BEAM BASED CALIBRATION MEASUREMENTS AT THE PSI CYCLOTRON FACILITY

C. Baumgarten, Paul Scherrer Institute, Villigen, Switzerland

Abstract

The PSI high intensity proton accelerator (HIPA) facility consists of a Cockcroft-Walton accelerator and two cyclotrons, INJECTOR 2 and the Ring machine (see Fig. 1). It is in operation since four decades [1]. Though the design details of the original machine are well documented, a considerable number of changes have been made to various components in the course of time. Moreover some measurements like magnetic field mappings or the survey of central region collimators can only be done in the construction and/or assembly phase, either for mechanical reasons, due to restrictions of time schedule or due to the activation of components. Further development of the facility requires precise beam dynamics models (for instance with OPAL [2]) which in turn requires an accurate machine description.

INTRODUCTION

An effective method to test the consistency of the data used to model the machine is based on the combination of beam tracking simulations and beam based measurements. We present some results of such beam based alignment and calibration measurements that have been made during beam development shifts with INJECTOR 2. They allows to cross-check collimator positions, Dee voltage distribution, turn patterns, beam energy and trim coil field profiles using measurements of radial probes, phase pickups and profile monitors. A sensible reconstruction of cyclotron parameters starts with the RF-frequency ω_{rf}, the parameter which is usually well-known or easy to measure. Based on the frequency it is possible to determine the average magnetic field as seen by the beam, provided that some kind of phase measurement is available. The PSI INJECTOR II for instance is equipped with 8 phase probes (MIF1-MIF8) required for the adjustment of the isochronism. The long radial probe (RIL1) can be used to localize the turns at the azimuth of the probe. The radius gains allow to reconstruct the energy gain as a function of radius. The energy gain per radius gain of the cyclotron is given by

$$\frac{dE}{dR}(R) = \frac{E\,\gamma\,(\gamma+1)}{R}\,, \tag{1}$$

which can be crosschecked also with computed equilibrium orbit data. Then the energy gain per turn is

$$\frac{dE}{dn}(R) = \frac{dE}{dR}(R)\,\frac{\Delta R}{\Delta n}(R)\,. \tag{2}$$

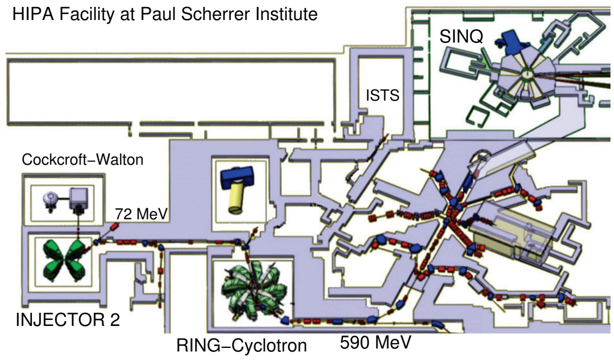

Figure 1: High Intensity Proton Accelerator (HIPA) Facility at PSI. The Cockcroft Walton delivers typically 10 – 12 mA protons DC. After the formation of bunches by two bunchers in the injection line of INJECTOR 2, the beam is accelerated to 72 MeV and transported to the RING cyclotron. The 590 MeV proton beam of maximal 2.4 mA is used to produce pions, muons using carbon targets and neutrons by spallation in the swiss neutron source SINQ.

Measurements with the long radial probe (RIL1) have been performed during a beam development shift in 2015. For this calibration measurement, the buncher located in front of INJECTOR II in the 870 kV injection line was switched off in order to ensure a beam of well-known and sharp energy. We picked the peak positions of RIL1-0005Y15.SDDS, shown together with RIL1-0002Y15.SDDS in Fig. 2. The PSI INJECTOR 2 is specifically well-suited for such measurements, as the phase curve of the beam is almost flat such that the radius gain can be directly used to compute the Dee voltage. Once frequency, dee voltage and field are resonably well known, it is possible to use the beam position measurements of the long probe RIL1 to match the starting conditions of tracking computation to the position data.

