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# BUNCH MEASUREMENTS WITH BPM AT LOW ENERGY HADRON ACCELERATORS

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*Abstract*

Beam Position Monitors (BPM) are one of the key diagnostics use in LINACs, BPMs should ensure a continuous monitoring of the beam position and energy. BPMs also give an indication of the beam transverse shape. For electron LINACs, beam longitudinal length is measured with BPMs. However, in hadron LINACs, it is performed with intrusive modules (wire scanners, beam shape monitors) This document relates the measurement of beam longitudinal length with BPMs. It is divided in two parts: first, a theoretical model of the BPM operation and the formulas driving the measurement of beam longitudinal length from BPM output signals. Second, an experimental study run at MYRRHA LINAC facility and showing good agreement between estimated values of beam longitudinal length from Tracewin simulations and BPM measurements.

## INTRODUCTION

It is important to know the bunch longitudinal length for beam dynamics optimization and loss reduction in linear accelerators. This is especially true for accelerators with flexible longitudinal settings like superconducting linacs having large numbers of independently powered accelerating cavities and uncorrelated amplitude and phase set points. Typically, the superconducting part of a linac has strong limitations on the use of interceptive diagnostics due to concerns regarding contamination of superconducting surfaces. This precludes the use of conventional longitudinal bunch profile diagnostics such as bunch shape monitors (BSM) [1] or similar devices. There are non-interceptive methods [2] [3] but they are either intended for electrons or not too precise particularly at low beam energies.

The main purpose of this article is to evaluate the measurement of the bunch longitudinal length with a non-interceptive method using button BPM.

## BUTTON BPM MECHANICAL MODEL

Button BPM is sketched in Figure 1. It is equipped with 4 identical feedthroughs attached to electrodes. The sets (feedthrough + electrode) are identical and symmetrical regarding the centre of the BPM.

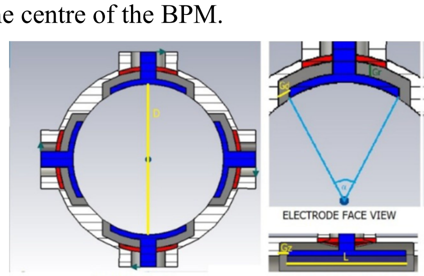


Figure 1: Layout of button BPM.

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Where D is the BPM diameter, L the BPM longitudinal length and α the BPM angular width.

## BUTTON BPM THEORETICAL MODEL

The LINAC RF structure generate a periodical beam bunches. The beam current or bunch $I_b$ may be represented by a Fourier series expansion in the frequency domain [4].

$$I_b(t) = \langle I_b\rangle \left(1 + 2\sum_{0}^{\infty} A_n \cos\left(2\pi n F_{acc} t + \varphi_n\right)\right) \quad (1)$$

Where $< I_b >$ is the average dc current, $A_n$ is a bunch-shape-dependent form factor, $F_{acc}$ is the bunching frequency, $n$ is the harmonic number, and $\varphi_n$ is the phase of the $n^{th}$ harmonic.

The beam distribution is supposed Gaussian; the beam current is modelled as:

$$I_b(x,y,t) = \langle I_b\rangle \frac{e^{-t^2/2\sigma_t^2} e^{-x^2/2\sigma_x^2} e^{-y^2/2\sigma_y^2}}{\sqrt{2\pi}\sigma_t \sqrt{2\pi}\sigma_x \sqrt{2\pi}\sigma_y} \quad (2)$$

The beam induces a wall current $I_{wall}$ on the on the BPM electrodes: for a line current $I_b$ at (r,θ), the rms image current density $I_w$ at the $n^{th}$ harmonic frequency and azimuthal position $\varphi$ on the conducting cylindrical beam tube is given by

$$I_{w,n} = \sqrt{2}\langle I_b\rangle A_n \sum_{m=-\infty}^{\infty} \frac{I_m(ngr)}{I_m(ngD/2)} \cos\left(m(\varphi - \theta)\right) \quad (3)$$

Where $I_m$ represents the modified Bessel function of order m and $g=2\pi F_{acc}\sqrt{(1-\beta^2)}/(\beta c)$ with c the light speed and β the relative velocity of the beam.

Figure 2 illustrates the different parameters in (3).

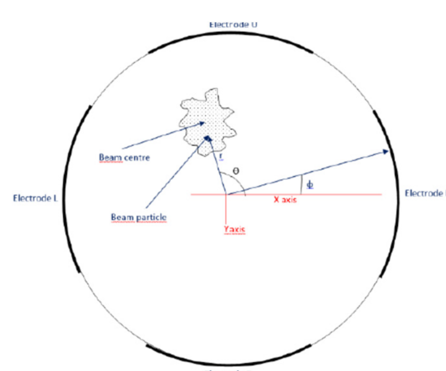


Figure 2: 2D presentation showing the parameters in (3).

