Abstract

Electromagnetic modeling of the beam position monitors (BPMs) for the Spallation Neutron Source (SNS) linac has been performed with MAFIA. The signal amplitudes and phases on the BPM electrodes are computed as functions of the beam transverse position using time-domain 3-D simulations with an ultra-relativistic beam. An analytical model is then applied to extrapolate the results to lower beam velocities. Based on the analysis results, an optimal BPM design with 4 one-end-shorted 60-degree electrodes has been chosen. It provides a very good linearity and sufficient signal power for both position and phase measurements, while satisfying the linac geometrical constrains and mechanical requirements.

1 INTRODUCTION

Beam position monitors (BPMs) in the SNS linac will deliver information about both the transverse position of the beam and the beam phase. Typical values for the beam position accuracy are on the order of 0.1 mm within 1/3 of the bore radius $r_b$ from the axis ($r_b$ is between 1 cm and 2 cm for the normal conducting part of the linac). The SNS linac BPMs will also serve as beam phase detectors, see [1] for details. The BPMs have a high signal processing frequency, equal to the microbunch repetition frequency in the linac, $f_b=402.5$ MHz (or one of its lowest harmonics). A rather limited length along the beam line is available for BPM transducers, as usually in ion linacs, especially at low beam energies. This imposes certain restrictions on the linac BPM design.

To study options for the transducers of the SNS linac BPMs, we use the EM code MAFIA [2]. Electrostatic 2-D computations are used to adjust the BPM cross-section parameters to have 50-$\Omega$ transmission lines. Then 3-D static and time-domain computations are applied to calculate the electrode coupling. Time-domain 3-D simulations with an SNS beam microbunch passing through the BPM at a varying offset from the axis are used to compute the induced voltages on the electrodes as functions of time. 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.
electrodes with a given potential on an active one. A similar procedure is used to adjust the BPM cross section for the electrodes to form 50-Ω transmission lines. In the dynamical 3-D problem, a 402.5-MHz sine-voltage with the amplitude increasing to some level is fed into a connector of an active electrode, and induced voltages on the passive ones are calculated. In both cases, the coupling coefficients are defined as ratios of the potentials or voltage amplitudes: \( k_{12}=A_2/A_1 \) for two adjacent electrodes, and \( k_{13}=A_1/A_1 \) for two opposite ones. Inserting the separators – the metal ridges connected to the BPM box and filling the gap between the adjacent electrodes – reduces the static coupling approximately by factor of two. With the separators, the coupling of 60° electrodes is reduced to about that of 45° electrodes.

Direct 3-D time-domain computations with an ultra relativistic (\( \beta=1 \)) bunch passing the structure at the axis or parallel to the axis have been performed for a few layouts of the BPM transducers. A Gaussian longitudinal charge distribution of the bunch with the total charge \( Q=0.14 \) nC and the rms length \( \sigma=5 \) mm, corresponding to the 56-mA current in the baseline SNS regime with 2-MW beam power at 60 Hz, was used in the simulations. The MAFIA time-domain code T3 at present cannot simulate the open (or waveguide) boundary conditions on the beam pipe ends for non-ultra relativistic (\( \beta<1 \)) beams. In Sect. 3, the ultra relativistic MAFIA results are used to fix parameters of an analytical model of the BPM at \( \beta=1 \), and then to derive results for \( \beta<1 \) analytically. Table 1 summarizes some results for a few types of the BPM electrodes with 60° subtended angle and length 40 mm: the dynamic couplings \( k_{12} \) (\( k_{13}=1/k_{12} \)), the maximal signal voltages \( V(t) \) on the electrodes, and the amplitude of the voltage 1st Fourier harmonic (402.5 MHz) from an on-axis beam.

Table 1: Comparison of electrode types

<table>
<thead>
<tr>
<th>Electrode</th>
<th>( k_{12} )</th>
<th>( V_{m}(t), V )</th>
<th>( \hat{A}_1, V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>0.036</td>
<td>12.5</td>
<td>0.189</td>
</tr>
<tr>
<td>Tapered end</td>
<td>0.036</td>
<td>13.9</td>
<td>0.245</td>
</tr>
<tr>
<td>Tapered + cone box end</td>
<td>0.037</td>
<td>14.0</td>
<td>0.244</td>
</tr>
<tr>
<td>Same + separators</td>
<td>0.017</td>
<td>11.5</td>
<td>0.161</td>
</tr>
<tr>
<td>Ridged end + cone box</td>
<td>0.051</td>
<td>18.0</td>
<td>0.255</td>
</tr>
</tbody>
</table>

One can see that the separators reduce the electrode coupling but at the same time the signal power decreases. Having 50-Ω connectors on both ends of the electrode also reduces the dynamical coupling, while the signal power is about the same as in the one-end-shorted design. However, such a design is more complicated and more expensive, as well as less reliable mechanically, compared to the one-end-shorted version.

