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POSITION BASED PHASE SCAN

N. Milas [*], R. Miyamoto, M. Eshraqi, D. C. Plostinar and Y. Levinsen
European Spallation Source ERIC, Lund, Sweden
Y. Liu, J-PARC, Japan

Abstract

Knowledge of the longitudinal beam parameters is important for understanding beam dynamics in linacs. As well as with transverse optics, the settings for the RF cavities have to be established and phase and amplitude seen by the beam must be determined in order to guarantee a stable motion in the longitudinal plane. This work presents an extension of the most widely used phase scan method, relying on time-of-flight, using only transverse positions measured at a few selected BPMs downstream of the cavity being scanned. In principle, the method can be applied both to normal conducting and SC. The suggested method is fast and relatively simple and is capable to provide the values for the cavity transverse misalignment (offsets and tilts) at the same time. It can be a useful part of the initial longitudinal beam tuning.

INTRODUCTION

The European Spallation Source (ESS), currently under construction in Lund, Sweden, will be a spallation neutron source driven by a superconducting proton linac [1]. The linac in is final configuration will accelerate a beam with a 62.5 mA peak current and 4% duty cycle (2.86 ms pulse length at 14 Hz) up to 2 GeV and thus produces an unprecedented 5 MW average beam power.

One important issue at ESS, as in many other hadron linacs, is to set the correct phase and amplitude for the cavities to ensure that the proton bunches receive the desired acceleration and energy gain. The settings for the RF cavities have to be established and phase and amplitude seen by the beam must be determined in order to guarantee a stable motion in the longitudinal plane. This work presents a novel method to determine the RF phase and amplitude using only position measurement at a few selected beam position monitors (BPMs) downstream of the cavity being scanned. In addition to the calibration it is also possible to extract the transverse offsets and tilts (pitch and yaw angles) of the cavities which can then be fed back into the machine model.

A series of measurement using the position based cavity tuning were performed at J-PARC in March 2019 and compared with conventional ToF and signature matching measurements [2–5] for the first buncher cavity in the MEBT1 section. Those measurements corresponds the a first proof of principle for the method and will be presented in this work.

THE METHOD

Consider a simple lattice setup composed of a drift-cavity-drift. When the beam goes through an RF cavity off centered it feels a transverse force proportional to the offset, which could be focusing or defocusing depending on the phase of the cavity. The amplitude of this effect depends both of the cavity phase and amplitude and thus affects the beam trajectory accordingly, in the thin-lens approximation

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/f(\phi,V) & 1 \end{bmatrix} \begin{bmatrix} x_0 \\ x'_0 \end{bmatrix}, \tag{1}$$

for the horizontal plane only, where $f(\phi, A)$ is the RF focusing which for a linear model can be expressed as

$$\frac{1}{f(\phi,V)} = -\frac{\pi q V T \sin(\phi)}{mc^2\lambda(\gamma\beta)^3} = F(V)\sin\phi, \tag{2}$$

where T is the cavity transit time factor, λ the wavelength, ϕ the RF phase seen by the beam and $V = E_0 L$ is the gap voltage, with E_0 the cavity field and L the gap length. Now calculating the transverse transfer matrix of the whole setup drift-cavity-drift it is possible to find the following relations

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} x_0 + L_d x_0/f + L_d x'_0 \\ x_0/f + x'_0 \end{bmatrix}, \tag{3}$$

where L_d is the length of the drift between cavity and the observations points, which in most cases will be a beam position monitor (BPM) and for this reason will be referred as such from this point on. By scanning the cavity phase and looking at the trajectory it is possible to calibrate the phase of the RF fields.

There are two ways of of calibrating the cavity amplitude. The first one is to run several phase scans for different amplitudes and record the maximum trajectory displacement, which happens when the cavity phase is at maximum focusing in the longitudinal plane. The trajectory deviation is connected to the cavity amplitude through the second term in Eq. (3) as $\Delta x_{\max} = L_d x_0 F(V)$. Since L_d and x_0 are known parameters and the calibration between $\Delta x_{\max}$ and the cavity amplitude, given by the function $F(V)$, can be resolved from simulation.