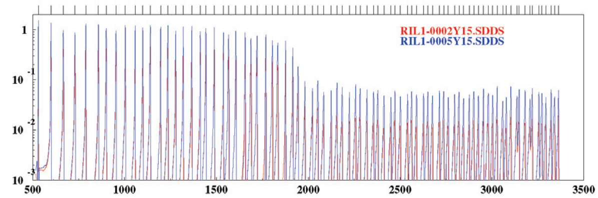

Figure 2: Measured raw data of the long radial probe RIL1 (INJECTOR II) and the beam positions. From turn number and extraction energy, one can directly compute the *average* energy gain per turn.

Figure 3 shows the resulting energy gain as derived from the RIL1 beam position measurements. The energy gain matches well to historical data of the resonator voltage profiles. The turn-by-turn analysis of the radius gain is shown in Fig. 4. Though we find a wide range between injection and extraction where the turn pattern is in excellent agreement with the simulated orbit, the agreement is less convincing in the more critical areas of injection and extraction, respectively. We hope that we can achieve further improvements

ISBN 978-3-95450-167-0

by the incorporation of the trim coil fields into the magnetic field model.

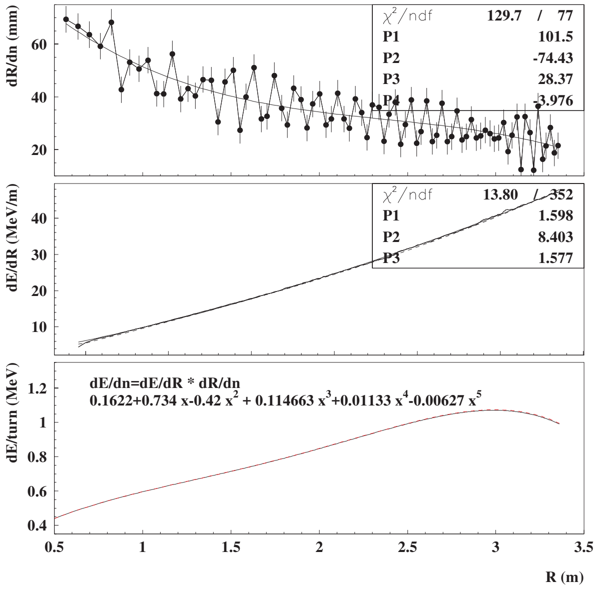

Figure 3: Upper: Radius gain of the turns as measured by radial probe, fitted by a polynomial. Center: Energy over radius gain according to Eq. (1) compared with E.O. computation. Bottom: Computed energy gain for INJECTOR II with polynomial fit.

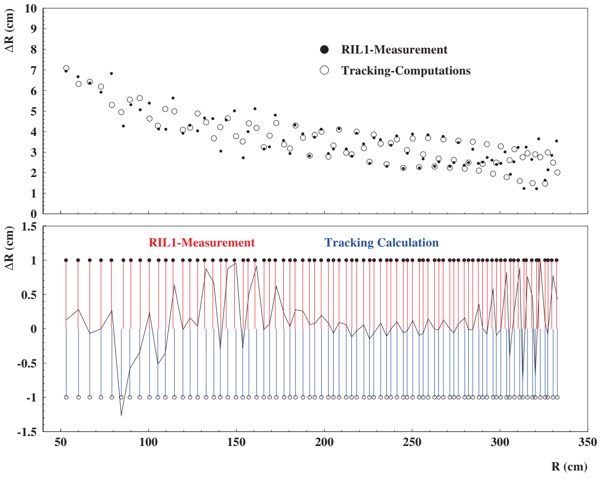

Figure 4: Top: Comparison of beam orbit tracking computation (open circles) with RIL1 peak positions (filled circles). Bottom: Comparison of radius gains, the red lines are indicating measured peak positions while the blue lines indicate the tracking results. The black curve shows the difference between both. In the range from 180-300 cm, the agreement is excellent, but at small and high radius, significant deviations are observed. However, the purpose, namely to determine the beam positions in the center, could be achieved.

