BEAM PHASE DETECTORS FOR SPALLATION NEUTRON SOURCE LINAC

S.S. Kurennoy, LANL, MS H824, Los Alamos, NM 87545, USA

Abstract

An ability to measure the beam phase accurately – within a fraction of a degree – is a requirement to the Spallation Neutron Source (SNS) linac diagnostics. Electromagnetic simulations and measurements have demonstrated a strong dependence of the measured beam phase on the transverse beam position inside a probe, when signals are picked up from individual electrodes. Two candidates for the beam phase detectors for the SNS linac – capacitive probes and beam positions monitors, either with signals from individual electrodes or with summed signals – are studied and compared using MAFIA simulations with an ultra-relativistic beam.

1 INTRODUCTION

One possible option for the beam phase detectors is to use capacitive probes, as was proposed, e.g., for the APT/LEDA diagnostics [1]. The advantages of the capacitive probes include their simple design, short length on the beam pipe, convenient calibration, and simple signal processing. However, an essential dependence of the phase on the beam transverse position inside the probe was found: the phase difference between an on-axis beam and that half-aperture displaced from the chamber axis can be as large as a few degrees [1,2].

Beam position monitors (BPMs) in a linac can deliver information about the beam phase as well as about the beam transverse position. The advantage of using BPMs is that no additional devices on the beam line are required for phase measurements. The SNS linac BPMs have been discussed in [3]; here we will look only at their application for the beam phase measurements.

To compare these two options for the phase monitors, we have performed electromagnetic simulations with the MAFIA code package [4]. Time-domain 3-D simulations with an SNS bunch passing through the corresponding beam-line device at a varying offset from the axis are used to compute the induced voltages on the electrodes as functions of time, see [3] for details. After that an FFT procedure extracts the amplitudes and phases of the signal harmonics at individual outputs, as well as the amplitude and phase of the combined (summed) signal, versus the beam transverse position. We concentrate primarily on the first and second harmonics of the SNS bunch repetition frequency f_b=402.5 MHz as the most appropriate ones for the beam position and beam phase diagnostics.

2 CAPACITIVE PROBES

A capacitive probe consists of a ring inside a shallow cavity on a beam pipe. Its simplified MAFIA model is presented in Fig. 1. The probe ring (dark) has two 50-Ω coaxial connectors at the diametrically opposite locations (not shown). For this particular case, the probe dimensions correspond to the beam pipe radius of 15 mm: the ring length along the beam is about 5 mm, and the total cavity length is 12.5 mm. The ring is recessed 0.5 mm inside the cavity, so that its inner radius is 15.5 mm. The connectors are modeled by discrete elements, 50-Ω resistors.

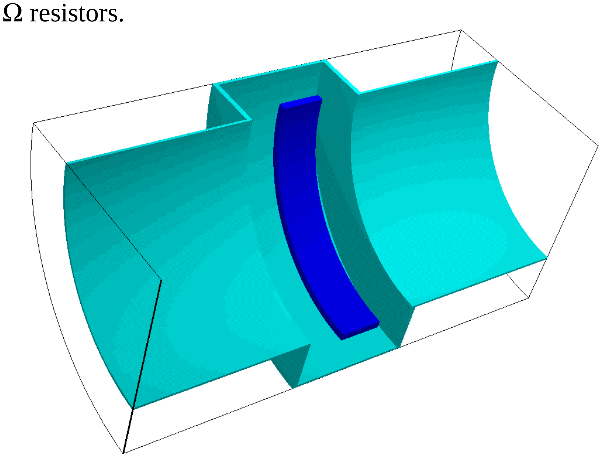

Figure 1: Capacitive probe model (one-quarter cut).

In MAFIA 3D time-domain simulations, we use a bunch with the total charge Q=0.14 nC having a Gaussian longitudinal charge distribution with the rms length σ=5 mm, which corresponds to the 56-mA current in the baseline SNS regime with 2-MW beam power at 60 Hz. Unfortunately, the time-domain code T3 in MAFIA at present cannot simulate the open or waveguide boundary conditions on the beam pipe ends for non-ultra relativistic (β<1) beams, so we work with an ultra relativistic (β=1) case. The bunch passes the structure at or parallel to the axis. For each beam displacement, the phases of the voltage Fourier transforms, as well as the amplitude and phase of the summed signal, have been calculated. Figure 2 shows the signal voltages induced on the probe electrodes by the bunch passing through the device with the transverse offset $x=r_b/2$, $y=r_b/4$; it should be compared with similar Fig. 2a of ref. [3] for the BPMs.

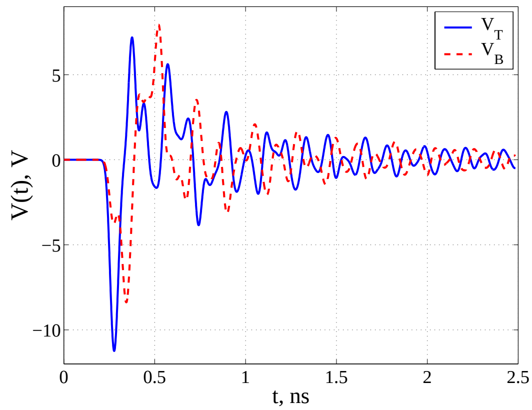

Figure 2: Signal voltages on capacitive probe electrodes from a passing transversely displaced ($x=r_b/2$, $y=r_b/4$) bunch versus time.

