

DESIGN OF BPMs FOR A 750 MHz HADRONTHERAPY LINAC

A. Rodríguez[†], P. Calvo, J. Etxebarria, G. Moreno, C. Oliver, M. León, D. Gavela,
J. M. Perez, CIEMAT, Madrid, Spain
J. M. Carmona, A. Tato, AVS, Elgoibar, Spain

Abstract

This work presents the design of Beam Position Monitors for a 750 MHz Linac for hadrontherapy studies.

BPMs will be installed in different sections of the Linac, operating at different energies, from the RFQ exit at 5 MeV/u to the end of the line after IH cavities at 10 MeV/u. The BPMs will allow measurement of the beam position, phase and time of flight (tof) measurements. Therefore, they are fundamental for commissioning and operation of the prototype hadrontherapy Linac.

In the analysis we compare the expected signal from stripline and button BPMs using analytical and CST models, studying the BPMs dimensions and response at different energies, and BPMs sensitivity for position, phase and tof measurements.

INTRODUCTION

The LINAC6+ is a project currently under development, with the goal of performing radiobiology studies for hadrontherapy using a Carbon 6+ beam. The Beam Position Monitors (BPMs) are crucial diagnostics both for the accelerator commissioning and during operation. The BPMs will be installed at different Linac sections after the RFQ, giving information about the beam position and phase, and allowing energy measurements through time of flight.

The LINAC6C+ will be composed of an ion source and LEBT up to 15 keV/u, a 750 MHz RFQ up to 5 MeV/u [1] and IH cavities up to 10 MeV/u [2]. The Linac will operate with beam pulse currents of 190 μ A, with pulse durations of 5-10 μ s at repetition rates of 200-400 Hz [3]. In Table 1 the expected BPM operation parameters are described.

For the design of the BPMs we have first studied the expected signal using analytical formulae, and then performed electromagnetic simulations using CST. The analysis allows comparison of stripline and button BPM, characterizing the expected signal for the definition of requirements for the amplification electronics.

Table 1: Main Operational Parameters for the BPMs

| Parameter | Value |
|---------------------|--------------|
| RF Frequency | 750 MHz |
| Beam Energy | 5-10 MeV/u |
| Beam Pulse Current | 190 μ A |
| Beam Pulse Duration | 5-10 μ s |
| Repetition Rate | 200-400 Hz |

* Work supported by CPP 03/2023

[†] angel.rodriguez@ciemat.es.

IMAGE CURRENT

When the beam passes through a Linac section an image (or wall) current is induced in its surrounding conducting elements. If electrodes are installed, they pick-up the signal, and with a configuration of four electrodes the beam position can be measured.

For the estimation of the BPMs signal first the image signal at the electrode location is estimated [4]:

$$I_{image}(\omega) = -\frac{I_{bunch}(\omega)}{2\pi} \cdot s(\omega) \quad (1)$$

$$s(\omega) = \alpha \cdot \frac{I_0(gR)}{I_0(gR)} + 2 \sum_{n=1}^{\infty} \frac{1}{n} \frac{I_n(gR)}{I_n(gR)} \cdot [\sin(n(\alpha/2 - \varphi)) - \sin(n(\alpha/2 + \varphi))] \quad (2)$$

The image current depends on the bunch current in the frequency domain $I_{bunch}(\omega)$, the position of the beam ($r; \varphi$), the beam energy ($\gamma\beta$) the beampipe radius (R) and aperture (α). The aperture α for a stripline BPM is its width angle, and for a button bpm of radius r_b is $\alpha = 2\pi \cdot r_b/4R$. $I_n(x)$ are the modified Bessel function of order n and $g = \frac{\omega}{\beta\gamma c}$ the dependence on energy.

For the LINAC6+ BPMs the expected pulse current is 190 μ A with a bunched structure of $\sigma \sim 20$ ps at 750 MHz. Solving Eq. (1) and applying Fourier transform, the results in time domain are obtained. In Figure 1 we show the bunch current and its image current. For low beta beams the signal is distorted, since the field is not transversal, and the observed signal duration increases from $\sigma \sim 20$ ps on the beam to ~ 150 ps on the image signal.

