International Beam Instrumentation Conference
Monterey, California, USA September 14–18, 2014

DEVELOPMENT OF A BUTTON BPM FOR THE LCLS-II PROJECT*

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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

Operation Mode	CW
Beam Energy	4 GeV
Bunch charge	10 ÷ 300 pC
Bunch length, rms	0.6 ÷ 53 μm
Emittance (at 100 pC, normalized)	~ 0.3 μm
Bunch rate	< 0.93 MHz

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 BPM 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 pickups 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 frontend 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 bandpass filters and pickup cables will have smaller losses
c) signal of L-band linac may leak into the BPM.

While items a) and b) may compensate each other depending on the actual pickup cable parameters, prevention of effect c) requires that the upper bandwidth should be reduced significantly below 1.3 GHz. This might directly 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 standard BPM readout electronics for LCLS II will measure position, intensity, and phase using direct digital down-conversion scheme at ~ 1 GHz button signal. A simplified block diagram is shown in Figure 12. A 2D polynomial fit to the difference over sum in each plane will be used to correct position and intensity for nonlinearities in the button pickup shown here.

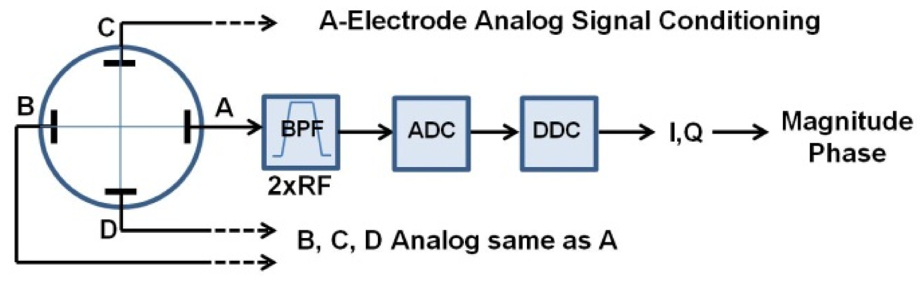


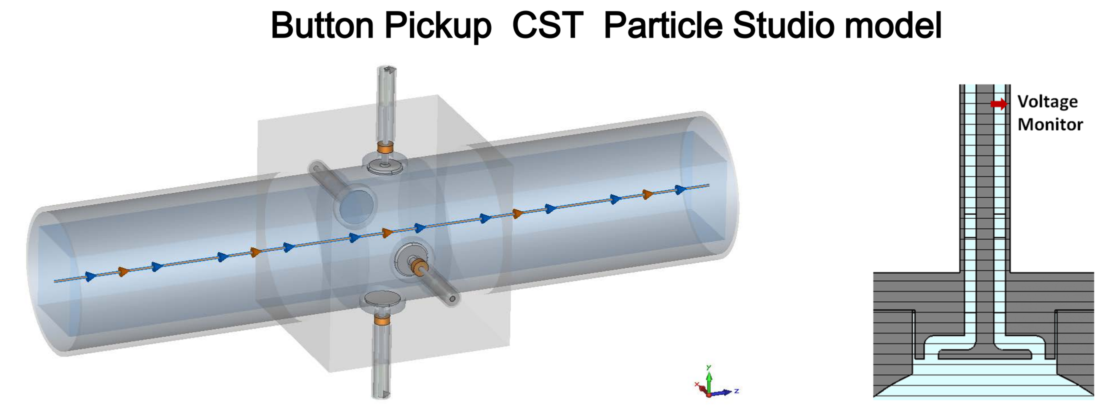
Figure 12. Block diagram for BPM electronics.

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

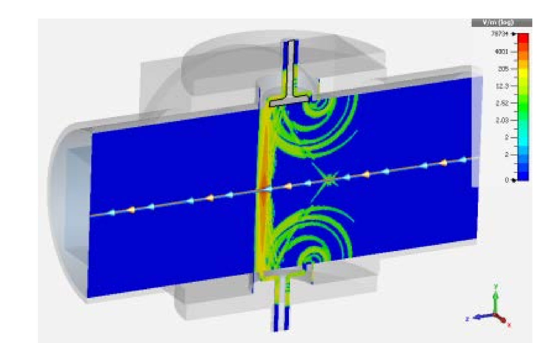
CST Particle Studio Simulation

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.