Another way to calibrate the amplitude, easier to visualize however with a more difficult setup, is to measure the real focal length of the cavity transverse focusing component. In this method the initial trajectory angle has to be correctly set to zero and it is also assumed that a previous beam based alignment of the nearby BPMs was performed and the remaining trajectory errors are small. An amplitude scan is then perform for two different initial trajectory offsets x_0^1 and

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[*] natalia.milas@esss.se

x_0^2 with $x_0'^1 = x_0'^2 = 0$. The crossing point is where $x^1 = x^2$ and thus using Eq. (3) can be written as

$$\frac{1}{f} = -\frac{1}{L_d}(1+\delta) \tag{4}$$

with the error in the focal length determination given by

$$\delta = \frac{1}{x_0}\left[\frac{\delta x_0}{L_d} + \delta x_0'\right] \tag{5}$$

meaning that: the larger the initial offset the smaller is the contribution of the error sources to the final focal length. In reality the crossing point is found after a linear fit on the BPM data and thus the value from Eq. (5) is an upper bound to the initial offset x_0. The final values for the amplitude will depend if the crossing is observed at the BPM in question and also on the number of measurements used for the fit.

Since the RF amplitude is a linear function of the inverse of the focal length, given the BPM errors for position and angles, it is possible to estimate the amplitude of the bump needed to have an accurate amplitude calibration. In other words, to calibrate the RF amplitude with 1% accuracy it is necessary to have $\delta \leq 1\%$. Since in the suggested measurement the amplitude of the cavity is scanned and the crossing points is obtained with a fit to the data this condition can be relaxed however that's a good rule of thumb in order to set up the initial measurements.

Cavity Errors

The method is very compact and simple but once cavity errors (tilts and offsets) are included some care must be taken. For the case of offset it is straightforward that each trajectory will see a different focusing force. From Eq. (3), assuming a cavity offset of $-\Delta_{RF}$ in the horizontal plane the measured trajectories will be:

$$\begin{aligned} x_+ &= x_{0+} + \frac{L_d}{f}(\Delta_{\mathrm{RF}} + x_{0+}) + L_d x_{0+}' && (6)\\ x_- &= x_{0-} + \frac{L_d}{f}(\Delta_{\mathrm{RF}} + x_{0-}) + L_d x_{0-}' && (7)\end{aligned}$$

and it is possible to eliminate the error just by calculating the sum or difference trajectory

$$\begin{aligned} x_{\mathrm{sum}} &= \frac{L_d}{f}(x_{0+} + x_{0-} + 2\Delta_{\mathrm{RF}}) + \Delta_+ && (8)\\ x_{\mathrm{diff}} &= \frac{L_d}{f}(x_{0+} - x_{0-}) + \Delta_- && (9)\end{aligned}$$

where $\Delta_\pm = L_d(x_{0+}' \pm x_{0-}') + (x_{0+} \pm x_{0-})$. It is thus possible to still calibrate amplitude and phase and at the same time estimate the cavity offset. At this point the term coming from the initial trajectory angles only adds an offset to the measurement and can be excluded when fitting the data. It is important to stress that from here on it is assumed to have only small angular errors and offsets and that there is no coupling between the transverse planes.

The effect of the a cavity tilt (θ) is a second order effect and can be modeled for $\theta \ll 1$ as

$$k(\theta, V, \phi) = B(V)\theta\cos\phi \tag{10}$$

where $B(V)$ is a function of the RF amplitude and phase.

Separating the constant terms that contribute only to an overall offset from terms that depend on the cavity amplitude and phase it is possible to write the following expressions

$$\begin{aligned} \frac{x_{\mathrm{sum}} - \Delta_+}{L_d} &= \frac{2\Delta_{\mathrm{RF}} + x_{0+} + x_{0-}}{f(V,\phi)} + \frac{k(\theta,V,\phi)}{L_d} && (11)\\ \frac{x_{\mathrm{diff}} - \Delta_-}{L_d} &= \frac{x_{0+} - x_{0-}}{f(V,\phi)} && (12)\end{aligned}$$

PROOF OF PRINCIPLE

In order to test the new method a set of measurements was performed at MEBT1 section in J-PARC using the first buncher cavity and the two subsequent BPMs. The results are shown and discussed below.

