1.8 MW UPGRADE OF THE PSI PROTON FACILITY

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Abstract

The PSI proton accelerator delivers currently a 590 MeV beam with an intensity of 2 mA. The upgrade programme aiming at boosting the beam power from 1.2 to 1.8 MW includes the ongoing installation of new bunchers in the transfer lines to the injector cyclotron and between injector and Ring Cyclotron , the replacement of the Al-cavities of the Ring Cyclotron by Cu-cavities operated at 1 MV, and the design and future installation of additional accelerating cavities in the injector cyclotron. Simulation studies are under way to improve our understanding of the space charge effects at the different stages of acceleration. The present status of the project is presented.

INTRODUCTION

A beam current of 1.9 mA is routinely extracted from the Ring Cyclotron, delivered to the production targets M and E for secondary meson beams, and partially transported to the spallation neutron source SINQ. With a 4 cm thick Target E the transmission to SINQ amounts to about 70%, thus a beam of 1.2 mA is available at this facility. Since this target is designed for a load of 2 mA the main proton beam should be increased to 2.7 to 2.8 mA to fully exploit the potential of the facility. For higher currents an improved design of the target is requested.

The present project aims at an increase of the beam intensity to 3 mA. The maximum beam current will not longer be given by the performance of the accelerators, but by the temperature limit of the meson production target E.

The current limit of the PSI cyclotrons is essentially determined by the the losses at the extraction septa. A large turn separation, i.e. a high energy gain per turn in comparison to the energy spread induced by the space charge effects, is requested to keep the losses at an acceptable level. For routine operation we accept at most 0.5 μA for each element (extraction from the injector cyclotron, injection into and extraction from the Ring Cyclotron)

The installation of new copper cavities in the Ring Cyclotron opens the way to a significant increase of the beam intensity. The new cavity which was designed for a peak voltage of 1 MV was tested up to 1.4 MeV on the test bench. Two such cavities are now in operation. The installation of all 4 new cavities will be completed in 2008.

The injector cyclotron is now able to deliver beam currents up to 2.2 mA and the "round beam" operation mode (i.e. acceleration of a beam prepared such that a stable bunch structure of very small phase width is conserved) is well established The upgrade of this machine can be realized in several steps. While some improvements are achievable on a short range at relatively low costs, the final step will request substantial investments for two additional accelerating cavities in order to increase the turn separation at the extraction.

BEAM SIMULATIONS

The prediction of the performance of a high power accelerator is a difficult task since the relevant factors are not accessible by usual beam dynamical calculations. The current limit is given by the losses due to tails and halos several orders of magnitude smaller than the beam itself. In the routine operation at 1.9 mA for example, the injection and extraction losses tolerated are in the range of 0.02% of the beam intensity. A reliable beam simulation requests tracking of millions of particles, a good knowledge of the initial conditions, the consideration of higher order effects, and detailed beam diagnostics for comparison and validation of the calculations. The development of the computational tools needed for such simulations (MAD9P, efficient parallel programming) is in progress [1], and the results obtained so far are very promising. Fig. 1 shows a simulation of the cleaning of the 870 kV beam entering the injector cyclotron. The calculated and measured loads on the collimators used for this purpose agree within 10 %.

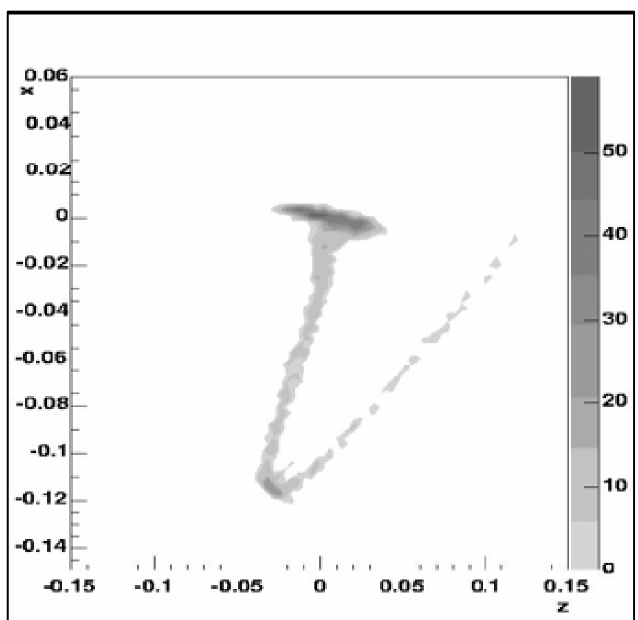

Figure 1: Density distribution of the beam entering the injector cyclotron after passing the first phase collimators.

A second collimator eliminates the remaining tail.

