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BENCHTOP BPM CALIBRATION USING HELICAL PULSE LINES FOR NON-RELATIVISTIC BEAMS*

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Abstract

Calibration of capacitively-coupled beam position monitors (BPMs) for use in non-relativistic beam lines has proven to be challenging. This is due to the fields generated by the beam being non-transverse causing the measured signals to depend on the measured frequency and the beam velocity [1]. In order to correct for these effects, calibration of BPMs may be done with an apparatus that is capable of simulating the fields generated by non-relativistic beams for several beam velocities. One possible method of simulating these beams is to use a helical pulse line. This paper studies the ability of helical lines to simulate the fields generated by slow beams for BPM calibration.

INTRODUCTION

Capacitative beam position monitors (BPMs) are commonly used to measure the orbit of relativistic beams in particle accelerators. They can also be used in non-relativistic beamlines, however, the measured positions from the BPMs become dependent on the beam velocity and measurement frequency [1, 2]. These effects are due to the electromagnetic fields generated by the beam no longer being pancaked by relativistic effects. For an off axis beam, this results in a difference in the extents of the fields along the pipe which cause the BPM pickups on opposite sides to measure a different frequency spectrum. This effect needs to be carefully calibrated in order to achieve accurate measurements.

Typical calibration of BPMs is performed using a straight wire strung through the BPM. Signals are sent down the wire that create electromagnetic fields that mimic the fields generated from a beam. The wire is moved along a grid of positions in the pipe and at each location the position of the wire is calculated from the BPM signals using a difference-over-sum formula. By comparing the calculated wire positions to the actual positions, non-linear effects and abnormalities in the measured positions can be determined.

However, signals on a straight wire propagate at the speed of light, therefore straight wires cannot be used to calibrate BPMs that will be used to measure non-relativistic beams. Currently, BPMs for non-relativistic beamlines are calibrated primarily with simulations to determine non-linear effects as well as frequency and velocity dependence of the measurements. Benchtop, straight wire calibrations are also performed to determine the effects of any physical abnormalities of each BPM [3].

To ensure proper calibration of BPMs for use in non-relativistic beamlines, the signals sent through the BPM should travel at the expected beam velocity to properly simulate the fields on the pick-ups.

Helical Wire Phase Velocity

One method to propagate signals at low velocities is to send pulses down a helical wire. Helical lines in free space have been shown to propagate signals at any phase velocity less than the speed of light by choosing the correct parameters for the helix [4].

A singal propagating down a helical line can be modelled using the sheath helix approximation. A sheath helix is constructed by winding a thin wire in a helix. A second thin wire is then wound directly above the first and this process

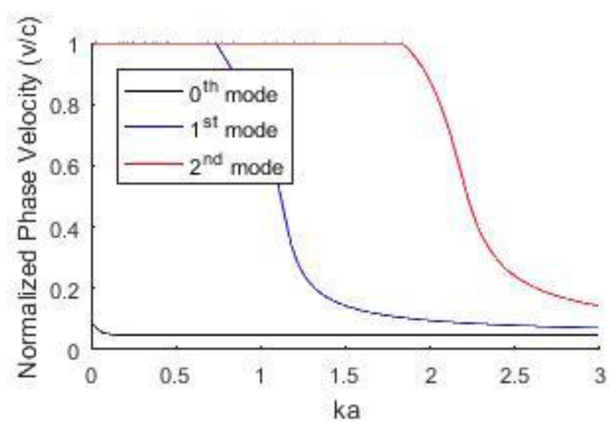

Figure 1: Normalized phase velocity of the first three modes of a sheath helix, pitch angle is 0.048 rad and R/a=4. K is the free space propagation constant and a is the helix radius.

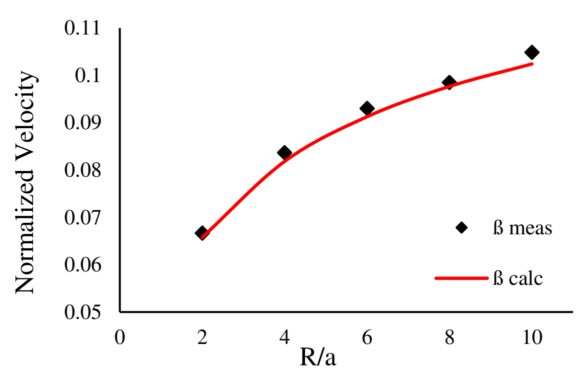

Figure 2: Velocity comparison for different ratios of pipe radii, R, to helix radius, a. Sheath helix phase velocity of 0^{th} mode in red and results of simulations in black.

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is repeated until the entire gap in the helix is filled. Taking the limit of the wire radii going to zero, the result is a cylinder or sheath where the surface current travels along a helical path. This model is used to simplify the boundary conditions at the helix by removing azimuthal and longitudinal variations.