Button Pickup CST Particle Studio model



Instant Electric Field of induced by 1mm bunch



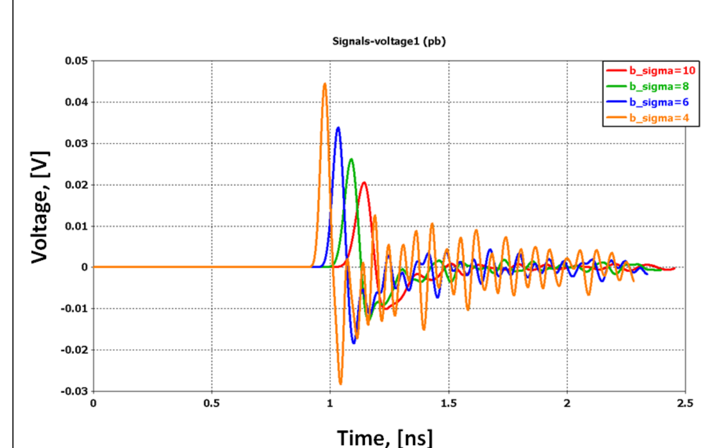


Figure 2. Time domain BPM output signals produced by 1pC bunch with different lengths.

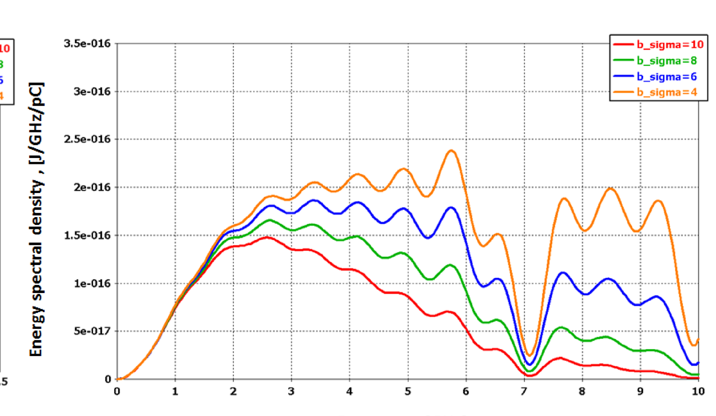


Figure 4. BPM output signals spectral density for various bunch lengths.

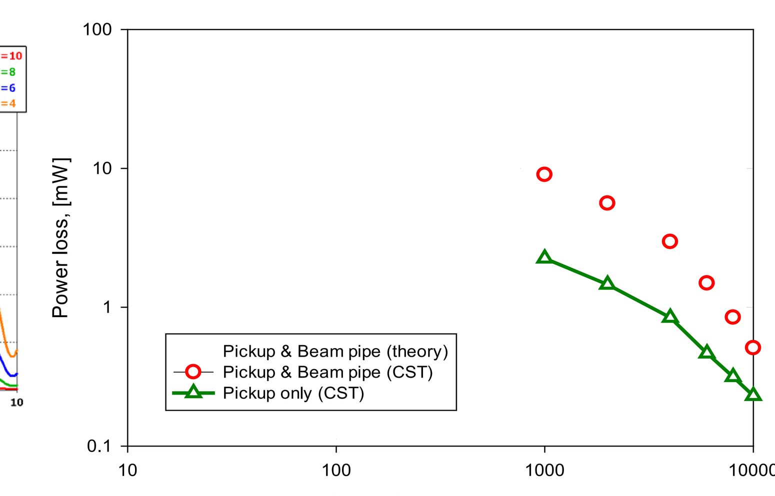


Figure 3. Full (blue and red) and relative (green) power losses generated by the 300pC and 1MHz pps beam passing through the Ø20 mm button BPM.

