flux in the vault.

6 SPACE CHARGE EFFECTS IN THE RINGCYCLOTRON

The beam bunches in the Ringcyclotron are not circular as in the case of the Inj.2, but very elongated. Hence, space charge forces and especially longitudinal effects [5,10,12,13 and references therein] have to be accounted for. Due to the strong coupling between longitudinal and radial motion in the cyclotron the longitudinal components generate a tilt of the elongated bunch in the radial direction. Using a flattop system and adjusting its phase relative to the RF–cavities for acceleration, the tilt can be compensated. The non-linear nature of space charge fields results in a filamentation in phase space and a broadening of the orbits. This finally impairs extraction and limits the beam intensity. An accurate prediction of this limit is difficult, since the filamentation process depends very much on the charge distribution within the bunch, which is not accurately known.

Based on simple models W.Joho [5] predicted that the maximum beam current should be proportional to the third power of the average energy gain per turn. The upgrade in the peak voltage in the four acceleration cavities of the Ringcyclotron was, therefore, a very important step towards higher beam currents. Indeed the maximum beam current reached when each year one cavity was upgraded from 450kV to 730kV followed exactly the prediction of this law as shown in figure 4.

The Ringcyclotron also has well separated turns at extraction. The turn separation due to acceleration alone amounts to 6mm. This is doubled by a coherent betatron oscillation induced by off-centre injection on the first orbit in the cyclotron. The resulting separation of 12mm corresponds to about 7σ of the observed beam profile at 1.8mA (see figure 5). Also an optimised mismatch in both the horizontal phase space and the energy dispersion onto the first orbit are employed to further separate the last turns. As for the Inj.2 the beam loss at extraction is low and the extraction rate is 99.98% averaged over one year of routine operation at 1.5 to 1.8mA beam intensity.

The prediction of the performance of the facility for 10MW beam power makes use of the experience from the upgrade of the PSI Ringcyclotron as shown in figure 4. It has been assumed that longitudinal space charge effects would limit the 10mA cyclotron. With eight acceleration cavities, which are expected to operate at a peak RF voltage of 1MV [18], the proposed 1GeV cyclotron has an averaged energy gain of 6.3MeV/turn, compared to 2.4MeV/turn in the PSI Ring with four acceleration cavities at 730kV. Taking account of the different size and the different final energy of the 1GeV cyclotron, with such an energy gain, a maximum beam current of 10mA can be expected, as shown in the dashed line in figure 4. A turn separation of 7σ similar to the situation today in the Ringcyclotron can be expected under the following assumptions: an acceleration of the beam into the fringing field of the 1GeV cyclotron to where ν_r drops to 1.5, an increased beam emittance from the injector cyclotron as extrapolated from figure 3 and no limitation from other sources. A rebuncher in the injection transport line might be necessary if the energy spread of the beam from the injector cyclotron becomes too large.

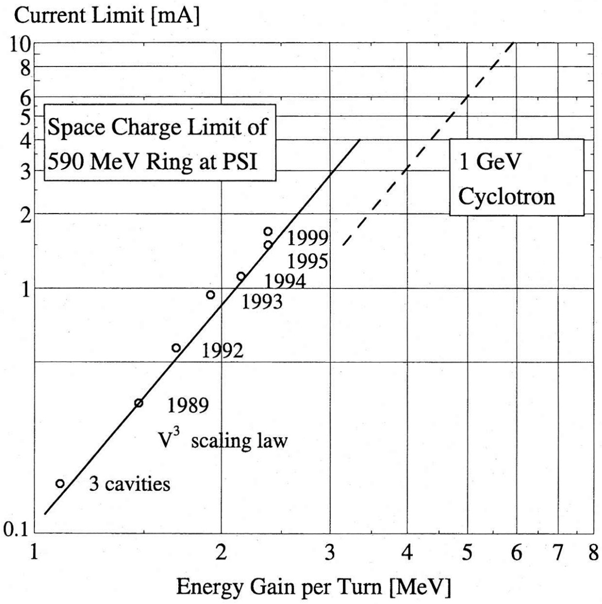

Figure 4: The observed maximum beam current extracted from the Ringcyclotron in function of the average energy gain per turn as established during the upgrade of the cavity voltage. The solid line is the dependence expected if the limitation is due to longitudinal space charge. Also shown is the extrapolation to a tentative facility with a 1GeV, 10mA cyclotron (dashed line).

