SIMULATION OF BUNCH LENGTH AND VELOCITY DEPENDENCE OF BUTTON BPMS FOR LINACS USING CST PARTICLE STUDIO®

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Abstract

At non-relativistic velocities at a proton LINAC, the electromagnetic field generated by the beam has a significant longitudinal component, and thus the time evolution of the signal coupled to the BPM electrodes depends on bunch length and beam velocity. Extensive simulations with the electromagnetic simulation tool CST Studio® were executed to investigate the dependence of the induced BPM signal on different bunch lengths and velocities. Related to the application, the simulations are executed for the button BPM arrangement as foreseen for the FAIR Proton LINAC. These investigations provide the required inputs for the BPM system and its related technical layout such as analogue bandwidth and signal processing electronics. For the BPM electronics, it is important to estimate the contribution of the harmonic used for the data processing. Additionally, the analogue bandwidth of the BPM system is determined from studying the output signal of the button BPM as a function of bunch length at different beam velocities. This contribution presents the results of the simulations and comments on general findings relevant for a BPM layout and the operation of a hadron LINAC.

INTRODUCTION

The electromagnetic fields generated by a beam and thus the time evolution of the signal coupled out by a pickup depend on beam velocity. In the limit of relativistic velocities, the generated beam fields are pure transverse electric and magnetic known as Transverse Electric and Magnetic (TEM) mode. A TEM mode has an electric and magnetic field vector perpendicular to the propagation direction. Thus, the electric field is longitudinally concentrated above and below the beam [1]. For moderate beam velocities $\beta > 0.9$ the resulting field can be also approximated to first order by TEM field distribution and the image current mirrors the same time behavior as the beam is traveling. At low beam velocities $\beta < 0.5$, the electromagnetic field is no longer a TEM wave [2]. In this regime the power coupled out by the pickup is much lower than the power carried by the beam due to the reduction in the coupling of high-frequency Fourier components.

On the other hand, it is important to keep in mind that the accurate determination of the bunch length is not trivial. The reason is the presence of the advanced Coulomb-field of the moving bunches, in particular for low $\beta < 0.5$ range [3]. The geometric length of the bunch Δz along the $z-$axis depends on the particle velocity β which can be calculated from [3]

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$$\Delta z = \beta c \Delta t_b \qquad (1)$$

where $\Delta t_b = 2\sigma_b$. The reason is that the derivative of a Gaussian Function has the maximum and the minimum exactly at $\pm\sigma$.

CST STUDIO® SIMULATIONS

The simulations have been carried out using the CST Particle Studio Wakefield solver [4] to study bunch length and velocity dependence of button BPMs for LINACs. The Wakefield solver is the most appropriate for studying the BPM response and the simulations are driven by a bunch of charged particles in the time domain. A 3D model of a BPM of four button pickups has been created in the CST Particle Studio® as shown in Figs. 1.

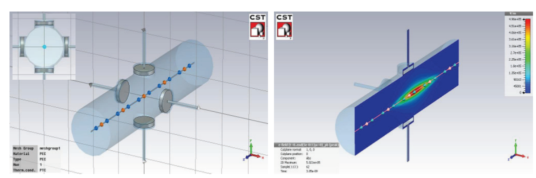

Figure 1: Left: A 3D model of the pick-up monitor as simulated in CST Particle Studio®. Right: The absolute value of the electric field of a bunch of $\sigma = 100$ ps long and $\beta = 0.37$

The wakefield has been simulated up to a 150 *mm* length along the beam coordinate. The excitation source is defined by a Gaussian-shaped longitudinal charge distribution with beam bunch charge of 1 nC in the z direction. The pickup response, expressed as the output signal in time and frequency domains, is obtained for each simulation run reflecting the pickup's interaction with the beam. The output voltages convergence versus mesh size has been investigated prior to utilizing the results. The convergence has been examined at three beam velocity $\beta = 0.08$, 0.27 and 0.37 with a bunch length chosen to be 150 ps. Figs. 2 demonstrates the results of the Wakefield solver at different mesh settings. The results show a solid convergence of the output signals and frequency spectrums in the interesting frequency range for $\beta = 0.08$, 0.27 and 0.37. A visible difference is only observed in the frequency spectrum for $\beta = 0.08$ with the mesh setting of 150000.

