BPM TIME OF FLIGHT MEASUREMENTS FOR SETTING-UP THE RF CAVITIES OF THE CERN LINAC4

M. Bozzolan†, CERN, 1211 Geneva 23, Switzerland

Abstract

The newly constructed H- LINAC4 at CERN has recently completed its first extended reliability run. It is equipped with Beam Position Monitors (BPMs) based on shorted-stripline pick-up electrodes to measure both position and Time of Flight (ToF). The ToF, in turn used to calculate the kinetic energy of the beam, is determined through signal phase shift measurements between pairs of BPMs. ToF measurements are performed by scanning of the phase of the RF injected into the cavities to find the nominal RF settings for optimal beam acceleration. This paper focuses on the technical aspects of the ToF measurement as well as on the results obtained during beam commissioning and their comparison with beam dynamics simulations.

INTRODUCTION

At the restart of the CERN accelerator complex in 2020, following a long shutdown (LS2), the CERN LINAC4 will be the first stage in the LHC injector chain for protons, replacing the ageing LINAC2. It is a normal conducting 80 m long H- LINAC which will supply beam pulses up to 600 µs long with an initial peak current of 25 mA, later to be increased to 40 mA [1].

The nominal output energy of 160 MeV is reached after a sequence of RF cavities, which include a Radio Frequency Quadrupole (RFQ), 3 Drift Tube Linac Tanks (DTL), 7 Cell Coupled DTL modules (CCDTL) and 12 Pi-mode Structures (PIMS) operating at f_{RF}=352.2 MHz

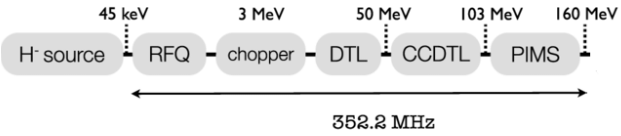

Figure 1: LINAC 4 accelerating structure – not to scale.

There are 15 BPMs installed inside the LINAC between the DTL (12 MeV) and the last PIMS module (see Fig. 1) and another 27 in the transfer line which connects LINAC4 with the PS booster [2].

Each BPM stripline electrode is directly connected to a 50—Ω cable, with lengths of the order of 100 m. These feeds the first analog stage of the acquisition system located in the instrumentation rack outside the tunnel, where the signals are amplified, downconverted to an intermediate frequency (IF) of 22.0125 MHz, filtered and digitized individually.

A ToF-based beam energy measurement is performed by measuring the time delay of the beam between two BPMs in a drift space (Fig. 2). As the distance between BPMs *L* is known the kinetic energy of the beam can be calculated by mean of the relativistic formulas

$$\beta = \frac{L}{TOF \cdot c}$$

$$E_{KIN} = \frac{m_0 \cdot c^2}{\sqrt{1-\beta^2}} - m_0 \cdot c^2$$

The electrode output signal, bandpass filtered at the LINAC bunching frequency f_{RF}, for the two BPM locations can be written as

$$y_{BPM1}(t) = A_1(t) * \sin(\omega_{RF} * t + \varphi_1)$$

$$y_{BPM2}(t) = A_2(t) * \sin(\omega_{RF} * t + \varphi_2)$$

Bunch shape, and therefore the amplitude modulation *A(t)* is not conserved, so a calculation of the time delay by cross correlation is not an option and only phase shift Δφ is used.

Since the phase wrap around every 360 °, we know only the fractional part **δ** of the ToF

$$TOF = NT + \delta = \frac{1}{f_{RF}}\left(N + \frac{\Delta\varphi}{360°}\right)$$

while the integer number *N* of RF periods (i.e. the number of bunches between the two BPMs) cannot be measured.

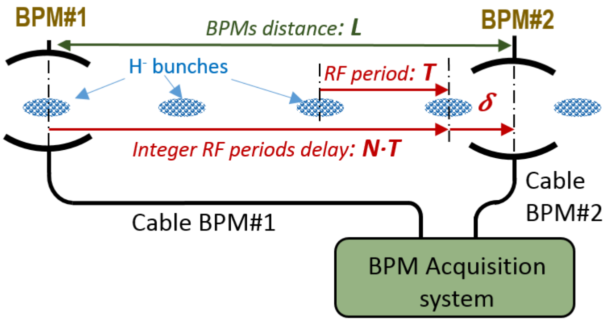

Figure 2: ToF principle.