To study the BPM linearity, we perform simulations with the beam bunch passing through the BPM at different transverse positions. Figure 2 shows the voltages on all four electrodes for the case of a beam displaced from the chamber axis, and their Fourier transforms, for the BPM design with ridged electrode end (Fig. 1, and the last line in Tab. 1). Indices \( R,T,L,B \) here refer to the right, top, left and bottom electrodes. The Fourier spectra of the signals have first peaks near 2 GHz, that approximately corresponds to the wavelength \( \lambda/4=l \). For this BPM design, at high beam energies the signal power at 402.5 MHz changes between +4.6 dBm and −12.3 dBm as the beam position moves within a rather wide range, \( \{x,y\} \in (-r_y/2,r_y/2) \), i.e. the signal dynamical range is 16.9 dB.

The BPM linearity results are presented in Fig. 3. MAFIA data for the horizontal signal log ratio \( \ln(A_R/A_L)/2 \) or the difference-over-sum \( (A_R-A_L)/(A_R+A_L) \) for different vertical beam positions overlap, so that it is difficult to distinguish between the five interpolating lines. One can conclude that the BPM design with 60° ridged electrodes (Fig. 1) is insensitive to the beam position in the direction orthogonal to the measured one, and has a good linearity. The BPM position sensitivity is equal to \( 20 \log_{10}(A_R/A_L)/x \) \( \equiv 1.4 \) dB/mm. As for other BPM designs considered, we have found that the linearity of BPMs with separators is much worse, in spite of the lower coupling.
The best fit to the numerical data was obtained on the electrode, compared to a circular pipe segment since more electric field lines from a passing bunch ends up on the electrode, compared to a circular pipe segment of the same radius and angular extent. We use Eqs. (1) to describe the effective values of the voltages on the electrodes, \( (E_{\text{ge}}/E_{\text{fa}}/E_{\text{gb}}/E_{\text{fb}}) \) are \((0,0)\) for \( R/L \), with our results strongly suggest very small coupling between the BPM electrodes. This seems to contradict the dynamical coupling coefficients in Table 1. One should note, however, that Eq. (2) does not take into account that the inter-electrode coupling is mostly reactive, and \( k_s \) in (2) should be complex, mostly imaginary.

Matching the amplitude of 402.5-MHz harmonics from an on-axis ultra relativistic SNS beam bunch with Eqs. (1) fixes the constant \( C=1.232 \text{ V} \). The 402.5-MHz signal amplitudes for the displaced beams in Table 2 are then reproduced by the model with the accuracy of 1-2%. Assuming that these effective parameters of the model are applicable at lower beam velocities, we extrapolate \( \beta=1 \) to \( \beta<1 \). The signal power level for the on-axis beam is reduced by about 9 dB at \( \beta=0.073 \) (2.5 MeV). For the strongest signal in the beam displacement range \((-\Delta r/2, \Delta r/2)\) both vertically and horizontally, this reduction is 4.4 dB, and for the weakest one it is 12.9 dB. As a result, the dynamical range of the 402.5-MHz signal increases from about 17 dB for \( \beta=1 \) to about 25 dB at \( \beta=0.073 \), if the same radius of BPM is assumed. Of course, at the low-energy end the bore and BPM radii are smaller, which increases the power level.

4 SUMMARY

Electromagnetic MAFIA modeling of the SNS linac BPMs has been performed. The signal amplitudes and phases on the BPM electrodes are computed as functions of the beam transverse position. Based on the analysis results, an optimal BPM design with 4 one-end-shorted 60-degree electrodes has been chosen. It provides a good linearity and sufficient signal power for both position and phase measurements, while satisfying the geometrical and mechanical requirements. Using the BPMs for accurate beam phase measurements is discussed in [1].

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REFERENCES