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RF CHARACTERIZATION OF A CRYOGENIC X-BAND CAVITY BEAM POSITION MONITOR FOR SUPERCONDUCTING UNDULATOR APPLICATIONS AT SLAC*

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Abstract

Superconducting undulators (SCUs) have gained significant interest due to their advantages over permanent magnet undulators, including the ability to achieve higher magnetic fields and shorter periods, leading to enhanced photon energy gain.As part of the SCU project at SLAC, an X-band cavity beam position monitor (BPM) has been designed and fabricated. This BPM plays a crucial role in the SCU assembly ensuring precise beam alignment with sub-micron resolution. The BPM incorporates two rectangular cavities for X- and Y-position measurements and a cylindrical reference cavity, all housed within a single copper block. Each cavity is separated by approximately 30 mm, which eliminates cross-talk between channels. The design of each cavity includes a single WR-75 waveguide port with a ceramic window as vacuum-air interface for out-coupling the EM field from the cavity to the external circuit. Additionally, each cavity is equipped with a tuner pin for resonant frequency adjustments. In this work, we report on the RF characterization of the BPM cavities conducted at both room and cryogenic temperatures. A consistent resonant frequency shift of approximately 37 MHz was observed when cooling the cavities from room temperature to 40 K, which is the nominal operating temperature within the undulator cryomodule. These measurements validate the predictions made during the BPM design phase through simulations. We also discuss future plans and possible applications beyond the SCU project.

INTRODUCTION

Precision alignment of components in the undulator beamline at the Linac Coherent Light Source (LCLS) is critical in achieving the desired performance of the X-ray Free Electron Laser (FEL). To ensure lasing, the X-ray photon beam must overlap with the electron beam across the entire beamline with micron-level accuracy. This alignment precision is attained only by using the electron beam itself as a reference in a procedure known as beam-based alignment [1]. A magnetic focusing quadrupole and BPM are mounted in each interspace region between the undulators on a micro-movable girder, together with each undulator, allowing the beam to be iteratively steered straight by moving each girder in X and Y directions. The success of this procedure relies upon BPMs to measure the beam trajectory on a single-shot basis with sub-micron resolution at the typical beam operating current. For this purpose, we have successfully used copper RF cavity BPMs operating at 11.424 GHz X-band frequency to achieve submicron resolution at 100 pC bunch charge [2]. Recently, we have been developing a new Superconducting Undulator (SCU) with superior performance capability than the existing Permanent Magnet Undulators (PMUs) to achieve shorter X-ray wavelengths and higher X-ray intensities [3]. The operation of the SCUs at cryogenic temperatures requires, in a compact design layout, that the RF cavity BPM is also located in the cryostat and cooled to cryogenic temperatures [4]. In this paper, we discuss the design challenges this poses and how we choose to overcome them. The copper cavity BPMs still operate in the normal conducting mode, but large changes in material properties must be accounted for at cryogenic operating temperatures. Large dimensional changes occur when the BPM is cooled from room temperature; the resistivity of the copper changes significantly, and consequently, the cavity resonant frequency, the cavity Q, and the cavity coupling ratio change. The cavity BPM is also no longer accessible once it is installed inside a cryomodule, so we had to rethink how the cavity would be tuned prior to installation and cooling. This led us to make conceptual changes in the design [5] where the single, cylindrical X and Y dipole mode cavity was replaced with two rectangular cavities to allow independent, uncoupled measurement of the X and Y dipole modes. The tuning of the new cavity design is much simpler and requires only one tuning pin in place of the four on the previous cylindrical cavity, and the tuning is now very repeatable, even after extended thermal cycling to cryogenic temperatures. The cavity BPM has also been made more mechanically robust by replacing the coaxial SMA vacuum feedthroughs with X-band waveguide windows, which are more tolerant to thermal cycling than the fragile coaxial feedthroughs. Waveguide-to-coax adapters allow cables to be easily attached to the BPM inside the cryomodule. RF measurements of the new BPM have been performed both at room temperature and cryogenic temperature to compare with RF design predictions. Installation on the LCLS beamline is being prepared so that we can compare the performance with the electron beam at room temperature with the existing BPMs before installing the new BPM inside the cryomodule.

