MEASUREMENTS OF THE BEAM PHASE RESPONSE TO CORRECTING MAGNETIC FIELDS IN PSI CYCLOTRONS

A. Parfenova[†], C. Baumgarten, M. Humbel, A. Mezger,
Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
A. Petrenko, CERN, 1211 Geneva 23, Switzerland

Abstract

The cyclotron-based proton accelerator facility (HIPA) at PSI is presently operated at 1.3-1.4 MW beam power at a kinetic energy of 590 MeV/u to drive the neutron spallation source SINQ and for production of pion and muon beams. Over the years HIPA facility has developed towards increase of the delivered beam current and beam power (0.1 mA in 1974 till 2.2 mA in 2010). During the last few years several upgrades of the Ring cyclotron field correction and beam phase monitoring systems were made. RF voltage was also increased. In order to test the performance of the upgraded system the phase response measurements were carried out.

INTRODUCTION

The core of HIPA facility consists of two isochronous sector cyclotrons operating at the frequency of 50.6 MHz: Injector 2 and Ring (Fig. 1). In 2015 the beam current was raised frequently (~ 5% of operating time) to 2.4 mA [1]. The present work can help in keeping the relative beam loss at the extraction from the Ring cyclotron close to 10^{-4} as required by machine protection considerations [2, 3] and losses according to the ALARA principle.
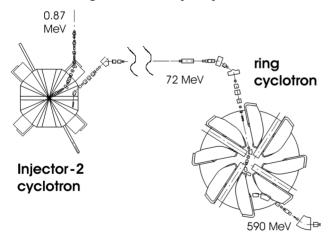

Figure 1: Schematic view of the two HIPA cyclotrons.

The beam phase probes measure the beam phase at different radial positions in the ring and detect the phase of the beam with respect to the accelerating RF field in the cavities. They pick up two signals, a pulsed one from the beam and a continuous one from the RF field (noise). The measurement system picks up a low harmonic where the signal-to-noise ratio is large enough. The beam phase correction system consists of trim coils which are used in cyclotrons to correct the magnetic field profile to keep the

†angelina.parfenova@psi.ch

phase of the beam as close as possible to the reference RF-phase. There are 9 (MIF) and 13 (MRF) beam phase probes; 11 and 15 trim coils in Injector 2 and Ring cyclotrons, respectively (Figs. 2 and 3). Trim coil 15 in Ring cyclotron is used for consciously shifting off the phase to avoid losses via crossing $\nu_r = 2\nu_z$ resonance [4].
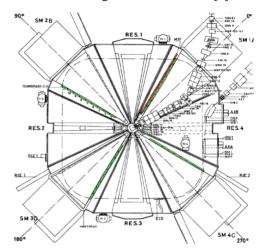

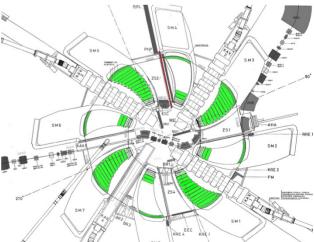Figure 2: Layout of Injector 2 cyclotron with phase probes (red) and side placed trim coils (green).

Figure 3: Layout of Ring cyclotron with phase probes (red) and gap trim coils placed on top of the main magnets' pole plates (green).

MEASUREMENTS AND DATA ANALYSIS

The phase correction method utilized in the PSI cyclotrons is similar to the well-known orbit response matrix technique for synchrotrons: storage rings [5] and fast cycling machines [6, 7].

The beam phase response to the change of current in trim coils and main field was measured. In both cyclotrons, the measured data are in good agreement with the assumption of linear response (Figs. 4 and 5). Fig. 5 shows the two measurements for the Ring cyclotron separated by almost two months of operation. The same reproducibility is also observed for the Injector 2. The measurements were structured into response matrices for both cyclotrons (Figs. 6 and 7). According to these measurements the beam probe MRF150 in the Ring cyclotron (Fig. 7) is not working properly. The reason for this is not clear at the moment.
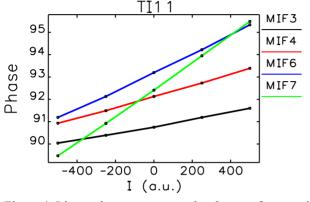

Figure 4: Linear phase response to the change of current in trim coil TI11 of the Injector 2.
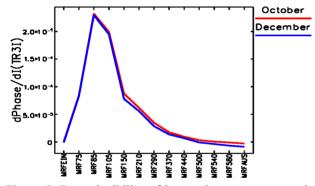

Figure 5: Reproducibility of beam phase response to the change of current in trim coil TR3I in the Ring.
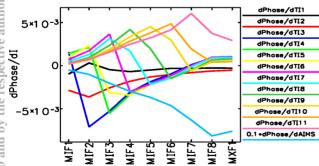

Figure 6: The beam phase response to the change of current in trim coils and main field in the Injector 2.