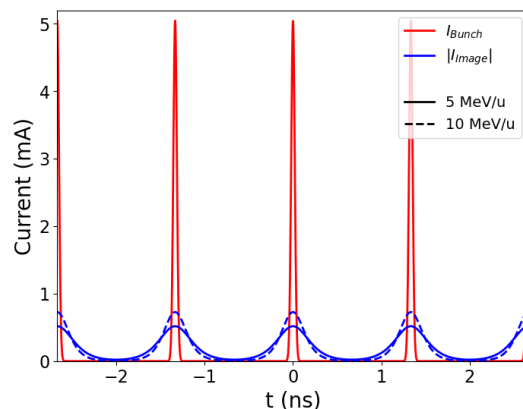


Figure 1: Bunch current and image current for a beam with pulses of 190 μ A at 750 MHz and 20 ps bunches.

STRIPLINE BPM

In a stripline BPM the signal collected in upper electrode depends on the termination of the lower end, which can be either matched, shorted or open.

If the termination is matched, Eq. (3), the signal picked in the first electrode will correspond to half the image current upon beam arrival, and half upon beam leaving the stripline. In case of shorted electrode, Eq. (4), only the signal upon beam arrival and the inverted reflection are picked and in an open electrode, Eq. (5), both the signals upon beam arrival and leaving and the reflections are picked.

Mathematically the impedance for the different terminations is [5]:

$$Z(\omega) = \frac{Z_0}{2} \cdot \left[1 - e^{-j\omega \cdot \left(\frac{l}{c} + \frac{l}{\beta c} \right)} \right] \quad (3)$$

$$Z(\omega) = \frac{Z_0}{2} \cdot \left[1 - e^{-j\omega \cdot \left(\frac{2l}{c} \right)} \right] \quad (4)$$

$$Z(\omega) = \frac{Z_0}{2} \cdot \left[1 + e^{-j\omega \cdot \left(\frac{2l}{c} \right)} - 2 \cdot e^{-j\omega \cdot \left(\frac{l}{c} + \frac{l}{\beta c} \right)} \right] \quad (5)$$

where Z_0 is the termination impedance, typically 50 Ω , c the speed of light, β the beam velocity and l the stripline length.

From the impedance and image current the signal is calculated:

$$V(\omega) = Z(\omega) \cdot I_{image}(\omega) \quad (6)$$

The total signal is the contribution from different bunches, which are separated a distance $\beta c/f$. For matched and open terminations, the signal is maximized for a length of $l = \beta c/2f$, which for 5 MeV/u at 750 MHz is ~ 20 mm. For a shorted termination, the signals from beam arrival and its inverted reflection cancel, obtaining lower signal levels. For the aperture an angle of $2\pi/3$ is chosen.

The analytical solution of the BPMs has been solved using python and compared to CST simulations using wakefield solver, see Figure 2.

In Figure 3 we show the results, showing good agreement between analytical and CST simulations. The signal levels are of ~ 2 mVpp (-50 dBm) for a shorted stripline, to ~ 5 mVpp (-42 dBm) for a matched and, ~ 8 mVpp (-38 dBm) for an open stripline. The signal is maximum for an open stripline, which picks up the beam signal and the reflection at the arrival and exit of the stripline.

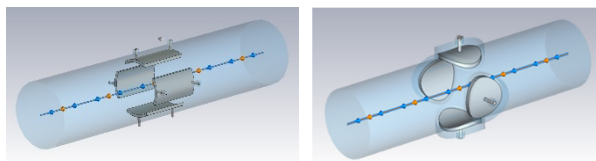


Figure 2: CST Models for a stripline (left) and button (right) BPMs.

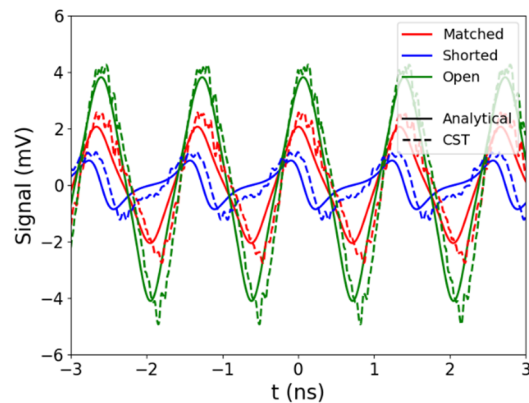


Figure 3: Stripline BPM signal estimation with analytical and CST models. BPM stripline with 20 mm length, $2\pi/3$ aperture on a $\Phi 20$ mm beam pipe and a beam of 5 MeV/u, 190 μ A, 750 MHz and $\sigma=20$ ps bunch length.