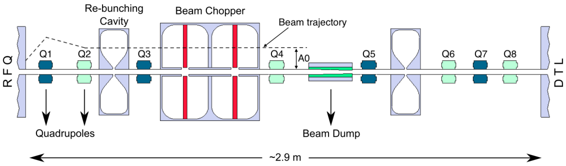

Figure 1: Layout of the MEBT1 section showing the positions of the buncher cavities and quadrupoles. The BPMs and steerers are co-located inside each of the quadrupoles.

Measurement Setup

For this test the second and third quadrupoles (Q_3 and Q_4 in Fig. 1) in the MEBT1 section were turned off, turning the lattice downstream into a simple drift-cavity-drift system. Right after the BPM$_4$, located inside Q_4, there is a beam dump, consisting of a pair of scrapers, which was closed during the measurement so that no beam would reach the DTL entrance. The main parameters for the buncher cavities, relevant for the simulations, are described in Table 1.

Table 1: Parameters for the First MEBT Buncher Cavity

Parameter	**Value**	**Unit**
Input energy	3.0	MeV
RF frequency	324	MHz
Design accelerating voltage (E_0TL)	164	kV
Transit time factor (TTF)	0.55	-
Gap length	18	mm

To create the bumps necessary for the amplitude and phase measurements we used as reference a trajectory obtained after a beam based alignment of the quadrupoles. Over this trajectory we used the steerers located inside the first two quadrupoles (Q_1 and Q_2) to manually create a bump with a given offset and zero angle going into the buncher cavity. For now on the term x' is always considered zero.

At J-PARC, in order to avoid transporting unwanted particles, throught the MEBT1 and into the DTLs the whole set RFQ and the first two quadrupoles in the MEBT1 section are intentionally displaced by −1 mm in the horizontal plane. This offset made the measurement on the horizontal plane extremely difficult. In addition, the beam chopper represents an extra aperture restriction in the horizontal plane, with an aperture of 13 mm in contrast with the 20 mm aperture on the vertical. In view of these issues and the limited amount of time, the scans were performed only on the vertical plane.

Phase Scan

The first step was to find the phase for maximum transverse focusing, which in the longitudinal plane corresponds to maximum defocusing, or debunching phase. At this stage any bump can be used without much care of canceling angles or knowing the initial conditions precisely.

Figure 2 shows such a simple scan and the corresponding sinusoidal fit to the data. The measured phase was 39.9 ± 0.5 degrees using BPM$_3$ and 40.1 ± 0.8 degrees using BPM$_4$, while the phase measured from the traditional phase scan, using ToF, was 39.9 ± 1.0 degrees.

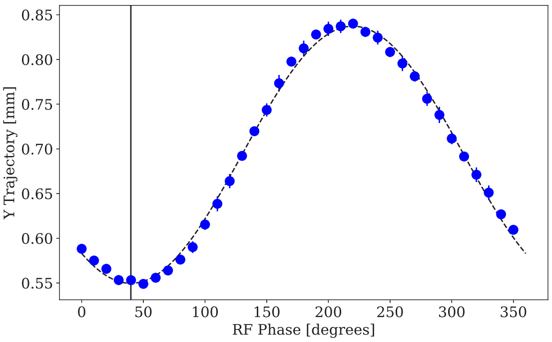

Figure 2: Example of trajectory measured at BPM$_3$ at the MEBT1 section. The blue dots are the data, the dashed lines are the sinusoidal fit and the vertical line represent the debunching zero crossing phase. The error bars are standard deviation from 10 measurements.

It is worth to note that the reading from BPM$_4$ is not as good as BPM$_3$. Since the two quadupoles after the buncher were turned off the beam loss at the chopper was equivalent to half of the total current. This made the accuracy of the measurement at BPM$_4$ worse.