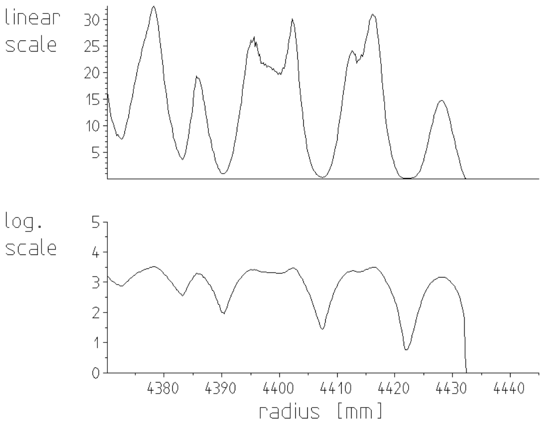

Figure 5: Beam profiles of the last 12 turns in the Ringcyclotron at a beam current of 1.8mA as measured with a radial probe equipped with a thin carbon wire.

7 BEAM LOSS AND RADIATION PROBLEMS

In the discussion of high power accelerators all problems concerning radiation have to be considered. Four aspects are of importance: i) activation of the facility and its components impairing service and maintenance, ii) reduced lifetime of component due to radiation, iii) neutron skyshine outside of the vault due to neutrons penetrating the shielding and iiii) the decommissioning of radioactive material. Beam loss in the accelerator and along the beam transport lines is the main source term for maintenance dose, reduced lifetime and skyshine. Hence a continuous control and optimisation of the beam loss is mandatory. The questions concerning skyshine and the total inventory of activated material is less dominated by the small amount of beam lost during acceleration, but rather by the target, where the whole beam is dumped.

The maintenance dose and the lifetime of components vary by orders of magnitude depending on the design and the materials used. If accounted for in the design phase corresponding problems can be avoided. Installations for easy and quick repair have been successfully employed at PSI [16] and the dose due to accelerator maintenance in the PSI accelerator division could be kept constant while the beam production was raised 10^3 fold (fig.3 ref. [19]). Most procedures for quick and remote removal of components from an activated part of the machine make use of an overhead crane as a very versatile yet cheap manipulator. In a shielded transport box the activated piece is then brought to a repair area equipped with general manipulators for remote handling.

The beam loss at extraction from both cyclotrons is about 0.02% averaged over one year of routine operation. Typical beam loss data are shown in figure 6, which shows recordings of the beam loss in 10-minute intervals over 30 days in July 2000 in function of the beam current extracted from the Ringcyclotron. The typical increase in beam loss at intensities of 1.7mA and above is interpreted as resulting from insufficient turn separation when the tails of the beam becomes larger and the profiles start to overlap. The beam current at which the beam loss starts to increase, scales with the energy gain per turn as described above. The strikingly large scattering in the data points is seen as an indication that the beam loss depends very much on the fine-tuning of the beam, mainly at the low energy end in the 870keV beam transport line and at injection into Inj.2. It is observed that especially the amount of beam collimated in the centre region of Inj.2 produce stray beams that contribute to the beam loss.

The extrapolation to a facility for 10mA is difficult. We are, however, convinced that a 5 to 10 times higher beam loss can be acceptable, provided the cyclotron is properly designed for remote removal of all major components, with well controlled collimation of the beam, with the installation of specially designed dumps, scrapers and local shielding at points where beam loss can not be avoided.

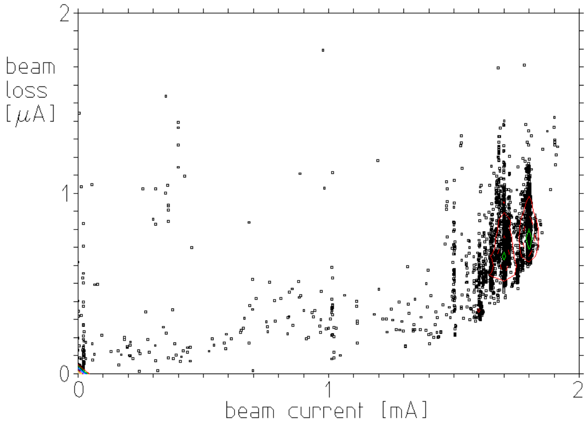

Figure 6: Beam loss at extraction from the PSI Ring as a function of the extracted beam current. Plotted are recordings in 10 minute intervals during routine operation of the facility at 1.5-2.0mA in July 2000.

8 CONCLUSIONS

With 2mA beam current extracted at the energy of 590MeV, the PSI facility is only a factor 5 from the beam current anticipated for a tentative facility for 10MW beam power. Based on our experience, such a facility is feasible and within reach. In spite of the fact that most projects for high power beams are based on linacs as accelerators, the cyclotron option also looks very promising due to its compactness. Finally, as ultimate cyclotron experience, an extremely outstanding performance can be expected if once a high-energy cyclotron is being built, that can be operated with circular bunches as in the PSI Inj.2.

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