COLLIMATOR POSITIONS IN THE CENTRAL REGION

The last possibility to shape the beam without activating components is the central region of INJECTOR II. For this purpose INJECTOR II is equipped with a considerable number of moveable collimators that allow to cut the beam in the first turns. Several of these collimators have two jaws that can be moved independently in order to provide maximal flexibility of beam collimation. Only two resonators accelerate the beam in this area, which allows to obtain an individual voltage calibration of all accelerating dees. A precise mechanical survey of the collimator positions is challenging due strong limitations for a direct access. Though the absolute calibration of the positions is not essential for machine operation, it is important for a precise beam dynamics model [3].

Due to the strong space charge the beam developes a vortex-motion about its own center, which is responsible for the formation of a compact core but also for the formation of the beam halo. This process of beam and halo formation is strongly influenced by the various collimators in the central region of INJECTOR II. Therefore reliable position informations are of vital importance for a realistic beam model with space charge. The 3D-PIC code OPAL [2], developed at PSI, allows to model high intensity beams including space charge and first steps towards a precise beam dynamics model have been done [3].

As the collimators are equipped with beam current readouts, they might also be helpful to survey the intensity distribution of the beam in the central region. Figure 5 shows examples of the position measurements and Fig. 6 how these positions were connected with beam tracking and RIL1 measurements to a complete model. We hope that this model will help us in the future to better understand the space charge induced vortex motion and halo formation in the center of INJECTOR II and to further reduce beam losses at extraction. Low extraction losses are also the precondition for a further increase of beam current.

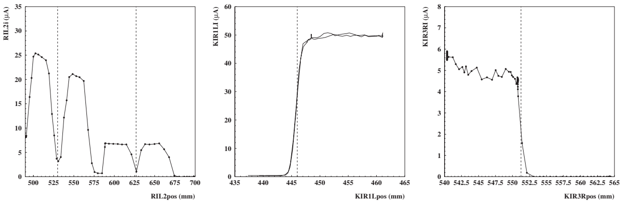

Figure 5: Examples of scans of current readings as a function of the collimator positions. Left: Collimator mounted on RIL2-drive. Center: KIR1L (left jaw of KIR1). Right: KIR3R (right jaw of collimator KIR3).

The replacement of the 3rd harmonic resonators, formerly used as flattop resonators, by normal accelerating resonators with higher voltage is planned for 2017/2018. This upgrade will further increase the turn separation and is thus expected to allow for an even higher beam intensity [4]. Specifically for a precise beam dynamics model of the INJECTOR II is expected to be helpful.

As shown in Fig. 6, the results of the beam based survey confirmed most but not all position readings.

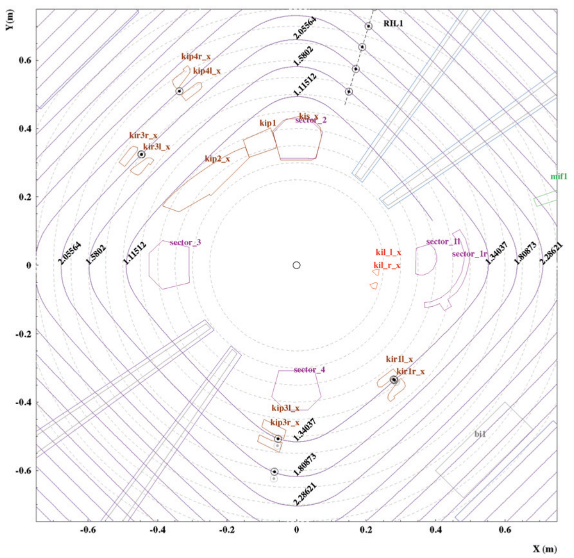

Figure 6: Top view of the central region of INJECTOR II. With the beam positions fixed at RIL1 (at $\theta \approx 80^\circ$) the tracking and the voltages of resonator 1 (gaps in cyan) and resonator 3 (gaps in magenta), the beam position at the various collimator angles are computed (open black circles at the collimators) and compared to the position reading of the collimators. We found two devices, namely the RIL2-collimator and KIR1 where the computed beam positions deviated from the position readings of the device (grey open circles). For the KIP3-collimator mounted on the drive of RIL2, the deviation was found to be about 20 mm and for KIR1 about 5 mm, while all other positions agreed well with the computed beam positions.