Similar measurements were carried out in 1991 and 2013. The power supplies of the trim coils were upgraded between 2003 and 2005. In 2009, new cavities allowed to increase the RF voltage, thus further reduced the turn number from 315 in 1991 to 185. The measurements of the new

cyclotron configuration made in 2013 are shown in Fig. 8. There is a good agreement between previous measurement data (2013) and recent measurements (2015) at the Ring cyclotron. Furthermore, the diagnostics of the beam phase monitoring system was upgraded in 2015. Based on the comparison of Figs. 7 and 8 we conclude that the new beam phase probe diagnostics (except for MRF150) and trim coil correction system are working as expected.
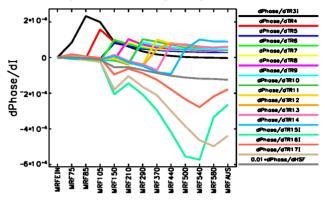

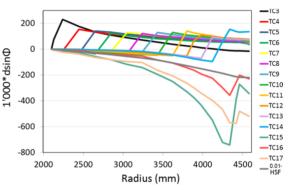Figure 7: The beam phase response to the change of current in trim coils and main field in the Ring.

Figure 8: The measurements of the new Ring cyclotron configuration (2013).

SIMULATIONS

To compare the phase measurements with simulated data, we used measurements of $\Delta \sin\varphi$ from 1989 for Injector 2, taken with the former radial probe, which is now used for other purposes. The radial field profile of the trim coils can be obtained from the first radial derivative of these curves according to

$$\Delta B \sim - \frac{B(R) \cdot R \cdot q \cdot V(R)}{\left(E(R) \cdot \gamma(\gamma + 1)\right)} \cdot \frac{d\sin\varphi}{dR},$$

where R is radius; V(R) is energy gain; φ is beam phase; q is charge, E is kinetic energy and γ is Lorentz factor. The resulting profiles are used to modify the main field of the sector magnets of the orbit tracking code to obtain the simulated phase shifts at the positions of the MIF phase probes (Fig. 9). The simulations performed with the trim coil profiles derived from old data agreed reasonably well with the recent measurement results (Fig. 6 and 9).

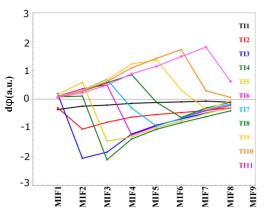**04 Hadron Accelerators**

A13 Cyclotrons

Figure 9: Simulation: phase shifts (responses) for equal excitation of single trim coils in Injector 2.

PHASE CORRECTION ALGORITHM

The beam phase Y is a function of the current X in trim coils $\vec{Y} = \vec{Y}(\vec{X})$. A variation of the current in trim coils $\vec{X} = \vec{X}_0 + \Delta\vec{X}$ produces the variation in the beam phase

$$\vec{Y}(\vec{X}) = \vec{Y}(\vec{X}_0 + \Delta\vec{X}) = \vec{Y}_0 + \left.\frac{\partial\vec{Y}}{\partial\vec{X}}\right|_{X_0} \cdot \Delta\vec{X},$$

where $\vec{Y}_0 = \vec{Y}(\vec{X}_0)$ is an initial measurement. The solution for the change in trim coils is defined via Jacobian − matrix of the first-order partial derivatives as

$$\Delta\vec{X} = \left(\left.\frac{\partial\vec{Y}}{\partial\vec{X}}\right|_{X_0}\right)^{-1} \cdot (\vec{Y} - \vec{Y}_0). \quad (1)$$

Eq. (1) is an ill-posed problem, since the number of trim coils is exceeding the number of phase probes (measurements) and needs to be regularized using additional condition or information to obtain a stable solution for trim coils. The phase measurement (column Y) was extended by the difference of currents of the two consecutive neighbouring trim coils.
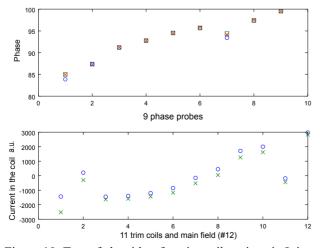

Figure 10: Test of algorithm for trim coil settings in Injector 2: circles – initial values; squares – reference or desired phase; crosses – found solution (correcting setting).