The phases of the voltage harmonics on two connectors, as well as the phases of the summed signal harmonics, at 402.5 MHz and 805 MHz are listed in Table 1 for a few different beam offsets. Since here we are mostly interested in the phase difference between the signals from an on-axis and off-axis beams, only the phase difference between the signals from an off-axis and on-axis beams is given by subtracting the beam phases of the centered beam, -138.99° at 402.5 MHz and 167.30° at 805 MHz.

Table 1: Phases of signal harmonics on probe electrodes

Position		**402. 5 MHz**		**805 MHz**	
x/r	**y/r**	ϕ_T ϕ_B, °	ϕ_Σ, °	ϕ_T ϕ_B, °	ϕ_Σ, °
0	0.25	2.81 -2.45	0.18	3.71 -3.68	0.03
.25	0.25	2.26 -2.43	-0.08	4.60 -3.62	0.07
0.5	0.25	1.16 -2.33	-0.57	3.34 -3.49	-0.04
0	.375	4.13 -3.36	0.37	5.15 -5.09	0.04
0	0.5	6.30 -4.60	0.80	7.17 -7.03	0.07
0.5	0.5	2.32 -4.34	-0.95	6.43 -6.53	0.07

The MAFIA computations for the capacitive probes have been performed on a relatively crude mesh with a step d=0.5 mm in all three dimensions. One can roughly estimate the accuracy of calculated phases as corresponding to the time interval $\Delta t=d/2/c$=0.83 ps, where c is the speed of light, which leads to ±0.12° for 402.5 MHz and twice that at 805 MHz. Clearly, the phases of the summed signal harmonic at 402.5 MHz in Table 1 are outside of this interval for all cases when the beam offset is larger than ¼ of the pipe radius at least in one plane. They also differ by almost 2 degrees for the two last rows, in spite of the same vertical beam displacement. One the other hand, the phases of the summed signal at the second harmonic, 805 MHz, are amazingly close to each other for all beam offsets. It is worthwhile to notice also that the amplitudes of the summed signal harmonics for the considered capacitive probes are 4-5 times lower than for the BPMs in Sect. 3.

3 BPM AS PHASE MONITORS

For the normal-conducting part of the SNS linac we have chosen a 4-electrode BPM design having stripline electrodes with one end shorted. The BPM design and electromagnetic modeling have been discussed in [3]; its MAFIA model is shown in Fig. 3. The electrodes are flush with the beam pipe, shorted at one end, and have 50-Ω connectors on the other end. The beam pipe radius in this model is r_b=20 mm, the electrode length along the beam is 40 mm, and the electrode subtended angle is 60°.

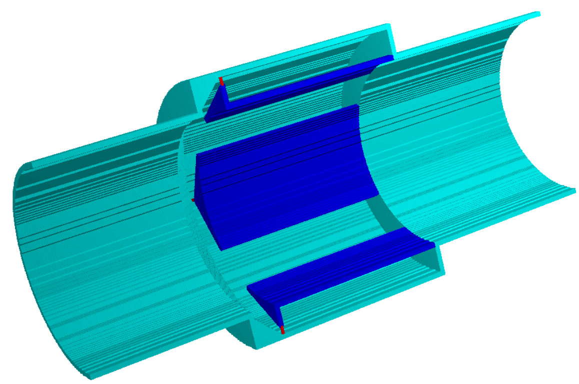

Figure 3: BPM model (1/2-cutout) with cone-tapered box end and electrodes (dark) with ridges near connectors.

For the BPMs we perform the same type of 3D time-domain computations with the MAFIA T3 code as for the capacitive probes, driving an ultra relativistic Gaussian bunch with the total charge Q=0.14 nC and the rms length σ=5 mm through the structure on- or off-axis. An example of the signal voltages induced on the electrodes by an off-axis bunch passing through the BPM is shown in Figs. 2 of ref. [3]. Tables 2-3 present some results for signal phases versus the beam position for the first two harmonics. Again, as well as in Table 1, the phases of an on-axis beam (-170.09° at 402.5 MHz and 114.80° at 805 MHz) are subtracted from the values in the tables. The MAFIA mesh for the BPMs had the same mesh step as for the capacitive probes, d=0.5 mm in all three dimensions, that resulted in about 3 millions mesh points. Therefore, the estimated accuracy of the calculated phases is expected to be the same, i.e. ±0.12° for 402.5 MHz and ±0.25° at 805 MHz. The signal phases on individual electrodes differ by a few degrees, while the phases of the summed signals are equal, within this accuracy interval, for all beam displacements. The only exception is possibly the case of a rather strong offset $x=r_b/2$, $y=r_b/2$ at 805 MHz. However, even in this case the deviation is only about 0.6°, which could be just as well a numerical effect, and it is very small compared to the phase difference for the individual electrodes that spans about 17° in this case.