PHASE MEASUREMENT & CALIBRATION

The sampling clocks at 4 times the IF frequency are phase locked to the linac RF, so that amplitude and phase of the signals can be recovered as

$$A = \sqrt{I^2 + Q^2}$$

$$\varphi = arctg\left(\frac{Q}{I}\right)$$

where I and Q are two consecutive samples.

For an operational system a precise phase (and amplitude for position measurement) calibration is needed

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† michele.bozzolan@cern.ch

in order to distinguish the different contributions of cable and acquisition electronic.

In the LINAC4 BPM system this is performed by injecting a short, 352.2 MHz pulse into the cable coming from the electrode. Half the power of that signal (direct pulse) appears at the analog input, the other half travels down the cable, where it is fully reflected at the shorted end of the stripline electrode, and travels back to the electronics (reflected pulse) (Fig. 3).

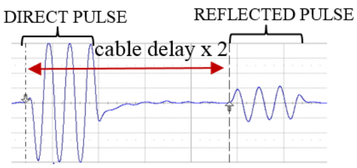

Figure 3: Calibration signals.

Since the calibration signal carries the reference phase for all the BPMs, it is distributed in such a way that it arrives at all the input channels with the same phase. Active components have been avoided in the calibration path because of the amplitude and phase shifts that occur due to temperature variation and aging.

TIME OF FLIGHT CALCULATION

The phase delay α between two BPMs is measured as the difference in phase of the signal from a given electrode (e.g. upper BPM electrode: H+)

$$\alpha = \Delta\varphi_{H+} = \varphi_{H+(BPM2)} - \varphi_{H+(BPM1)}$$

The measured delay has three contributions, the first is due to the beam, what we are looking for, the second is related to the cable delay difference and the third is related to the acquisition delay difference

$$\alpha = \Delta\varphi_{BEAM} + \Delta\varphi_{CABLES} + \Delta\varphi_{ELEC}$$

Since the calibration pulses are phase synchronous for all the channels, the phase shift due to the acquisition electronics is

$$\Delta\varphi_{ELEC} = \varphi_{DIRECT\_PULSE(BPM2)} - \varphi_{DIRECT\_PULSE(BPM1)}$$

Here no multiple integer parts of RF period are present because all the paths are virtually identical, with differences much less than one RF period.

The cable contribution $\Delta\varphi_{CABLES}$ is calculated from the individual phase shift of the cables

$$\Delta\varphi_{CABLES} = \varphi_{CABLE(BPM2)} - \varphi_{CABLE(BPM1)}$$

However what we actually measure for each BPM is

$$2 * \varphi_{CABLE} = \varphi_{DIR,MEAS} - \varphi_{REFL,MEAS} + M * 360° + 180°$$

where the 180° contribution is due to the shorted end of the BPM and *M* is an integer number of RF periods.

The Time of Flight can be written as

$$TOF = \frac{1}{f_{RF}} \cdot \frac{\Delta\varphi_{BEAM} + K * 180°}{360°}$$

with K=2N+M an integer number.

The periodicity becomes half an RF period as for the cable phase shift, since we can only measure the round trip of the signal.

K needs to be known in order to calculate the ToF and depends on the distance of the BPMs and the relativistic β of the beam. Putting an upper limit on the BPM distance ensures the value of *K* remains constant throughout the RF phase scan of the cavity, and it's value is known from simulations or from previous measurements. If this is not the case, the ToF is ambiguous as two or more values are possible.

However, reducing the distance between BPMs limits the precision, since a given error in the measured phase translates in a larger energy error for more closely spaced BPMs.

BEAM MEASUREMENTS

For the ToF we always have to ensure that there is no acceleration occurring between the involved BPMs. Therefore, in LINAC4, the cavities downstream of the first BPM used are switched off and detuned.

Moreover, the choice of BPMs that can be used for the RF scan of the cavities often have a distance that results in multiple possible values of K.

To overcome this it is possible to use two or more BPM pairs, calculate the energy as a function of K and then select the energy value that provides the smallest variance for all the pairs used. This method works well at the end of the LINAC4, for the scan of the last PIMS cavities where the absolute energy can be directly found with this method.

Figure 4 shows a graphical explanation of the method for a single energy using two BPMs pairs. The different calculated energy values as a function of K are plotted for each pair, with an energy of 160 MeV fittings precisely a particular K for both pairs.

Unfortunately this method does not work well for lower beam energies, providing inconsistent results. While the actual reason is not yet fully understood, a possible explanation is related to beam losses, which results in charged particles hitting the BPM electrodes and then altering the measurements. More beam studies are foreseen during the next run of the LINAC4 to improve the ToF algorithm for lower energies.