SIMULATIONS AND RESULTS

The CST simulations have been carried out to investigate the bunch length characteristics for the interesting dynamic range in proton LINAC which assumed to be between 50 to

ISBN 978-3-95450-177-9

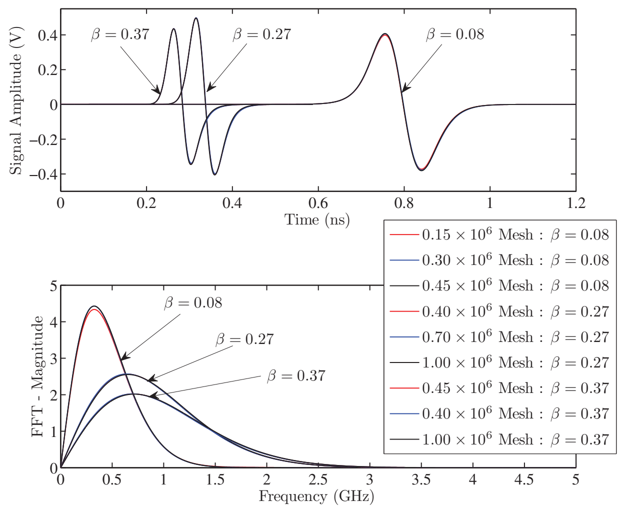

Figure 2: BPM output voltage from a single port in time (up) and frequency (down) domains versus mesh size. The beam parameter are $\beta = 0.08$, 0.27 and 0.37, $\sigma = 150$ ps, 1 nC bunch charge.

700 ps [5,6] . The length of the signal produced by the pickup Δt_s is compared with bunch length $\Delta t_b = 2\sigma_b$ at different beam velocities $\beta = 0.08$, 0.27 and 0.37, correspond to $E =$ 3 MeV, 30 MeV and 70 MeV, respectively. A centered beam is used in the simulations and the bunch length is varied. A button pickup of 14 mm diameter was used and beam pipe is chosen to be 30 mm. The span of simulated bunch length starts from $\sigma_b = 30$ up to 960 ps. The first set of results are shown in Figs. 3, 4 and 5 illustrating the pickup signals in the time domain (left) and the corresponding Fourier transformation in the frequency domain (right) as a function of the bunch length σ_b.

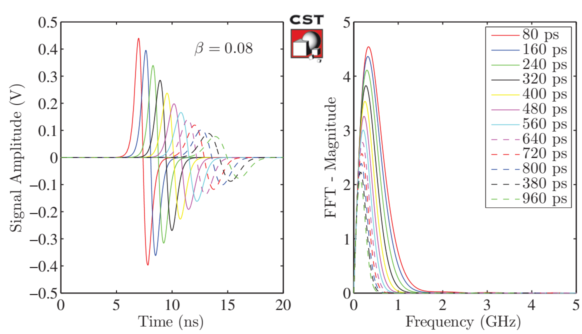

Figure 3: The legend shows the bunch length σ_b and the plotted signals represent output voltage from a single port in time (left) and frequency (right) domains for $\beta = 0.08$.

One can observe the response of the pickup signal σ_s to the change in bunch length. For low β beam the amplitude of the output signal is lower and the signal is longer. The reason is that the electric field components are less perpendicular to the beam direction as for higher values of β as discussed in [2] for a moving charge. Fig. 6 shows the change in

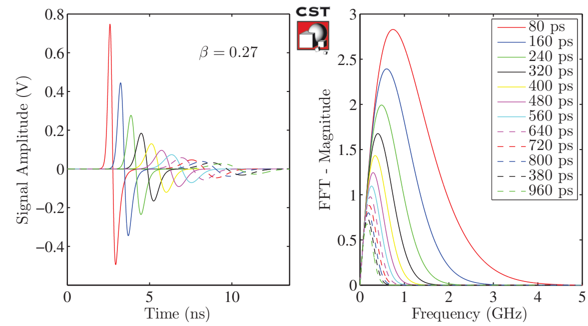

Figure 4: The legend shows the bunch length σ_b and the plotted signals represent output voltage from a single port in time (left) and frequency (right) domains for $\beta = 0.27$.

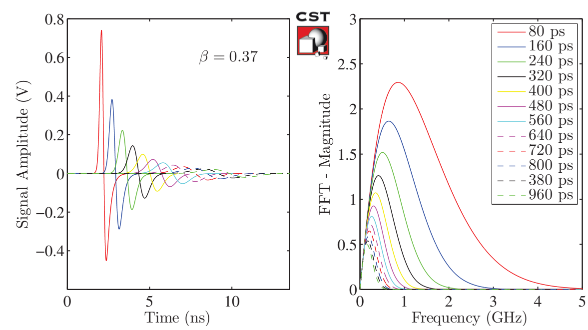

Figure 5: The legend shows the bunch length σ_b and the plotted signals represent output voltage from a single port in time (left) and frequency (right) domains for $\beta = 0.37$.