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For a beam located in a radius up to 20% of the tube radius, $I_m(ngr)/I_m(ngD/2) \leq 1\%$ for m>2, therefore, wall current equations are simplified by taking up to m=2 in the sum in (3).

Integration of $i_{R,n}$ over bunch particles gives the rms wall image currents $I_{R,n}$ at the n[th] harmonic mentioned in (4).

$$I_{R,n} \approx \frac{\langle I_b \rangle A_n}{\sqrt{2\pi}} \left( \frac{\alpha}{I_0\left(\frac{ngD}{2}\right)} + \frac{4g\sin\left(\frac{\alpha}{2}\right)}{I_1\left(\frac{ngD}{2}\right)} \frac{X_0}{D} + \frac{g^2 \sin(\alpha)}{4I_2\left(\frac{ngD}{2}\right)} \left( \frac{X_0^2 - Y_0^2 + \sigma_x^2 - \sigma_y^2}{\left(\frac{D}{2}\right)^2} \right) \right)$$

Where $X_0$ and $Y_0$ are the beam center coordinates and

$$A_n = \exp\left(-(2\pi n F_{acc})^2 \sigma_t^2 / 2\right)$$

The current $I_{L,n}$ in combination with $I_{R,n}$ will give a formula for $X_0$ calculation. The currents $I_{D,n}$ and $I_{U,n}$ will give a formula for $Y_0$ calculation. The four currents will give a formula for $\sigma_x^2 - \sigma_y^2$ calculation.

The integration of the charge density over the electrode length L is performed. The BPM electrode electrical model is a parallel RC: R is the feedthrough resistance; C is the electrode capacitance.

The n[th] harmonic of the BPM Right Electrode voltage level is calculated in (5)

$$\begin{aligned} U_{R,n}(dBm) \approx \frac{20}{\ln(10)} \Bigg( & \ln\left( \frac{4\sin\left(\frac{n\pi L}{\lambda}\right) R}{\sqrt{1+(2\pi n F_{acc} RC)^2}} \frac{\langle I_b \rangle}{\sqrt{2\pi}} \right) - 2(\pi n F_{acc})^2 \\ & + \ln\left( \frac{\alpha}{I_0\left(\frac{ngD}{2}\right)} + \frac{4g\sin\left(\frac{\alpha}{2}\right)}{I_1\left(\frac{ngD}{2}\right)} \frac{X_0}{D} \right. \\ & \left. + \frac{g^2 \sin(\alpha)}{4I_2\left(\frac{ngD}{2}\right)} \left( \frac{X_0^2 - Y_0^2 + \sigma_x^2 - \sigma_y^2}{\left(\frac{D}{2}\right)^2} \right) \right) \Bigg) \end{aligned} \quad (5)$$

$U_{R,n}$ is proportional to the square of $\sigma_t$. The differences between $U_{R,1}$, $U_{R,2}$ and $U_{R,3}$ should give estimations of the beam longitudinal length.

The harmonics should be strong to make a robust estimation. The harmonics level mostly depends on the beam relative velocity β and the BPM electrode length L.

The separation between two consecutive bunches is λ:

- If L is equivalent to $\beta c/F_{acc}$ (2L< λ <5L), estimation based on harmonics 1 and 2 is the best to use.
- If L is shorter than $\beta c/F_{acc}$ (5L< λ <10L), all estimations might work.
- If L is much shorter than $\beta c/F_{acc}$ (10L< λ), estimation based on harmonics 2 and 3 is the best to use.

The following sections relates an experimental study run at MYRRHA LINAC facility showing the good agreement between estimated values of beam longitudinal length from Tracewin simulations and BPM measurements.

## GENERAL DESCRIPTION OF MYRRHA

The MYRRHA accelerator is a high power proton accelerator with strongly enhanced reliability performances. The adopted LINAC scheme to fulfil the reliability goal is mentioned in Figure 3.

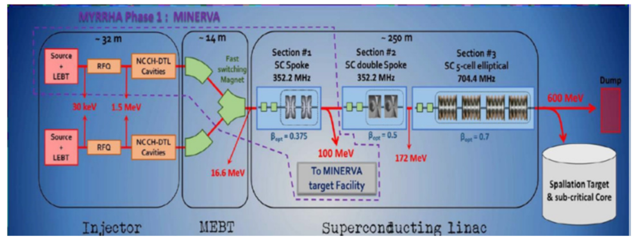


Figure 3: Conceptual scheme of MYRRHA accelerator.

Table 1 shows the different beam time and current configurations at the injector level.

