Cold BPM for the LCLS-II Project

Abstract

A high sensitivity button BPM is under development for a linac section of the LCLS-II project. Since the LCLS-II linac will operate with bunch charge as low as 10 pC, we analyze various options for pickup button and feedthrough in order to maximize the BPM output signal at low charge regime. As a result, the conceptual BPM design is proposed including an analytical estimation of the BPM performance as well as numerical simulation with CST Particle Studio and ANSYS HFSS. Both numerical methods show a good agreement of BPM output signals for various design parameters. Finally, we describe the signal processing scheme and the electronics we are going to use.

INTRODUCTION

Achieving a low beam emittance is one of key factors for reliable operation of the LCLS-II project [1]. In order to preserve a low emittance during beam transportation through the superconducting linac, Beam Position Monitors (BPM) will be installed in every cryomodule with a quadrupole. These BPMs will be used to monitor the beam orbit and provide transverse beam position data for beam steering.

Table 1: Electron Beam Parameters of the LCLS-II Linac.

<table>
<thead>
<tr>
<th>Operation Mode</th>
<th>Beam Energy</th>
<th>bunch charge</th>
<th>Bunch length, rms</th>
<th>Emittance (at 100 pC, normalized)</th>
<th>Bunch rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW</td>
<td>4 GeV</td>
<td>10^-3</td>
<td>0.6-55 μm</td>
<td>0.3 μm</td>
<td>&lt;0.93 MHz</td>
</tr>
</tbody>
</table>

Specific requirements of the cold BPMs:

- The space inside the cryomodule for installation is limited to ~180 mm length and ~200 mm transverse size (with feedthrough).
- The beam pipe aperture is circular, having 78 mm diameter.
- The beam pipe has to operate under ultra-high vacuum (UHV) conditions, and in a cryogenic environment at a temperature of ~2-10 K.
- A cleanroom class 100 certification is required to prevent pollution of the nearby SC cavities.

The LCLS-II linac can operate in a variety of regimes with parameters of electron beam shown in Table 1. A single bunch (bunch-by-bunch) resolution of < 100 μm at 10 pC is required to preserve the low emittance by applying dispersion-free orbit correction methods during single short operation. Based on the above requirements the choice of BPM is limited mostly to beam orbit monitoring with button BPM due to its compactness, simple mechanical design and reliability.

The design of the cold XFEL BPM with large 20 mm diameter buttons was chosen as a prototype pickup for beam diagnostic in the LCLS-II cryomodule [2]. According to the baseline scheme of a signal processing the front-end electronic will downmix the button signal in the pass band around 1 GHz comparing to 1.5 GHz = 2.3 GHz frequency band used for the XFEL cold BPM. Despite the simplicity of a processing scheme at low frequencies there are pro and contra arguments of working around 1 GHz instead of 2 GHz:

- a) the pickup will produce fewer signals
- b) the RF bandwidth filters and pickup cables will have smaller losses
- c) signal of L-band signal can leak into the BPM.

While items a) and b) may compensate each other depending on the actual pickup output parameters, prevention of effect c) requires that the upper bandwidth should be reduced significantly below 1 GHz. This compromise usable signal level and, thus, the position noise. Because the exact relation of position noise versus bandwidth remains to be determined we don’t limit ourselves with a design of low frequency button pickup only and propose the optimal geometry of a button and feedthrough assembly for 2 GHz also as a backup option.

BPM Readout Electronics

The high performance signal processing scheme used by XFEL is a backup option depending on actual configuration of connecting cables and electronics frontend.

Development of a Button BPM for the LCLS-II Project

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Abstract

Relativistic charged particles moving inside a hollow metal beam pipe is followed by a pancake like electromagnetic field with longitudinal extension of the bunch size itself. The field on the inner wall of a beam pipe is diffracted on the button gap and induces wakefield travelling in the beam pipe and rf signal radiating through pickup ports. For long or low beta bunches with limited frequency spectrum a simplistic analytical model can be used, while short relativistic require numerical simulations in order to obtain accurate BPM response at frequencies above 1 GHz.

Figure 3. Full (blue and red) and relative (green) power losses generated by the 300pC and 1MHz pps beam passing through the 020 mm button BPM.

The FFT transform of a time domain voltage signal u(t) preserves the Parserval identity with omega:

\[\|u(t)\|^2 = \|\hat{u}(\omega)\|^2\]

Figure 2. Time domain BPM output signals produced by 1pc bunch with different lengths.

Since the diameter of the output coaxial is small (~7÷8mm), the cutoff frequency of the second propagating mode in the coaxial is above 20 GHz which is higher than simulated bunch bandwidths. Hence, most of the power is radiated through coaxial line as the lowest TEM mode. Therefore one can define the instant power in coaxial as \(P_{\text{TEM}} = U^2 / R\), where \(U\) is an instantaneous voltage and \(R\) is the impedance of coaxial line. Integrating the instant power over the time we obtain the total energy radiated through the pickup port:

\[E_{\text{rad}} = \int_0^T P_{\text{TEM}}(t) dt\]

Figure 4. BPM output signals spectral density for various bunch lengths.

Feedthrough Optimization

New version of the C100 feedthrough for the 1.3 GHz cavity HOM coupler has been recently redesigned by JLAB in order to meet the LCLS-II parameters. The feedthrough assembly is shown in Figure 5. This feedthrough meets all UHV and cryogenic requirements and can be easily adapted to the cold button BPM design. Thus, we took it as a prototype for our simulations.

Figure 5. C100 feedthrough for the HOM coupler developed by JLAB.

Figure 6. CST models of various ceramic feedthroughs with attached 020 mm button used for BPM simulations.

Signal reflections introduced by the feedthrough ceramic window travel back and forth between the window and the button and, hence, creating a local standing wave. While it difficult to form such a resonance at low frequencies around 1 GHz, it looks feasible to do it at frequencies of 2 GHz. For verification we modified the C100 feedthrough and used ANSYS HFSS eigenmode solver for finding optimal feedthrough geometry. Figure 8 illustrates the final result of optimization, a low-Q resonance at 2 GHz frequency.

Figure 7. BPM signal spectral density for original (blue) and modified (red) ceramic feedthrough and for the ideal 50Ω line (green).

Based on results of BPM signal spectral densities simulation it is possible to estimate particular amounts of energy captured by the readout electronics in given frequency bandwidth. Integrated pulse energies at the pickup coaxial output are summarized in the Table 2 for 10 pc bunch charge.

Table 2: Pulse energy at the BPM output.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Energy (10 pC) (J/GHz/pC)</th>
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<tbody>
<tr>
<td>1 GHz</td>
<td>1e-18</td>
</tr>
<tr>
<td>2 GHz</td>
<td>1e-17</td>
</tr>
<tr>
<td>3 GHz</td>
<td>1e-15</td>
</tr>
</tbody>
</table>

REFERENCES