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

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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 analyse 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. Since the "cold" BPMs are the only beam instruments inside the cryogenic sections of the linac, therefore a high reliability of the BPM systems is essential. Some of the specific requirements of the cold BPMs are listed below:

• 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. The BPM ability to perform at low charge regimes also allows for troubleshooting and diagnostics during the linac commissioning procedure, but can be guaranteed only nearby (± 1...2 mm) the electrical center of the BPM pickup.

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 large button cold BPM from the European XFEL is an existence proof of a design that has been successfully integrated into a cryomodule [2], which should be able to meet the resolution requirements here, but this has not been demonstrated at the low bunch charge expected and puts much more strenuous requirements on electronics processing scheme.

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

Thus, 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 [3]. 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 [4]. 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 [5]. 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.

GENERAL ASPECTS OF THE BUTTON TYPE PICKUP EM DESIGN

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 [6] can be used, while short relativistic require numerical

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simulations in order to obtain accurate BPM response at frequencies above 1 GHz.

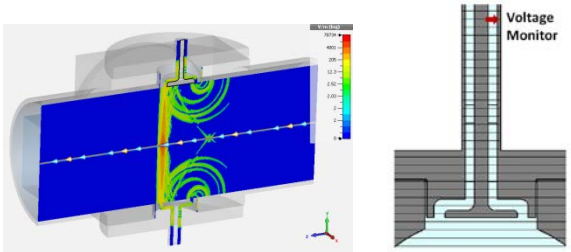

Figure 1: CST model of the button pickup (right) and a snapshot of the instant electric field induced by 1 mm bunch.

We chose the button size of 20 mm diameter with 3 mm gap similar to the cold XFEL BPM design. For numerical simulations we use the time domain CST wakefield solver [7]. The CST 3D model is illustrated in Figure 1 with a snapshot of the instant electric field induced by an interaction of the 1 mm bunch with a button pickup. In order to prevent signal reflections the model has multimode port boundary conditions at the ends of the beam pipe and coaxial lines. The BPM output signal is recorded with voltage monitor defined at the end of coaxial line.

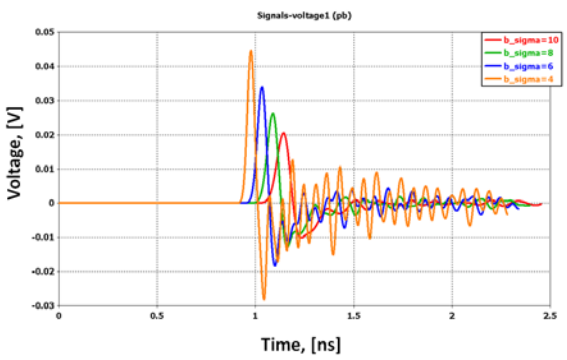

Figure 2: Time domain BPM output signals produced by 1pC bunch with different lengths.

Simulation a response of a short sub-millimeter bunches in time domain requires very dense mesh (> 100M cells) and, thus, results in a long calculation time. Therefore we started with simulation of the BPM response depending on the bunch length for the simple case where the button is loaded to the ideal 50 Ω coaxial line. The result is shown in Figure 2 as BPM output signal versus time. Since the diameter of the output coaxial is small (~ 7÷8 mm), 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:

$$E_{port} = \int_0^{t_{end}} P_{inst}(t)dt \qquad (1)$$

Based on Eq. 1 we calculated the amount of rf power radiated to all four coaxial port of the pickup depending on a bunch length and compared this value with the total power loss found by the wake loss factor simulation. The result for the maximum bunch charge of 300 pC and 1MHz repetition rate of the LCLS-II linac is illustrated in Figure 3. The dotted blue line corresponds to analytical approximation of the loss factor based on diffraction theory [8]. Only fraction of the total power lost by bunch is radiated to pickup ports. One can extrapolate that this fraction would be below 20÷25 % for the bunch size of tens microns.