BUTTON BPM

In the case of a button BPM with a symmetric circular electrode the impedance can be estimated as [6]:

$$Z(\omega) = \frac{2r_b}{\beta c} \frac{1}{C} \frac{j\omega Z_0 C}{1 + j\omega Z_0 C} \quad (7)$$

where r_b is the BPM button radius and C is the button capacitance, which can be approximated as [5] $C \approx \frac{\pi \epsilon t_b}{\ln\left(\frac{r_b+g}{r_b}\right)} + \frac{\pi \epsilon r_b^2}{d}$, with t_b the button thickness, g and d the radial and axial gap with the beam pipe. For a button with gaps ~ 1 mm the capacitance is ~ 1 pF, and it has no major effect on the signal. For electrodes with thicker buttons or smaller gaps the capacitance is higher and the signal reduced. Regarding the BPMs electrode radius, the signal increases with radius, which for a beam pipe of $\Phi 20$ mm is limited $r_b \sim 7$ mm due to mechanical constraints.

In Figure 4 the signal of a button BPM from analytical and CST simulations is shown. Both models give a similar signal, similar also to the signal obtained with an open stripline of similar aperture (see Figure 3), with a signal level of around 8 mVpp (-38 dBm).

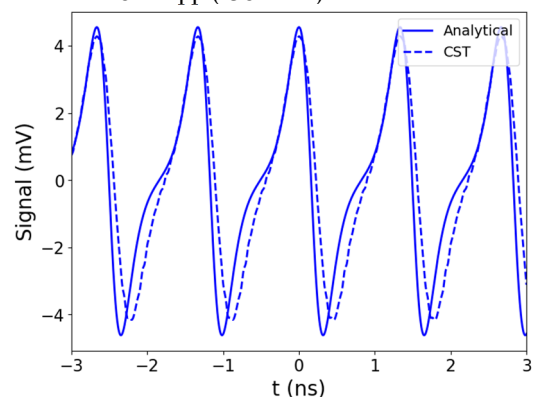


Figure 4: Button BPM signal estimation with analytical and CST models. Case for stripline BPM of 6 mm radius on a $\Phi 20$ mm beam pipe and a beam of 5 MeV/u, 190 μ A, 750 MHz and $\sigma=20$ ps bunch length.

POSITION AND TOF MEASUREMENTS

In a BPM, the beam position is measured comparing the signal of the opposite electrodes. Near the axis centre the BPM behaviour is proportional to the logarithmic ratio of the signals and the beam position can be estimated as:

$$x \cdot S_x = 20 \cdot \log_{10}(V_L/V_R) \quad (8)$$

$$y \cdot S_y = 20 \cdot \log_{10}(V_T/V_B)$$

where x, y are the beam position, S_x, S_y the BPM sensitivity and V_L, V_R, V_T and V_B the signal of the left, right, top and bottom electrodes.

To estimate the BPM sensitivity, simulations with the beam deviated from the axis centre have been performed using CST. The simulated sensitivity at 5 MeV/u is 4.17 dB/mm and the linearity error is less than 1% up to ~2mm and less than 5% up to ~5 mm of beam position. In Figure 5 the horizontal logarithmic ratio for different vertical displacements is shown. Note that the BPM sensitivity varies with the beam energy and should be corrected depending on the position in the accelerator section and from testbench calibration.

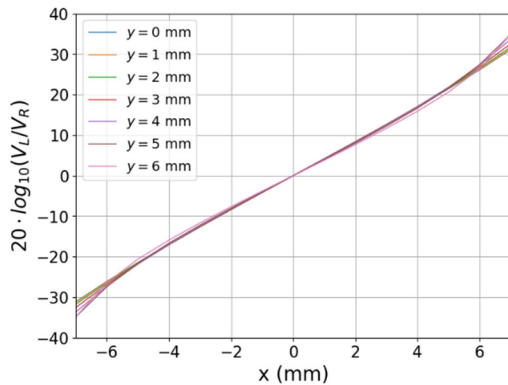


Figure 5: Logarithmic ratio of left (V_L) and right (V_R) electrodes for different vertical displacements. Case for BPM of 6 mm radius on a Φ 20 mm beampipe and a beam of 5 MeV/u, 190 μ A, 750 MHz and $\sigma=20$ ps bunch length.