This additional condition revises the system of equations as following:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \cdots \\ Y_n \\ X_1 - X_2 \\ X_2 - X_3 \\ \cdots \\ X_{m-1} - X_m \end{bmatrix} = \begin{bmatrix} Y_{1,0} + \frac{\partial\vec{Y}_1}{\partial\vec{X}}\Delta\vec{X} \\ Y_{2,0} + \frac{\partial\vec{Y}_2}{\partial\vec{X}}\Delta\vec{X} \\ \cdots \\ Y_{n,0} + \frac{\partial\vec{Y}_n}{\partial\vec{X}}\Delta\vec{X} \\ (X_1 - X_2)_0 + (\Delta X_1 - \Delta X_2) \\ (X_2 - X_3)_0 + (\Delta X_2 - \Delta X_3) \\ \cdots \\ (X_{m-1} - X_m)_0 + (\Delta X_{m-1} - \Delta X_m) \end{bmatrix} =$$

$$= \begin{bmatrix} Y_{1,0} \\ Y_{2,0} \\ \cdots \\ Y_{n,0} \\ X_{1,0} - X_{2,0} \\ \cdots \\ X_{m-1,0} - X_{m,0} \end{bmatrix} + \begin{bmatrix} \frac{\partial Y_1}{\partial X_1} & \frac{\partial Y_1}{\partial X_2} & \frac{\partial Y_1}{\partial X_3} & \cdots & \frac{\partial Y_1}{\partial X_m} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \frac{\partial Y_n}{\partial X_1} & \frac{\partial Y_n}{\partial X_2} & \frac{\partial Y_n}{\partial X_3} & \cdots & \frac{\partial Y_n}{\partial X_m} \\ 1 & -1 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \end{bmatrix} \begin{bmatrix} \Delta X_1 \\ \Delta X_2 \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \Delta X_m \end{bmatrix},$$

where n is the number of the phase probes and m is the number of trim coils including main field. The weights are chosen in such a way that partial derivatives in the Jacobian matrix are of the same order of magnitude. An example of possible correction is shown in Fig. 10.

CONCLUSIONS

Beam phase responses to trim coils and main field were measured. As a result, a malfunctioning beam phase probe in Ring cyclotron was identified. Phase response measurements agree well with the old measurements, except for the phase probe MRF150. Thus, we conclude that new beam phase probe diagnostics and trim coil correction system are working as expected. The simulations for Injector 2 were performed to compare with the measurement. The algorithm used in the old correction software for adjusting trim coils from phase measurements was revised and will be programmed in a new application.

REFERENCES

[1] A. Lüdeke, A. Mezger, A. Parfenova, M. Schippers, and M. Seidel, "Operation of the PSI Accelerator Facilities in 2015", PSI, Villigen, Switzerland, Jan. 2015; https://www.psi.ch/gfa/SCYearlyReportEN/OperationReport2015.pdf

[2] M. Seidel *et. al.*, in *Proc. IPAC'10*, pp. 1309-1313.

[3] J. Grillenberger, M. Humbel, A. Mezger, M. Seidel, and W, Tron, in *Proc. Cyclotrons'13*, pp. 37-39.

[4] Y.J. Bi *et. al.*,"Towards quantitative simulations of high power proton cyclotrons", *Phys. Rev. ST Accel. Beams*, Vol. 14, p. 054402, May 2011.

[5] J. Safranek and M.J. Lee, *AIP Conf. Proc.*, Vol 315, pp. 128-136, Dec. 1994.

[6] M. McAteer, S. Kopp, A. Petrenko, V. Lebedev, and E. Prebys, in *Proc. IPAC'12,* pp. 1251-1252.

[7] A. Parfenova, G. Franchetti, I. Hofmann, C. Omet, and S.Y. Lee, in *Proc. PAC'07*, pp. 3256-3258.