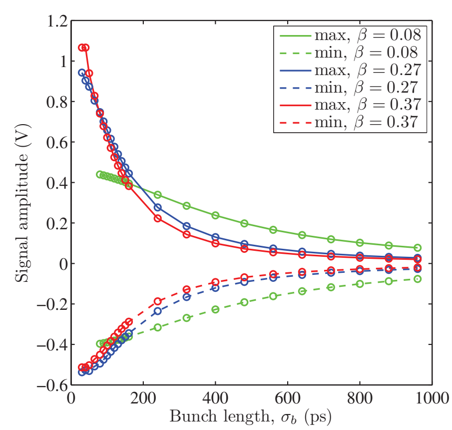

Figure 6: The change in the maximum and the minimum values of the pickup signal versus bunch length σ_b.

the signal maximum and the signal minimum values for different β values as a function of bunch length σ_b, which summarizes the output signal behaviour in Figs. 3, 4 and 5. One can notice that the maximum of the pickup signals decreases as a function of the bunch length as expected from some theoretical models [1]. For short bunches ($\sigma_b <$ 300 ps) and higher beam velocities ($\beta = 0.27$ and 0.37) the maximum and minimum (in the negative side) values of the pickup signal decrease much faster than for the low

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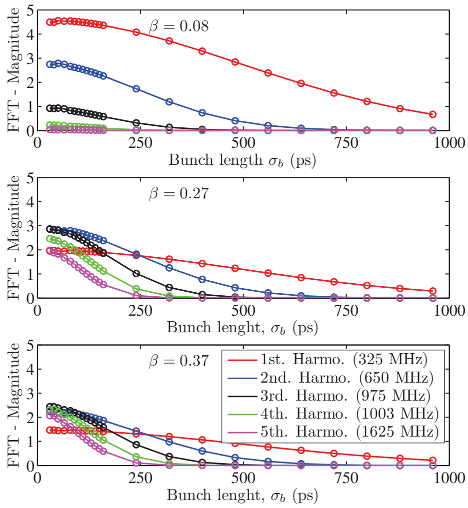

Figure 7: The Fourier components of the pickup signals at five harmonics of the bunching frequency versus bunch length.

β value (β = 0.08). For longer bunches (σ_b > 600 ps) the proportional decrease in the maximum and minimum values is still valid but the change is not significant. The signal amplitudes expressed in the Fourier components as a function of bunch length is depicted in Fig. 7 for five harmonics. The first observation is that for a short bunch lengths of σ_b < 200 ps the pickup signal contains a high amplitude value of higher harmonics of the beam-bunching frequency in comparison to the longer bunches. For $\beta = 0.08$, it is noticeable that the first harmonic is always dominant. The major contribution in the spectrum comes from the first two harmonics while the contribution is very weak for higher harmonics, especially for bunches longer than σ_b > 150 ps. As the beam becomes faster and the bunch is short σ_b < 200 ps the frequency spectrum is shifted so that the contribution of the 1st harmonics is smaller than the followings harmonics (2nd, 3rd and 4th harmonics). Based on Fig. 7, the 1st and the 2nd harmonics are present always in the spectrums with sufficient strength and both can be used for the data signal processing. However, the signal information should be obtained from the 2nd harmonic harmonic in order to suppress the rf-leakage contribution from the nearby CH-cavity to the BPM intertank.

A depictive aspect in this investigation is shown in Fig. 8. The bunch length Δt_b is characterized by relating bunch length with the time difference between the maximum and the minimum values of the pickup signal Δt_s. It shows a linear proportional relationship between the pickup signal and bunch length. This proportionality goes to a certain limit depending on β value. Below that limit there is no more change in the output signal length Δt_s so that the pickup signal remains constant as the bunch length further decreases. Knowing these limits and the proportionality range for each β value are useful for estimating bunch length from the output signal shape. For example, for β = 0.27 the pickup signal of length σ_s = 526 ps leads to a bunch length of σ_b = 480 ps. The linear limit was calculated for each β case by applying a linear fit on the curve from σ_b = 560 ps for both β = 0.27 and 0.37 and σ_b = 720 for β = 0.08. The slope of the curves a_1 are 0.89, 95 and 0.96 for β = 0,08, 0.27 and 0.37, respectively.

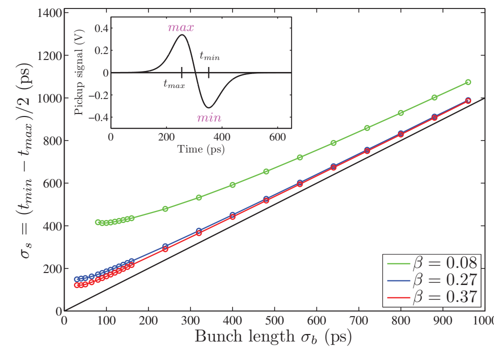

Figure 8: The relationship between the bunch length σ_b and the length of the pickup signal σ_s extracted from the time difference between the minimum and the maximum values of the pickup signal.

CONCLUSION

The CST simulations were executed to investigate the dependence of the induced BPM signal on different bunch lengths and beam velocities. These investigations provide useful inputs for the BPM system and its related technical layout. For the technical layout of the electronics, the signal amplitudes expressed in the Fourier components showed that the 2nd harmonic used for the signal processing is present always in the spectrums with sufficient strength. The bunch length shows a linear proportional relationship with the output pickup signal. This proportionality goes down to a certain limit depending on β value. These limits and the proportionality constants for each β value are useful for estimating bunch length from the output signal shape and to design the processing analogue electronics for the BPM system.

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ISBN 978-3-95450-177-9