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 $P_{inst} = U^2/R$, where U is an instant 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:

$$E_{port} = \int_0^{t_{end}} P_{inst}(t)dt$$

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

$$\int_{-\infty}^{\infty} |u(t)|^2 dt = \int_{-\infty}^{\infty} |U(\omega)|^2 d\omega$$

Therefore applying the FFT transformation we can plot the signal energy spectrum density normalized to the total amount of energy radiated through the pickup port (see Figure 4). One can see that the energy spectral density at low frequencies (< 2 GHz) is weakly dependent on the bunch length. Therefore, we chose the bunch of 4 mm rms size for further analysis as a good compromise between accuracy and a simulation time.

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 to 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.

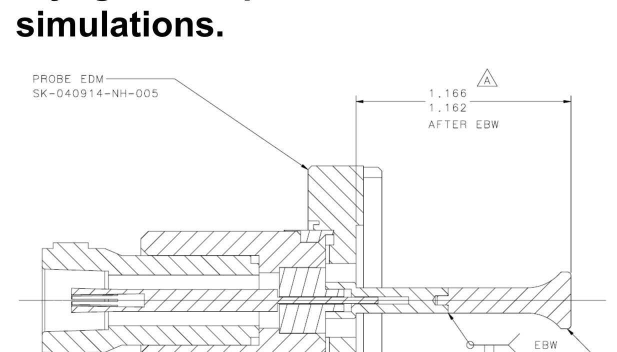


Figure 5. C100 feedthrough for the HOM coupler developed by JLAB

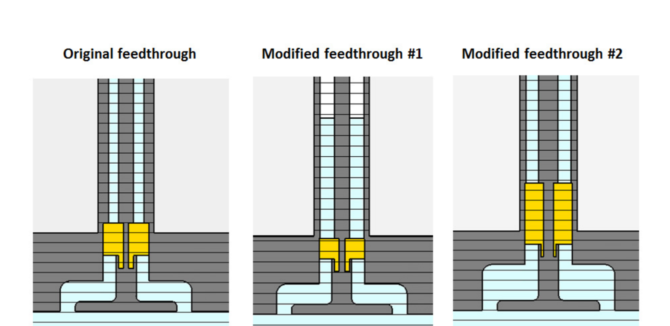


Figure 9. CST models of various ceramic feedthroughs with attached Ø20 mm button used for BPM simulations.

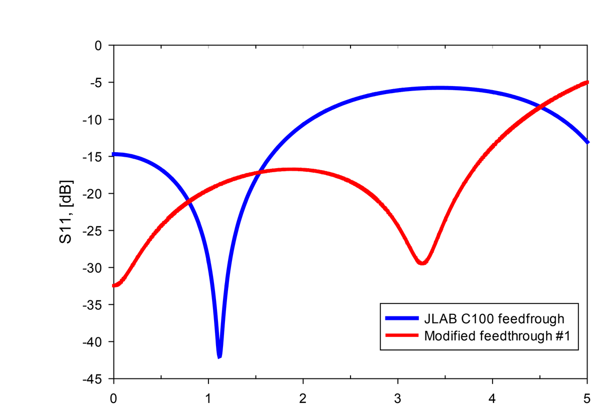


Figure 6. Reflection coefficients of original (red) and modified (blue) JLAB C100 feedthrough.

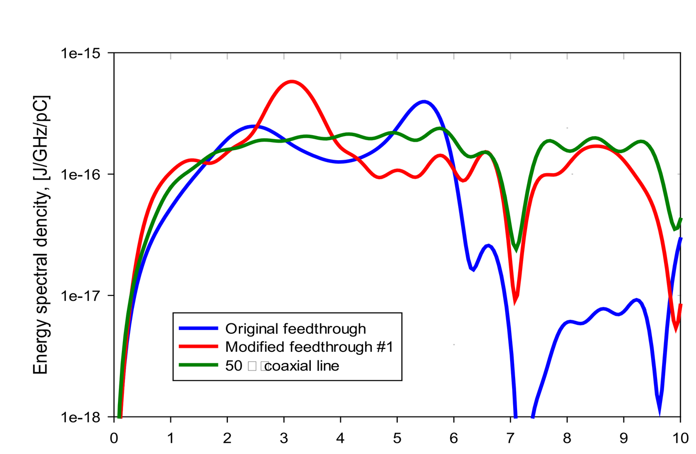


Figure 7. BPM signal spectral density for original (blue) and modified (red) ceramic feedthrough and for the ideal 50 Ω line (green).