Table 2: Phases of 402.5-MHz signals on BPM electrodes

x/r	y/r	ϕ_R ϕ_L ϕ_T ϕ_B, °	ϕ_Σ, °
0.25	0	0.94 -0.39 -1.25 -0.39	-0.04
0.25	0.125	0.89 0.14 -1.34 -0.98	-0.04
0.25	0.25	0.71 0.64 -1.66 -1.63	-0.04
0.5	0	1.68 -1.67 -2.85 -1.67	-0.03
0.5	0.125	1.65 -1.00 -2.97 -2.39	-0.03
0.5	0.25	1.57 -0.35 -3.35 -3.18	-0.03
0.5	0.375	1.39 0.30 -4.06 -4.09	-0.02
0.5	0.5	1.02 0.95 -5.23 -5.18	0.00

Table 3: Phases of 805-MHz signals on BPM electrodes

x/r	y/r	ϕ_R ϕ_L ϕ_T ϕ_B, °	ϕ_Σ, °
0.25	0	1.90 -0.62 -3.01 -0.62	-0.08
0.25	0.125	1.86 0.61 -3.22 -2.09	-0.06
0.25	0.25	1.73 1.61 -3.90 -3.85	-0.04
0.5	0	2.96 -2.73 -7.57 -2.73	-0.18
0.5	0.125	2.99 -0.86 -7.85 -4.99	-0.13
0.5	0.25	3.06 0.76 -8.77 -7.52	0.01
0.5	0.375	3.19 2.13 -10.55 -10.37	0.26
0.5	0.5	3.36 3.23 -13.72 -13.60	0.59

The behavior of the signal phases versus the beam vertical deflection is shown in Fig. 4 for a fixed horizontal beam position. As one can see, the signal phases on both horizontal electrodes behave similarly, but the phase changes on the vertical electrodes have opposite signs as the beam vertical position changes. At the same time, the phase of the summed signal remains equal to that of the on-axis beam, well within the computational errors (the error bars are shown only for the summed signal).

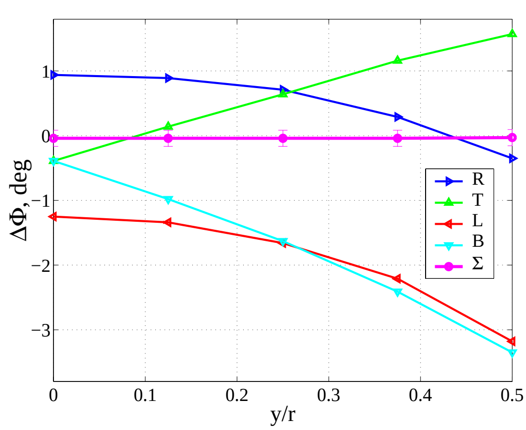

Figure 4: 402.5-MHz signal phases on BPM electrodes and for summed signal versus beam vertical displacement y/r_b, for the beam horizontal offset x/r_b=1/4.

Since we have modeled numerically the β=1 case, the beam fields reach the individual electrodes simultaneously independent of the beam transverse position. For example, in Fig. 2a of [3] the two peaks of $V(t)$ – from the bunch passing the gap and then its reflection at the short, – are aligned for all electrodes. However, the stronger signals from the electrodes that are closer to the beam, produce, via the reactive electrode coupling, large voltage peaks at the furthest from the beam electrodes at later moments, see Fig. 2a of ref. [3]. This leads to the observed signal phase differences on individual electrodes. A simple equivalent-circuit model explaining this effect was suggested in [5]. Obviously, a similar mechanism can produce the phase difference in the capacitive probes.

4 SUMMARY

Electromagnetic MAFIA simulations of the SNS linac BPMs and capacitive probes have been performed. The signal amplitudes and phases on the pickup electrodes are computed as functions of the beam transverse position.

The simulation results show that for both types of the phase monitors – the BPMs or the capacitive probes – summing the signals from all connectors is required to measure the beam phase accurately. For an off-axis beam, the signal phases from individual electrodes can differ from those for a centered beam by a few degrees, see Tables 1-3. On the other hand, the phase of a summed signal is significantly less sensitive to the beam transverse position inside the device. For the BPM it remains the same within the computation errors (0.1-0.2°), even for the beam offsets as large as the pipe half-aperture. In the capacitive probe, the phase deviations from the centered beam phase grow as the beam offset increases, approaching 1 degree difference for large (half-aperture) offsets at the frequency 402.5 MHz. Surprisingly, at 805 MHz no phase difference between off-axis and on-axis beams has been observed for the summed signal, within the calculation errors, for the capacitive probe. However, the signal processing at 805 MHz is difficult in the coupled-cavity linac (CCL) because of a strong interference from the 805-MHz RF. On the other hand, it could be a good option for phase detectors between the tanks of the drift-tube linac (DTL), where the RF frequency is 402.5 MHz. Based on the results of this analysis, we have chosen the BPMs with summed signals from all electrodes as the beam phase detectors for the CCL in the SNS linac.

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