INJECTOR II is equipped with additional short range radial probes RIE1 and RIE2 that allow to study the beam positions of the last turns prior to extraction with high accuracy (see Fig. 7). Analogue to the central region we plan to survey the exact positions of the septum of the electrostatic extraction element (EID) and the first septum magnet of the 72 MeV beamline (AXA). Both elements can be remotely controlled with respect to radius and angle. A direct mechanical verification of old calibrations of these elements is practically excluded due to the relatively high dose rate in the extraction area.

SUMMARY

In preparation of future machine upgrades and replacement of components we launched a program of beam based survey and alignment measurements. The purpose of this program is to achieve a self-consistent set of cross-checked calibration and alignment data of RF voltages, collimator positions, phase probe calibrations [5], trim coil and sector magnetic field strength that provides realistic boundary conditions for machine beam dynamics simulations. Furthermore the program provides the beam profiles and beam position data that are required for the validation of precise beam dynamics models and simulations with OPAL and other tracking tools. The long-term plan is to achieve detailed information for a better understanding of beam core and halo formation and that allows to reduce halo formation and to reduce beam losses.

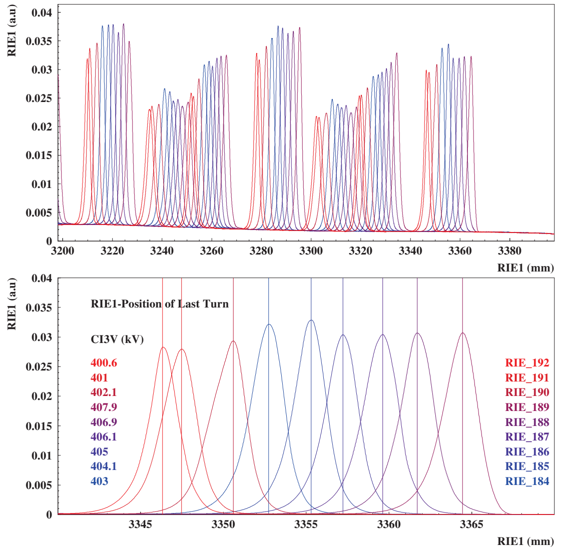

Figure 7: Top: Raw data of beam profiles as measured with the first radial extraction probe RIE1 for different voltages CI3V of resonator 3. Both, the absolute positions as well as the shift of the positions by the change of the resonator voltage can be compared with the tracking calculations. Bottom: A zoom of the last turn, the precise radial positions of highest intensity are indicated by vertical lines.

ACKNOWLEDGMENT

We thank the crew of the PSI machine operators for their kind support.

REFERENCES

[1] W. Joho, Contrib. to PAC 1975, *IEEE Trans. on Nucl. Sci.*, Vol. NS-22, No. 3 (1975), pp. 1397-1401.

[2] Y. J. Bi, A. Adelmann, R. Dölling, M. Humbel, W. Joho, M. Seidel, and T. J. Zhang, *Phys. Rev. ST Accel. Beams* 14, 054402 (2011).

[3] A. M. Kolano, R. J. Barlow, A. Adelmann, C. Baumgarten, "A Precise Beam Dynamics Model of the PSI Injector 2 to Estimate the Intensity Limit", in *Proc. of IPAC'14*, Dresden, Germany, paper TUPRI031 (2014)

[4] M. Seidel *et al*, "Production of a 1.3 MW Proton Beam at PSI", in *Proc. IPAC'10*, Kyoto, Japan, paper TUYRA03, pp. 1309-1313 (2010).

[5] A. S. Parfenova, C. Baumgarten, J. M. Humbel, A. C. Mezger, A. V. Petrenko, "Measurements of the Beam Phase Response to Correcting Magnetic Fields in PSI Cyclotrons", in *Proc. IPAC2016*, Busan, Korea, Mar. 2016, paper TUPMR019, pp. 1271–1273, `doi:10.18429/JACoW-IPAC2016-TUPMR019`, 2016.