Amplitude Scan

For the amplitude we set up bumps with four different amplitudes and the steerers before the cavity were set such that the angle of the beam going through the cavity was as close as possible to zero. The amplitude of each bump can be found in Table 2 and it was measured while the cavity and its downstream quadrupoles were turned off. For the amplitudes scans the cavity phase was set to 39.9 degrees, which gives the maximum transverse focusing kick.

Table 2: Vertical Bump Amplitudes at the MEBT1 Vertical Trajectory

Name	**Amplitude A_0 (mm)**
Bump 1	0.57 ± 0.01
Bump 2	1.14 ± 0.02
Bump 3	−0.59 ± 0.01
Bump 4	−1.13 ± 0.01

For the first measurement, for each bump the Amplitude of the cavity was scanned. The trajectory recorded was fitted with a straight line and the crossing point of all four bumps calculated. The results are displayed in Fig. 3 for BPM$_3$. From simulation we know that the crossing amplitude for BPM$_3$ is E_0TL = 805.2 kV and for BPM$_4$ it is E_0TL = 154.5. From the measurement it is possible then to get the calibration factor between the cavity amplitude and the effective accelerating voltage.

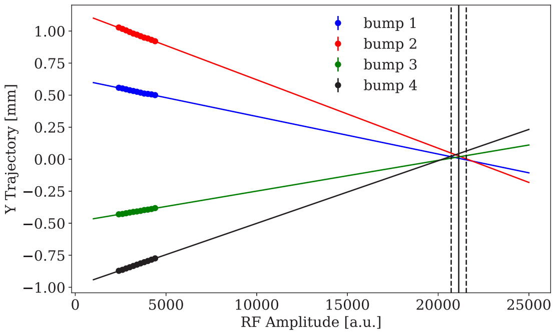

Figure 3: Vertical trajectory during the RF amplitude scan for fours different initial bump configurations for BPM$_3$. The dots are the measurements and the lines are linear fits to the data. The solid vertical black line represents the average crossing values and the dashed lines are indicating $\pm 1\sigma$.

Another way to calibrate the cavity amplitude is to perform phase scans at different cavity amplitudes and look at the max amplitude of the measuretrajectory wiggle. From Eqs. (6) and (7) we are looking at the term proportional to $1/f$, and assuming that $\Delta_{\mathrm{RF}} \ll A_0$, where A_0 is the bump amplitude. In this case the amplitude of the trajectory variation is given only by $F(V)L_dA_0$ and the calibration between this values and the E_0TL can be found from simulation, which is a similar approach as the signature match method. A set of three phase scan for different amplitudes for bump 2 were performed. The results for each phase scan of BPM$_3$ is shown in Fig. 4 and the combined processed results from both, BPM$_3$ and BPM$_4$, are in Fig. 5.

A summary of the results for all amplitude measurements and the corresponding calibration constants are in Table 3.

Cavity Misalignment

Once phase and amplitude are properly calibrated it is also possible to extract from the data the cavity misalignment for the plane measured. For the case of J-PARC data, since

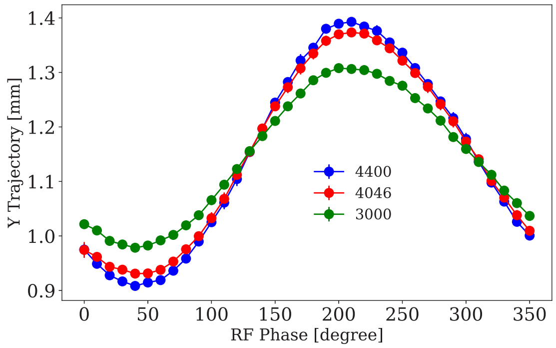

Figure 4: Example of a phase scan for three different cavity amplitude for BPM$_3$. The amplitude values are the ones set in the cavity controller and have no direct physical meaning. The default amplitude for this cavity is 4046 a.u.

Table 3: MEBT1 Buncher Amplitude Calibration Results (The calibration relates $E_0TL(V) = \alpha A$.)