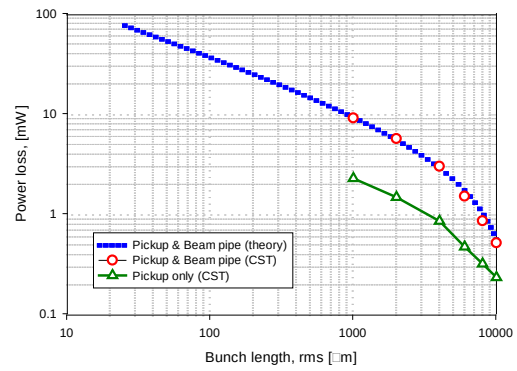

Figure 3: Full (blue and red) and relative (green) power losses generated by the 300 pC and 1MHz pps electron beam passing through the Ø20 mm button BPM.

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

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

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).

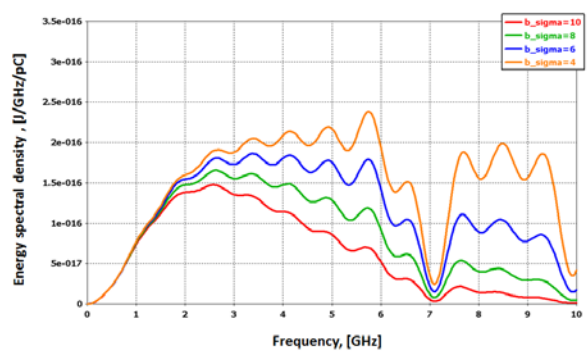

Figure 4: BPM output signals spectral density for various bunch lengths.

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.

PICKUP RF 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 [9]. 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.

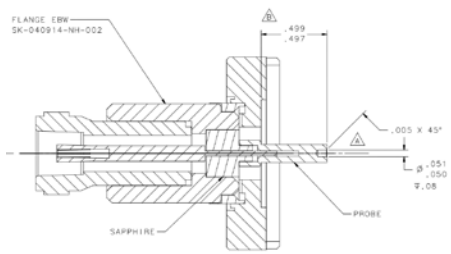

Figure 5: C100 feedthrough for the HOM coupler developed by JLAB

At first, we analysed the matching of the original JLAB feedthrough. Calculated reflection coefficient is shown in Figure 6 as a red S_{11} curve. The feedthrough demonstrates broadband matching up to about 4 GHz which satisfies the HOM damping goal. Next we modified the original feedthrough for better matching around the 1.1 GHz central frequency in order to improve the BPM performance when a low frequency (~ 1 GHz) signal processing scheme is applied. Blue curve in Figure 6 shows a reflection from the modified feedthrough #1.

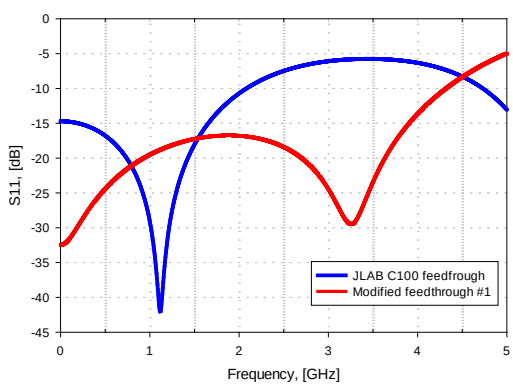

Figure 6: Reflection coefficients of original (red) and modified (blue) JLAB feedthrough.

We used then both variants, original and modified #1, of vacuum rf feedthroughs for ultimate CST time domain simulation of BPM output signals. The simulation results are presented in Figure 7 in forms of signal spectral densities. The spectral density of the BPM signal produced by button loaded to the ideal 50 Ω coaxial line is shown as green curve for the comparison. One can see that the spectral density is almost flat for this case while signals passed through feedthroughs with ceramic window contain quite broadband and low-Q resonances resulting local gain of the spectral density. This effect can be explained by the signal reflections introduced by the ceramic window, which travel back and forth between window and 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 again and used ANSYS HFSS eigenmode solver for finding optimal feedthrough geometry [10]. Figure 8 illustrates the final result of optimization, a low-Q resonance at 2 GHz frequency.

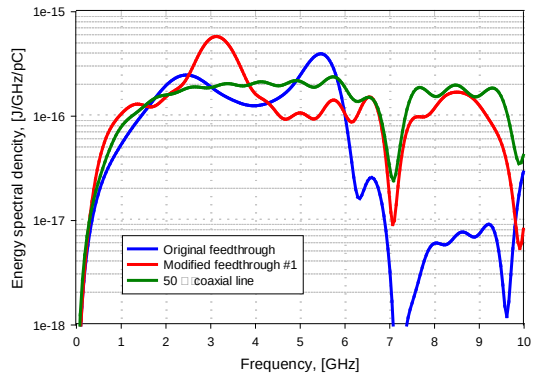

Figure 7: BPM signal spectral density for original (blue) and modified (red) ceramic feedthrough and for the ideal 50 Ω line (green).