It is however a long way until start-to-end simulations will be able to predict losses at the 10^{-3} level. At present, projections have still to rely on extrapolation and scaling based on the performances observed at different steps of the development of the facility.

IMPROVEMENT OF THE BEAM FROM THE INJECTOR CYCLOTRON

The quality of the beam extracted from the injector cyclotron depends crucially on the initial conditions at injection. In the past few years, significant progress has been made (in fact an increase of the beam current from 1.5 to 2 mA) mainly by better handling the space charge effects on the bunching of the 870 kV beam from the Cockroft-Walton pre-accelerator. Pursuing along this line a second buncher operated at the third harmonic (150 MHz) has been installed during the 2006 shutdown. First operational experience shows that the expected increase of the beam intensity in the phase space defined by the collimators at the injection and the generation of the conditions required for acceleration in the “round beam” mode are achieved. It is possible to reach 3.5 mA with a DC beam of 10 mA, compared with the previous 2.2 mA at 12.5 mA DC. From the observation of the losses in the Ring Cyclotron there are evidences that the beam quality delivered by the injector cyclotron has significantly improved, however this has to be confirmed by further studies.

In order to improve the stability and reduce the frequency of maintenance work we plan to replace the multi-cusp source by a device with better emittance and proton efficiency. A compact, permanent magnet microwave source has been constructed. Tests will start mid 2006.

The ultimate step to achieve maximum performance with the injector cyclotron will be the installation of two new resonators in order to replace the two flat-top resonators (that are obsolete in the “round beam” acceleration mode) by 50 MHz accelerating systems. The concept study led to the choice of single-gap cavities, as discussed in a previous publication [2]. The detail engineering phase has started and the installation is planned in 2009. The technical requirements set by this upgrade have been already considered in the ongoing renewal of the vacuum system of the injector cyclotron. Fig. 2 shows the estimated beam width at the extraction of the injector cyclotron as a function of the beam current. For acceptable beam losses, the turn separation at extraction should be at least 7 σ. Operation at 3 mA will be definitely far beyond this limit.

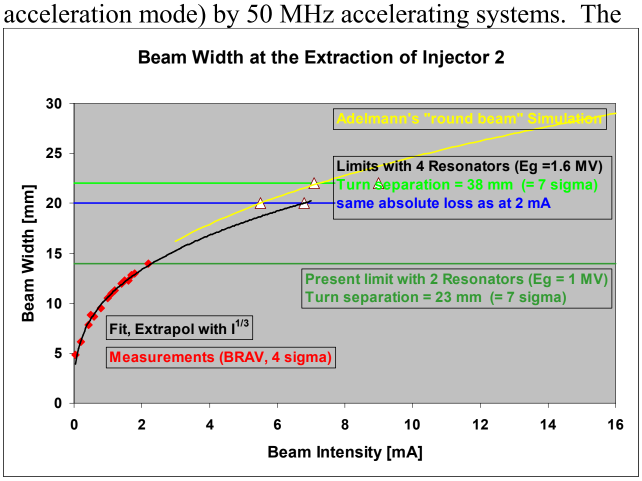

Figure 2: Expected beam width at the extraction of the injector cyclotron. The yellow line is the result of a full 3-D simulation.

72 MeV BEAM: TRANSFER AND BUNCHING

A significant reduction of the losses in the Ring Cyclotron can be achieved by judicious beam cleaning in the transfer line. Locally shielded collimators allow to cut out several µA of parasitic beam.

Measurements and simulations of the phase width along the transfer line shows that a “superbuncher” working at the 10^{th} harmonic and located in the middle of the 50 m long transfer line can be used for bunching or phase rotating the 72 MeV beam prior to injection into the Ring Cyclotron. The design chosen after a comparative study is a double-gap drift tube cavity [3]. The dissipated power of less than 30 kW is moderate for the infrastructure in the beam line vault. The buncher is ready for the power tests and the necessary infrastructure in the vault has been installed. Some of its components are shown on Fig. 3. We are currently awaiting the delivery of a suitable amplifier.

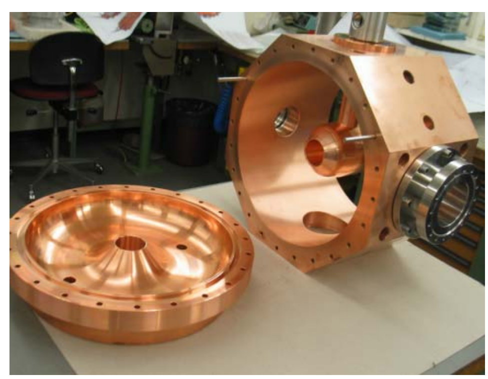

Figure 3: Double-gap drift tube buncher for the 72 MeV beam line.