Measurement type	**α (V)**
Crossing BPM$_3$	3.8 ± 0.7
Crossing BPM$_4$	9 ± 1
Signature match (BPM$_3$ and BPM$_4$)	4.49 ± 0.01
Standard Signature match using ToF	4.43

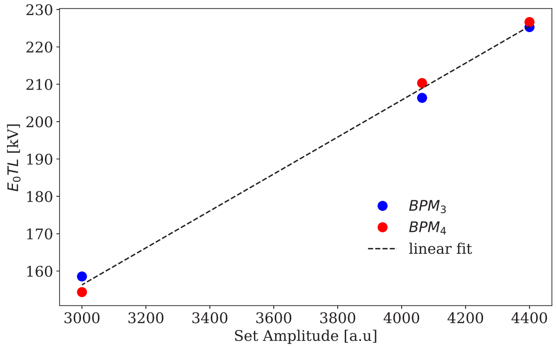

Figure 5: Amplitude scaled to E_0TL using the model. The dashed line is a linear fit to both data sets.

the measurements were performed on the vertical plane the vertical offset and the pitch angle can be estimated. All the phase scans were performed at the same cavity amplitude $V_0T = 164\,\mathrm{kV}$, which is the default value for operation.

The first step is to calculate the sum and difference trajectory for each pair of bumps, and for this measurement case it is possible to use the following simplified version for the sum and difference trajectories.

$$x_{\mathrm{sum}} = 2L_d\Delta_{\mathrm{RF}}F(V_0)\cos\phi + B(V_0)\theta\sin\phi \qquad (13)$$

$$x_{\mathrm{diff}} = 2x_0 + 2L_d x_0 F(V_0)\cos\phi \qquad (14)$$

where $B(V_0) = (-2.25 \times 10^{-2})$ and comes from simulations. Paring bumps 1 and 3 and bumps 2 and 4, the sum and difference trajectories are shown in Fig. 6.

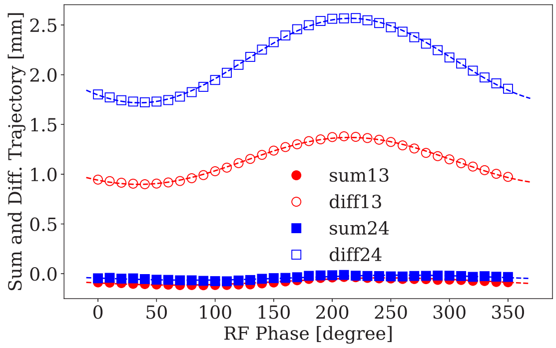

Figure 6: Sum and difference trajectories and the respective fit using Eqs. (13) and (14).

Fitting both sets of trajectories using Eqs. (13) and (14) it is possible to estimate both the cavity offset and tilt and also recover the bump amplitude. The results are summarized in Table 4. Note that the reconstructed bump values agree well with the values measured at the BPMs and from the misalignment results it is possible to see that the cavity is well aligned with the beam trajectory.

Table 4: Cavity Misalignment Results

Bump set	**Δ_{RF} (mm)**	**θ (mrad)**	**x_0 (mm)**
1 and 3	0.08 ± 0.04	0.72 ± 0.08	0.567 ± 0.001
2 and 4	0.05 ± 0.04	0.73 ± 0.08	1.071 ± 0.002

CONCLUSIONS

A new method for tuning the cavities in a hadron linacs was proposed and tested at JPARC and showed promising results, as accurate as the ones obtained from traditional phase scan measurements. In addition to tuning the cavity this new method also provides an direct way to estimate the cavity tilts and offsets with respect to the beam trajectory.

The main limitations of the new method lies in the fact that a clean path, without other focusing elements between the scanned cavity and the measurement point (usually a BPM) is preferred, this can be a challenge in machines, like ESS, which require extremely low losses. A work around is possible with one quadrupole in between and a combined measurement of the vertical and horizontal plane, which would still allow the cavity tuning but at the expense of of loosing the ability to infer the cavity misalignment. This work around remains still to be tested.

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