Using the sheath helix model the phase velocity can calculated for a helix with pitch angle, φ, and radius, a, inside a pipe of radius, R (figure 1). The high frequency limit of the phase velocity for all modes is $v/c=\sin(\varphi)$. The low frequency limit of the phase velocity for all modes except for the lowest order mode is the speed of the light. For the lowest order mode, the pipe causes the low frequency phase velocity to level off below the speed of light. For small enough pitch angles the phase velocity plateaus at approximately $v/c=\sin(\varphi)\ln(R/a)$. If pipe is removed from the calculation then the low frequency limit of the phase velocity of the lowest mode goes to the speed of light, the same as the other modes, and the high frequency limit does not change. The behaviour of the higher modes remains the same in this case. Without the pipe it would be necessary to go propagate signals above ka=1, which can correspond to tens gigahertz. The reduction of the phase velocity of the lowest mode at low frequencies caused by the pipe allows for helices to be used to reproduce beam signals.

HELIX SIGNALS

In order for helical lines to be used for BPM calibration they must be able to propagate signals of a desired shape at a specific velocity to be consistent with a bunch. The properties of the signals propagated on a helical line in a pipe were simulated using CST Suite® [5] and compared to the sheath helix model where applicable. The apparatus consisted of a 400 mm long helix in a 410 mm long pipe with inner diameter of 40 mm. The extra 5 mm of pipe on each side was used to transition the helix to a straight wire before the end caps. The ends of the pipe are blocked by plates that touched the pipe with a 50 Ω line for inputting and outputting signals. The end plates are not attached to the pipe to allow for the pipe to be moved to simulate different beam positions (Figure 3). The electromagnetic fields were measured using field probes at the inside surface of the pipe allowing for the fields that would be detected by a BPM to be measured. Currently, there is not a BPM in the simulation to simplify the model and reduce simulation time.

Pulse Velocity

The velocity of 1ns Gaussian pulses on the helical line was measured from the simulations and compared to the sheath helix approximation for several different pitch angles and pipe radii (figure 2). For all parameters used, the velocity of the primary pulse differed less than 2.5% from the low velocity limit of the lowest order pulse.

Pulse Shape

When a Gaussian pulse was propagated through the helical line, the signal separated into several lobes (Figure 4). Each consecutive lobe travels at a slightly slower velocity causing the lobes to spread apart as the signal propagates. The farther the signal propagates the amplitude of each lobe grows.

This effect may be explained by the pulse exciting multiple modes of the helix, however, the sheath helix model predicts that the n^{th} mode can only be excited by frequencies above approximately ka=n or f=nc/a where a is the helix radius and c is the speed of light. For the simulated 5mm radius helix, the first excited mode requires a frequency above 60 GHz. This is a much higher frequency than any of the simulated input signals contained. Another issue is the higher modes are capable of propagating with velocity from $c\cdot\sin(\varphi)$ to c. Because of this large range of velocities, a faster propagating lobe would be expected to exist. The absence of this behaviour makes higher mode excitation seem unlikely.

Another explanation is the formation of the lobes is caused by the input signal exciting the lowest order mode at a range of frequencies. This interpretation narrows the necessary frequency range to a range expected given the input signal. However, this explanation fails to explain the formation of discrete lobes because the Gaussian input pulse has no local peaks in the frequency spectrum to correlate with the phase velocity of the individual lobes.

Both these explanations fail to adequately explain the formation of the lobes, however, they agree that the lobes form due to higher signal content. This was found to be true. When Gaussian pulses of different widths were input into the same helix, the shorter pulses caused the lobes to form faster than the longer pulses. In fact, almost no deformation of the signal is seen if the initial pulse is broad enough (see Fig. 4).

Signal deformation is also impacted by the pitch angle of the helix. A helix with a smaller pitch angle will cause the amplitude of lobes to grow faster which results in more

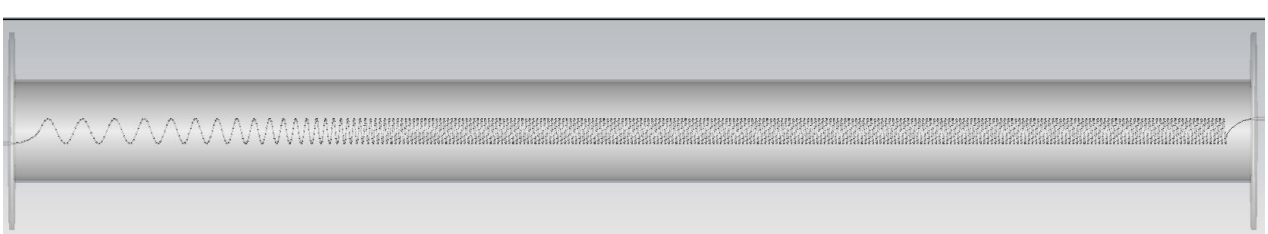

Figure 3: Model of helix in a pipe. The left side of the helix has a decreasing pitch angle for impedance matching and to improve signal shape.

