STEPS TOWARDS A 3 mA, 1.8 MW PROTON BEAM AT THE PSI CYCLOTRON FACILITY

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Abstract

The stepwise increase of the beam intensity of the PSI Proton Accelerator Facility up to 3 mA is discussed

INTRODUCTION

A beam current of 1.8 to 1.9 mA is routinely extracted from the Ring Cyclotron, delivered to the production targets M and E for secondary pion and muon beams, and partially transported to the spallation neutron source SINQ. Operation at 2 mA has been demonstrated, however with total losses exceeding the self-imposed limit of 1 µA. 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 successful installation of a new copper cavity 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. Upon installation of the prototype cavity in the Ring Cyclotron during the last shut-down it was reliably operated at 750 kV (like the 3 Al-Cavities) during 2004. While the installation of all 4 new cavities will be completed in 2008, a second cavity will be taken into operation in 2006, thus allowing, already at this time, first attempts to raise the beam current.

The Injector 2 Cyclotron is now able to deliver beam currents up to 2.2 mA, however it is questionable if the quality at maximum current is sufficient for injection into the Ring Cyclotron. In addition, since the extraction losses of this machine are the main source of the sky shine radiation around the facility, special caution is required for operation at currents above 2 mA. Local shielding will be installed in2006 to get more freedom in the exploration of the current limit of this machine.

The upgrade of Injector 2 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 to equip the Injector Cyclotron with two additional accelerating cavities in order to increase the turn separation at the extraction.

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 1.85 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 is in progress [1], and the results recently obtained for Injector 2 are very promising. This approach however is time consuming and, 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 INJECTOR 2

The quality of the beam extracted from the Injector 2 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. New calculations show that the installation of a second buncher operated at the third harmonic (150 MHz) can significantly increase the beam intensity in the phase space defined by the collimators at the injection, and generate the conditions required for acceleration in the "round beam" mode. It is, for example, possible to reach 3.4 mA with a DC beam of 9 mA, compared with the present 2.2 mA at 12.5 mA DC. The operation at lower currents allows for beams of higher quality, less space charge problems in the beam transport line and a reduced load on the CW. The confirmation of the buncher calculations by a full 6-dimensional simulation including also the beam cleaning at the phase collimators is under way. The new buncher will be developed in 2005. Only minor changes in the injection line are necessary to install the bunchers at suitable locations. We further plan to replace the multi-cusp source by a more stable microwave ion source with better emittance and proton efficiency.

Plans to replace the CW pre-accelerator by a RFQ are not longer considered to be urgent. Spare parts are available and the know-how for the repairs of critical components (HV-transformers) could be acquired at the last minute by our specialists. Thus we can concentrate our limited resources on the development of a new resonator for Injector 2 in order to replace the two flat-top resonators (now used as accelerators) by 50 MHz systems. The concept study led to the choice of single-gap cavities, as discussed in a previous publication [2]. The technical requirements set by this upgrade have been

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already considered in the ongoing renewal of the vacuum system of Injector 2.

72 MeV BEAM: TRANSFER AND BUNCHING

A significant reduction of the losses in the Ring Cyclotron can be achieved by judicious beam cleaning by collimators in the transfer line. Local shielding of the collimators helps to reduce the contribution to the sky shine and thus allows to cut out several μA of parasitic beam. The origin of undue beam losses at the Ring center could be traced back in 2004 and have been corrected by a readjustment of components in this region.

Measurements and simulations of the phase width along the transfer line have been performed recently. They confirm that a "superbuncher" working at the 10th harmonic can be used for bunching or phase rotating the 72 MeV beam prior to injection into the Ring Cyclotron. The 500 MHz technology is well known at PSI. The dissipated power is moderate for the infrastructure in the beam line vault, and a suitable amplifier can be acquired from LURE. The construction of a device based on drift tube cavities is in progress [3]. Its installation in the 72 MeV beam line is planned for the 2006 shut-down.

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 limits, observed during the previous stepwise reductions of the turn number, show an N^{-3} dependence, which corresponds to the rule proposed by W. Joho for the strength of the longitudinal space charge effects. Considering the $I^{1/3}$ width dependence of the beam from Injector 2, one can infer that, for a matched beam, 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 evaluated.

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 5 mA with four accelerating cavities at 1 MV. 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 delayed till results of the simulation and/or first experimental tests confirm or deny the applicability of the "round beam" technique in the Ring 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 $\mu A/cm^2$.

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 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.

CONCLUSION

A substantial increase of the beam current delivered by the Proton Accelerator Facility seems feasible in a medium time range. 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 Injector 2 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.

REFERENCES

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