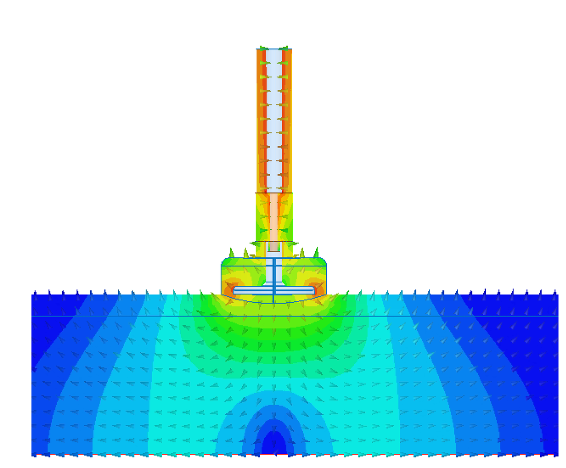


Figure 8. Low-Q resonance of button and modified feedthrough #2 at frequency of 2 GHz.

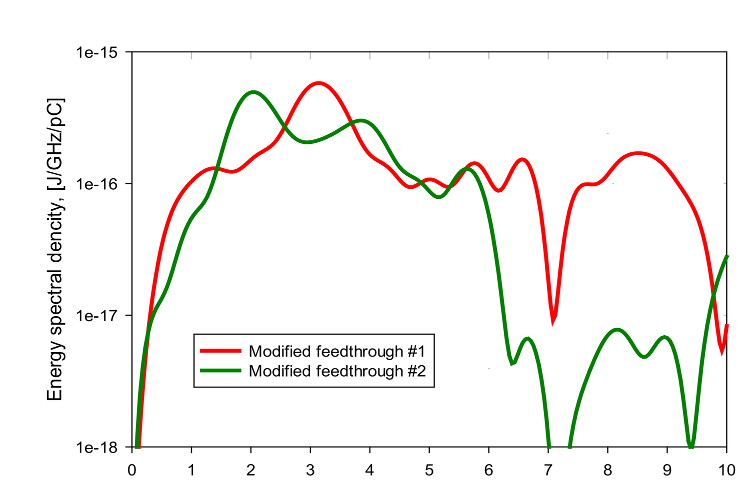


Figure 11. Signal spectral densities of the button BPM with modified feedthrough #1 and #2.

Table 2 Pulse energy for 10 pC bunch at pickup output

Feedthrough Type	Captured pulse energy, [fJ]	
	Frequency range 0÷1.3 GHz	Frequency range 1.5÷2.3 GHz
Original C100	4	13
Modified #1	8	12
Modified #2	4	35

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 frequency 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.

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.

Conclusion

A button-type BPM will be used in the LCLS II cryomodule. We presented two possible conceptual BPM designs based on the C100 HOM feedthrough developed at JLAB and optimized for signal processing at 1 GHz and 2 GHz passbands respectively. Further evaluation of BPM signal transmission and readout electronics performance is needed in order to meet the LCLS-II requirements for low charge single shot resolution.

REFERENCES

[1] LCLS-II Conceptual Design Report, SLAC Report, LCLSII-1.1-DR-0001-R0, 2014
[2] D. Lipka et al., "Button BPM Development for the European XFEL", MOPD19, DIPAC2011, Hamburg, Germany, 2011.

* Work supported by the U. S. Department of Energy, contract No. DE-AC02-07CH11359
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