Preliminary calculations show that space charge compensated bunching is applicable to generate a variety of starting conditions at the Ring Cyclotron. A full simulation of the beam injection is in preparation and should demonstrate if the “round beam” acceleration mode is practicable in this accelerator. If this technique does not work, the “superbuncher” can alternatively be used as phase rotator to improve the matching to the phase acceptance of the Ring Cyclotron.

RING CYCLOTRON

In the "round beam" acceleration mode a flat-topping cavity would not be longer required in the Ring Cyclotron. However, since results from a reliable simulation are not at hand at the moment, the further use of the flat-top system should be also considered.

The current limit, observed during previous stepwise reductions of the turn number, shows an N^{-3} dependence, which confirms the rule proposed a long time ago by W. Joho [4] for the strength of the longitudinal space charge effects in a cyclotron. The emittance term entering the calculation of the beam width in the Ring contributes the same way to the current limit. Since the emittance of the injected beam is known, both parts can be disentangled, and a calibration is obtained for the space charge contribution itself. With this knowledge, the beam width for any combination of emittance, space charge distribution and accelerating voltage shape can be estimated.

For identical conditions for the compensation of the space charge effect by means of a tilted flat-top, the maximum current achievable (with the present beam quality delivered to the Ring) will be about 5 mA with four accelerating cavities at 1 MV. This feature is illustrated on Fig. 2. However, the present flat-top system is already operated close to its thermal limit and will not be able to provide the optimal correction when the new cavities are operated at the rated voltage. Using a very simplified model to evaluate the shape of the longitudinal phase space one can estimate that beam currents up to 2.7 mA are achievable with the present flat-top performances in combination with the "superbuncher". Therefore, the decision whether the development of a new flat-top system should be undertaken can be postponed till results of the simulation and/or first experimental tests confirm or deny the applicability of the "round beam" technique in the Ring Cyclotron.

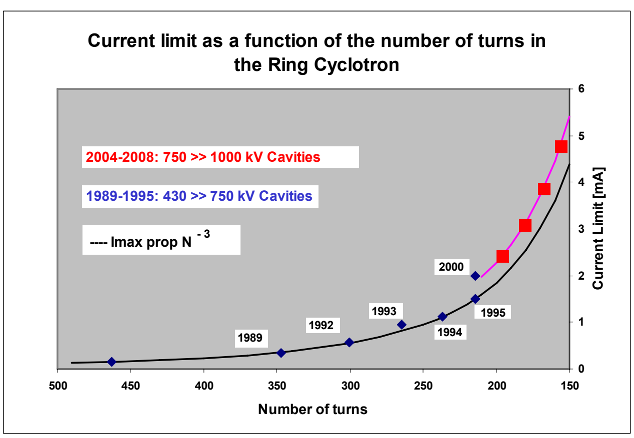

Figure 2: Observed and extrapolated current limit as a function of the number of turns in the Ring Cyclotron. The step between 1995 and 2000 is due to the improvement of the beam quality from the injector cyclotron.

TARGET E AND BEAM TRANSPORT TO THE SINQ SPALLATION TARGET

The load limit on Target E is set by the temperature at which it starts to evaporate. No problems are expected up to a beam current of 2.7 mA with the 4 cm thick target. The load on the surrounding heat shields is within the acceptable range. The second collimator defining the beam to SINQ will reach its limit. The beam optics remains the same. The current on SINQ is close to 2 mA and the maximum density is 55 μA/cm^2.

For 3 mA the thickness of Target E has to be reduced to 3 cm. In this case the load on the collimators is distributed differently, but remains in tolerable limits. The beam parameters on SINQ are slightly changed due to the modified beam optics. A more peaked beam distribution must be taken into account in a new design of the SINQ target. An alternative to the present design could be the use of Zirkalloy instead of steel for the cladding of the lead rods, which allows for a better local cooling.

CONCLUSION

An upgrade program aiming at an increase of the beam power delivered by the PSI Proton Accelerator to 1.8 MW is under way. While some intermediate steps are realizable in the framework of the smooth, continuous development of the facility, investments in new resonators and rf-equipment for the injector cyclotron will be needed to eventually reach the expected currents. With 2.8 mA extracted from the Ring Cyclotron, the current on SINQ is improved to 2 mA and the power to almost 1.2 MW, in an unchanged geometry. For a higher beam current the SINQ target should also be able to accommodate a sharper density distribution.

The limit of 3 mA for the extracted beam is set by the design of Target E. For higher current the diameter of the graphite wheel should be increased. The space requirements can only be fulfil with the reconstruction of the Target E region, which would mean considerable costs and a one year shut-down of the facility.

REFERENCES

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