The position resolution of the BPM is highly dependent on the electronics used for signal conditioning and its amplification bandwidth. The maximum position resolution (δx) is [7]:

$$\frac{\delta x}{R} \approx \frac{1}{4} \sqrt{\frac{P_n}{P_s}} = \frac{1}{4} \sqrt{\frac{kTB}{P_s}} \quad (9)$$

where P_n is thermal noises power, P_s the signal power, k the Boltzmann constant, T the temperature and B the electronics bandwidth. For a broadband system of 3 GHz at 300 K the thermal noise is ~79 dBm, which for a beampipe of $R=10$ mm and a signal $P_s \sim 38$ dBm gives a BPM resolution $\delta x \sim 23 \mu$ m.

The phase thermal noise ($\delta\phi$) can be expressed as:

$$\delta\phi \approx \tan^{-1} \left(\sqrt{\frac{P_n}{P_s}} \right) = \tan^{-1} \left(\sqrt{\frac{kTB}{P_s}} \right) \quad (10)$$

Which for a broadband system of 3 GHz at 300 K gives a phase resolution of 0.4° or 1.4 ps.

The beam energy can be measured from the phase at two BPMs using time of flight (tof) measurements. The beam energy is therefore estimated as:

$$\beta c = \frac{\Delta L}{N\tau + \tau \frac{\Delta\phi}{2\pi}} \quad (11)$$

where ΔL is the distance between BPMs, N the bunches between the BPMs, τ the RF period and $\Delta\phi$ the phase difference between the BPMs.

To improve the resolution of the measurement, the three BPMs method can be used. With two BPMs close (1-4 bunches) for a rough energy measurement, and a third at higher distance for a fine measurement.

The energy error can be estimated as:

$$\frac{\Delta E}{E} \approx 2 \cdot \frac{\Delta\beta}{\beta} = \sqrt{\left(\frac{\delta L}{L}\right)^2 + \left(\frac{\delta\phi}{N\tau + \tau \frac{\Delta\phi}{2\pi}}\right)^2} \quad (12)$$

where δL is the BPM longitudinal position error and $\delta\phi$ the phase measurement error. For a case with $\delta L \sim 1$ mm and $\delta\phi \sim 2^\circ$ and a BPMs separation of 0.4 m (10 bunches), the energy measurement error would be of ~0.5% (25 keV).

CONCLUSIONS

In this work we study the expected signal in stripline and button BPMs for LINAC6+ with carbon 6+ currents of ~190 μ A and energies of 5-10 MeV/u.

Use of BPMs seem a feasible option for the LINAC6+ for position, phase and energy measurements. With button electrodes with radius of 5-7 the expected signal is in the mV range, at around -40 dBm. Next steps will involve detailed definition of the electrode geometry, manufacturing specifications, and selection of amplification electronics.

REFERENCES

- [1] V. Bencini *et al.*, "750 MHz radio frequency quadrupole with trapezoidal vanes for carbon ion therapy", *Phys. Rev. Accel. Beams*, vol. 23, no. 12, p. 122003, Dec. 2020. doi:10.1103/PhysRevAccelBeams.23.122003
- [2] J. Giner Navarro *et al.*, "Conceptual RF design of 750 MHz IH cavities for $\beta=0.10-0.15$ ion beams in medical accelerators", *Nucl. Eng. Technol.*, Apr. 2024. doi:10.1016/j.net.2024.04.001
- [3] M. Koopmans *et al.*, "Preparations for beam commissioning of the carbon RFQ at CERN", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 5020-5023. doi:10.18429/JACoW-IPAC2023-THPM057
- [4] R. E. Shafer, "Beam position monitor sensitivity for Low-beta Beams", in *Proc. LINAC'94*, Tsukuba, Japan, Aug. 1994, paper TH-84, pp. 905-907. doi:10.1063/1.46975
- [5] M. Wendt, "A Brief Introduction to Beam Position Monitors for Charged Particle Accelerators", *IEEE Instrum. Measur. Mag.*, vol. 24, no. 9, pp. 21-32, 2021. doi:10.1109/MIM.2021.9620043
- [6] P. Forck *et al.*, "Beam position monitors", 2009. doi:10.5170/CERN-2009-005.187
- [7] R. E. Shafer, "Beam position monitoring", *AIP Conf. Proc.*, vol. 212, no. 1, p. 26, 1990. doi:10.1063/1.39710