Graphic visualisations of proposed feedthrough modifications #1 and #2 are presented in Figure 9. Finally we performed the BPM simulation with the feedthrough #2 attached and compared results obtained for the feedthrough #1. The time domain signals and their spectral densities are shown in Figure 10 and 11 respectively.

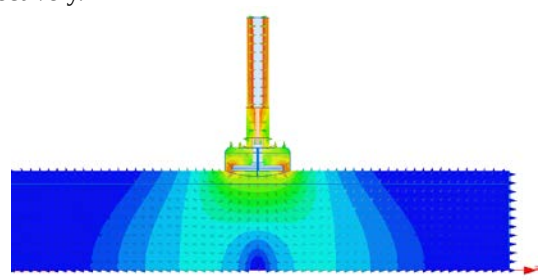

Figure 8: Low-Q resonance of button and modified feedthrough #2 at frequency of 2 GHz.

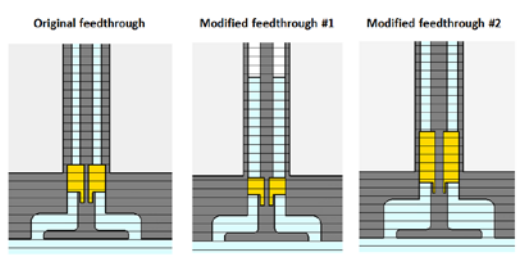

Figure 9: CST models of various ceramic feedthroughs with attached Ø20 mm button used for BPM simulations.

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.

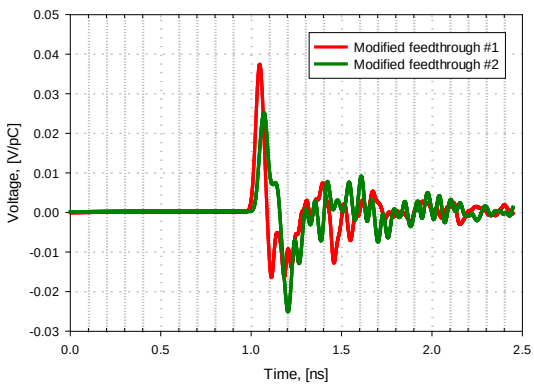

Figure 10: Time domain signals of the button BPM with modified feedthrough #1 and #2.

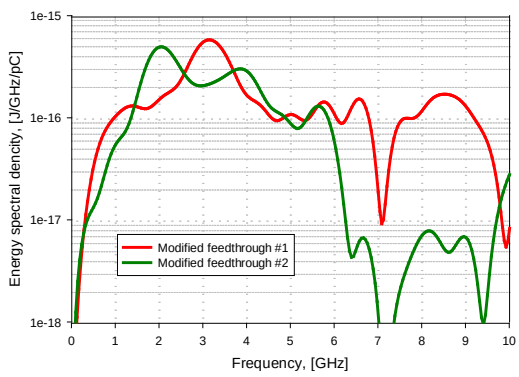

Figure 11: Signal spectral densities of the button BPM with modified feedthrough #1 and #2.

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

Further detailed study of BPM signal transmission and processing, including losses in rf cables and readout electronics performance, is needed in order to estimate the feasibility to have the BPM signal noise below the LCLS-II requirements for low charge single bunch resolution.

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.

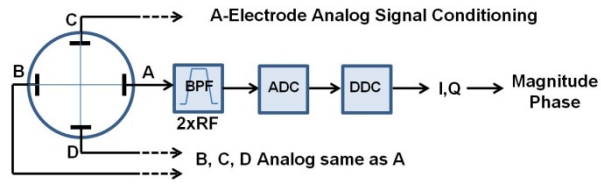

Figure 12: Block diagram for BPM electronics.

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

SUMMARY

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 make a final decision and meet the LCLS-II requirements for low charge single bunch position resolution.

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