For the ToF measurement early in the linac at low β (DTLs and CCDTLs), a different approach is used to overcome the limitations encountered before.

Instead of individually correlating pairs of BPMs at a given phase, only the first BPMs pair after the scanned cavity is used and multiple values of K are considered.

Figure 5 shows a RF phase scan of CCDTL1 with only one BPMs pair. To extract the correct beam energy, the measurement is compared with a simulated RF phase scan (Fig. 6).

Even though this method does not provide a direct measurement of the beam energy for a single RF phase setting, it allows the exact behaviour of the cavities to be recovered through a complete phase scan.

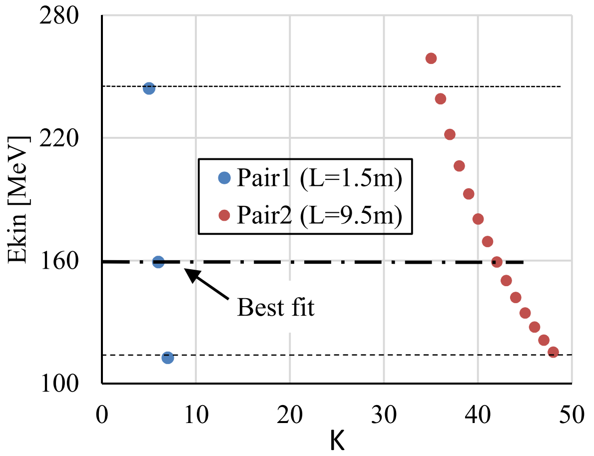

Figure 4: Single energy ToF measurement using 2 BPM pairs.
K=8 and 42 for PAIRS 1 and 2 give the same energy.

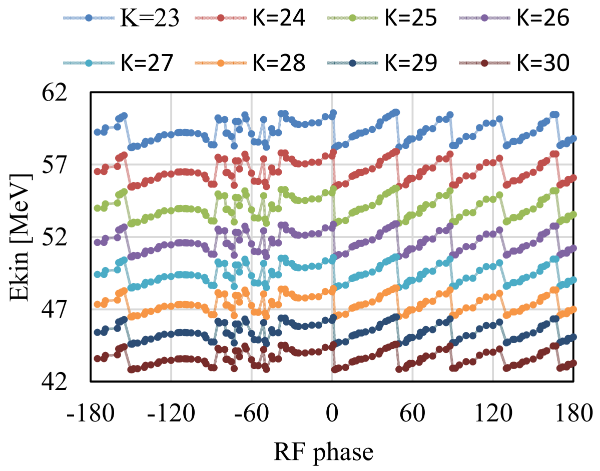

Figure 5: CCDTL1 phase scan: single BPM pair with different K values.

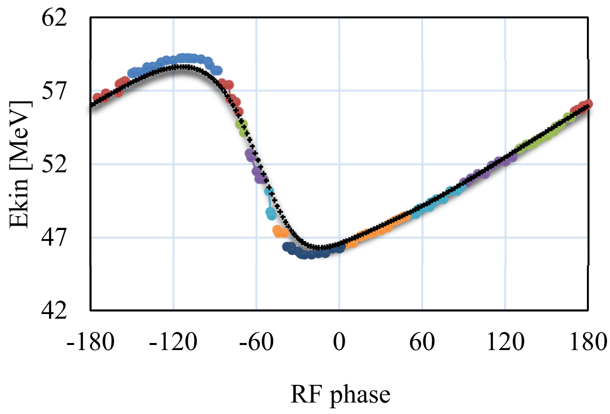

Figure 6: CCDTL1 RF phase scan cleaned after fitting. Simulated data as black crosses.

This procedure is still an expert task since the output beam energy depends not only on the RF phase but also on it's amplitude and on the energy of the beam entering the cavity.

The beam dynamics simulations provided so far show, for most part, a very good agreement with the measurements. Performing different phase scans for different amplitudes of the RF power has also been used as a crosscheck to validate the results.

CONCLUSIONS

The time of flight method for beam energy measurement in LINAC4 is now an operational tool for the RF phase adjustment of the cavities. While the high energy measurements are fairly simple, measurements for the DTL cavities, operating at low kinetic energy is still an expert task. The ToF algorithm is therefore being further refined, possibly to include changing the settings of the focusing elements during the RF phase scan, to provide a more automated measurement.

ACKNOWLEDGEMENTS

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