Table 1: Beam Configuration at MYRRHA Injector

| Parameter | Low | High |
|---|---|---|
| Energy | 1.5MeV | 17MeV |
| Relative velocity β | 0.0565 | 0.188 |
| Linac Tube diameter | 38mm | 38mm |

### *Bunch Length Measurement Configuration*

The injector [5] is presently installed in SCK facility at Louvain La Neuve (Belgium). The injector includes a source with LEBT line followed with a RFQ that brings beam energy to 1.5MeV. the CH-DTL cavities are not installed yet.

The configuration at the exit of the RFQ is sketched in Figure 4.

Characteristics of the installed BPM are in Table 2.

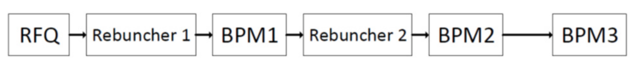


Figure 4: Linac configuration at RFQ exit.

Table 2: Injector BPM Characteristics

| BPM | 1 | 2 and 3 |
|---|---|---|
| Diameter | 38mm | 56mm |
| Length | 14mm | 62mm |
| Angular width | 45° | 60° |
| Capacitance | 7pF | 13pF |
| Resistance | 50Ohm | 50Ohm |

BPMs 2 and 3 are designed to offer strong signal at low beam current and measure with a better precision the beam position, transverse shape and energy. BPM1 electrode length is shorter than $\beta c/F_{acc}$ (~96mm), therefore harmonics 1 to 3 of the electrode output signal should give the best estimation of beam longitudinal length.

Rebuncher 1 phase is set to match the desired beam energy (1.494MeV). A sweep of ±50° around the set value is performed. Sweeping the phase of rebuncher 1 contracts/expands the beam longitudinal length, it also acts on the beam energy measured thanks to BPMs 2 and 3.

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For each rebuncher phase, the electrode output signal is measured with a spectrum analyzer, the harmonics levels and the beam position and energy are measured.

Beam length measurement with BPM is compared to TraceWin simulations [6].

Beam position is measured in a 1mm radius around the beam tube revolution axis, the values of components in (5) are shown in Table 3.

Table 3: Values of Components in (5)

| Harmonic | 1 | 2 | 3 |
|---|---|---|---|
| $\frac{\alpha}{I_0(ngD/2)}$ | 0.555 | 0.247 | 0.091 |
| $\frac{4g\sin(\alpha/2)}{I_1(ngD/2)}\frac{X_0}{D}$ | 0.134 | 0.082 | 0.04 |
| $\frac{g^2\sin(\alpha)}{4I_2(ngD/2)}\left(\frac{X_0^2-Y_0^2}{(D/2)^2}\right)$ | 0.003 | 0.002 | 0.001 |

The component related to the second quadrupolar moment is insignificant is beam longitudinal length calculations.

### *Bunch Length Measurement Results*

Sweep results are gathered in Figure 5.

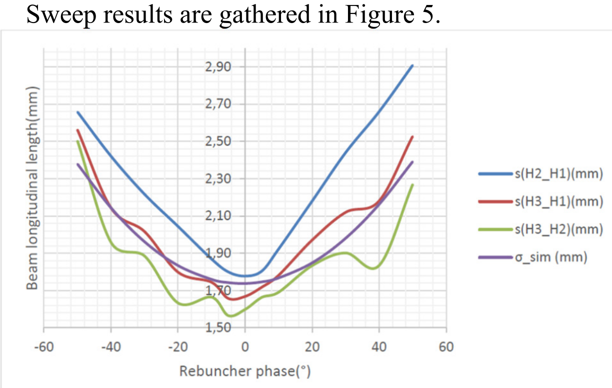


Figure 5: Beam longitudinal length estimations.

The longitudinal lengths are close for all estimations. As predicted, the estimation based on the 1st and 3rd harmonics is the best match.

The overall calculations are very sensitive to the errors in harmonic levels. It is also better to choose the robust estimation. For instance, sensitivities of each estimation are mentioned in Table 4.

Table 4: Sensitivity of Beam Longitudinal Length

| Estimation based on | H1-H2 | H1-H3 | H2-H3 |
|---|---|---|---|
| Sensitivity(mm/dBm) | 2.2 | 0.7 | 0.9 |

Estimation based on harmonics H1 and H3 is also the less sensitive.

## CONCLUSION

This document relates a theoretical study allowing the measurement of beam longitudinal length with BPM. The formulation was tested with low β beam delivered in MYRRHA facility. The results are encouraging, a good agreement is found between Tracewin simulations and BPM measurements. Attention should be put on a very precise measurement system and the choice of the harmonics allowing the best and most robust match of the beam longitudinal length.

Further measurements would be run on MYRRHA and other LINAC facilities.

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