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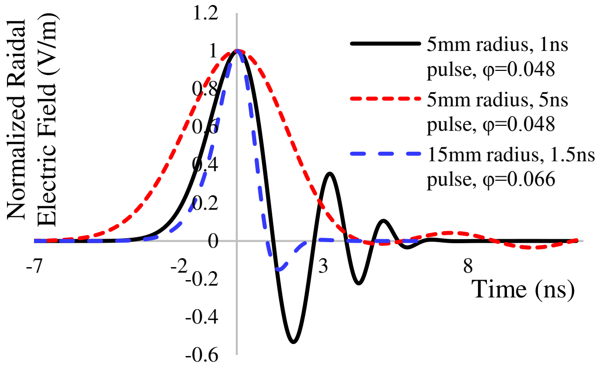

Figure 4: Example of lobe formation in a helix after Gaussian signal propagating 150mm. Increasing the pulse length decreases the signal deformation as well as increasing the helix radius and the pitch angle, φ.

lobes forming than a looser helix for the same input pulse. Therefore, the signal deformation can be reduced by increasing the pitch angle of the helix. However, this also causes the phase velocity to increase, but that can be compensated by increasing the radius of the helix to lower the R/a ratio.

The lobe formation can also be reduced by creating a section of helix with decreasing pitch angle. In these sections the input signal is compressed in length by the decreasing distance between the turns of the wire. If the signal is being compressed faster than the lobes are spreading apart due to differing phase velocities then the lobes cannot split from the original pulse. However, as soon as the pitch becomes constant the lobes diverge from the primary pulse. Therefore, if the BPM being calibrated is placed just passed the reducing pitch angle section of the helix it is possible to measure a pulse with minimal deformation that is traveling at the appropriate velocity. Another possibility is to decrease the pitch angle across the entire helix then the BPM can be moved to the region with the desired phase velocity.

These methods of reducing the formation of lobes have been found empirical and while they reduce the signal deformation they cannot completely remove it, nor do they address the root cause of the deformation. Because the signal deformation appears to be caused by the geometry of the helix, it is likely that the deformation cannot be completely removed. Therefore, it is recommended that the BPM is placed as close to the start of the line or end of the pitch reduction section to minimize the formation of the lobes.

IMPEDANCE MATCHING

To properly calibrate BPMs for non-relativistic beamlines, several frequencies should be tested because of the frequency dependence of the measurements. Therefore, to use the helical line for benchtop BPM calibration, the impedance of the input and output must be matched to the helical line across a range of frequencies.

Direct calculation of the impedance from the sheath helix model has proven to be insufficient, most likely due to the difference in the fields near the helix. Calculating the impedance at the input and output ports is further confounded because the wire must deform from the helix near the end cap in order to exit at the 50Ω line.

While a direct calculation of the impedance would be useful for exactly matching the impedance at a specific frequency it is less useful for broadband matching because the impedance may change greatly over a range of frequency. Instead geometric means can be used to help impedance matching. The decreasing pitch angle section described above not only compresses the signal it also slowly changes the impedance of the line. Therefore, by slowing decreasing the pitch angle from π/2, a straight wire, at the helix to the desired angle, the impedance is changed from that of a coax line to the impedance of the desired helix line. Matching the input to the helix then becomes a matter of matching two coax lines, a much simpler problem. Simulations show this can increase in the amplitude of the propagated signal by a factor of eight, without attempting to optimize the decrease in the pitch angle. Similarly, the output matching can be improved by increasing the pitch angle from the desired helix to π/2.

However, reducing reflections in this matter is best down by slowly decreasing the pitch of the helix. But, in order to maintain pulse shape, the pitch angle must be quickly decreased to stop the lobes from spreading apart. Therefore, when using this method a trade-off must be made between signal shape and impedance matching.

CONCLUSION

While helical lines show promise for use in benchtop BPM calibration. They are capable of propagating pulses are any desired velocity less than the speed of light by changing the parameters of the helix. Therefore the same device can be used for calibrating for different beam velocities simply by changing the helix. Also, signal deformation can be almost completely removed by increasing the pitch angle and propagating a longer pulse.

However, there are still some issues to be worked out. Most importantly, the impedance matching needs to be improved and the signal deformations need to be reduced for tighter helices and shorter pulses. However, varying the pitch of the helix is a major step in alleviating both these problems.

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