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BPM DESIGN

In designing our new cryogenic cavity BPM, we retained certain parameter specifications from the room-temperature version, of which dozens of units are currently deployed across the LCLS undulator beamlines. These include the X-band frequency (11.424 GHz) chosen for compactness and resolution, allowing the use of common signal processing electronics, and the loaded quality factor Q_L. The latter is important for keeping the signal decay time similar for single bunch resolution at high repetition rate. Assuming a residual resistivity ratio of ~ 50 for oxygen-free high-conductivity copper, conductivity data suggests an increase in Q_0 by a factor of roughly 6-7 at cryogenic temperatures (~ 20-40 K) compared to room temperature. Consequently, the external coupling factor (β) had to be significantly increased to maintain the same Q_L range.

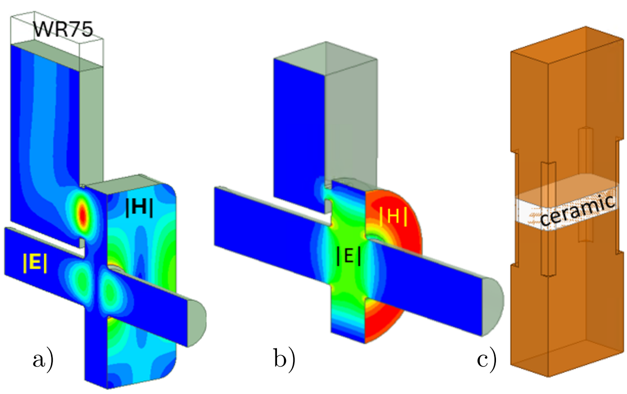

Figure 1: Split geometries and *Ansys HFSS* field plots of the dipole cavity a), reference cavity b), and the matched waveguide vacuum window geometry c).

While spatially efficient, extracting both X and Y signals from a single cylindrical cavity presents a drawback: cross-talk between modes must be tuned out using multiple tuning pins. Although the LCLS cavity BPMs achieve adequate signal independence, it is challenging to predict or verify whether this optimized decoupling will hold under cryogenic cooling. Moreover, re-tuning or replacing a BPM inside a cryomodule would be considerably more difficult. To address these concerns, we opted for separate dipole cavities for X and Y signals. This also removed the need for two pickups per mode to preserve symmetry, where one pickup is terminated with a load that absorbs half the signal. By routing the stronger coupling through a single port, we compensate for the added signal loss incurred during extraction from the cryomodule.

A final significant modification involves the vacuum interface. The coaxial feedthrough antennae used in the LCLS cavity BPMs incorporated small ceramic windows which - despite improved production reliability over time - proved to be a weak point, leading to several unit failures due to leaks. A liquid nitrogen cool-down test on one such failed unit revealed an additional leak, reinforcing the concern. As

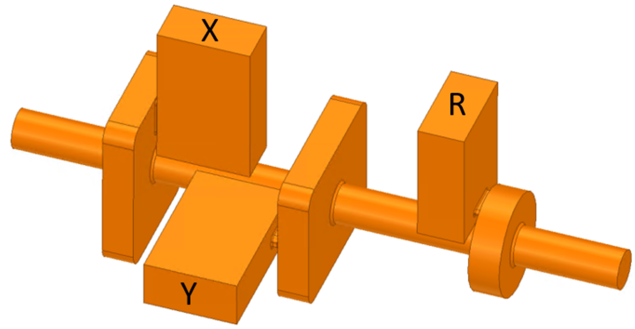

Figure 2: Combined vacuum geometry of the BPM's position and reference cavities and waveguide ports.

a result, we chose to couple into WR75 waveguide and adopt more robust waveguide block windows. An optimal match is achieved with an Al_2O_3 window approximately 4.3 mm thick ($\varepsilon_r = 9.5$). Commercial WR75-to-SMA adapters are then used to route the signals to the cryomodule wall via flexible, pre-shaped SiO_2 cables.

Our final design comprises two orthogonal dipole cavities, rectangular in shape to eliminate mode degeneracy, and a cylindrical monopole reference cavity. Each has the same $^1/_4$" axial length as the original room - temperature design and is magnetically slot-coupled into a WR75 waveguide. The cavities were dimensioned to tune up by approximately 0.33% to reach 11.424 GHz when cooled to the operating temperature of 40 K. Figure 1 depicts the cavity designs, along with the ceramic window of optimized thickness. Figure 2 illustrates the internal geometry of the combined device. The specified cavity separation, equivalent to four beam pipe diameters, ensures negligible signal leakage while providing sufficient space for longitudinally oriented waveguides. Additionally, the beam pipe diameter was reduced from 9 mm to 8 mm to enhance compactness, which also improves shunt impedance.

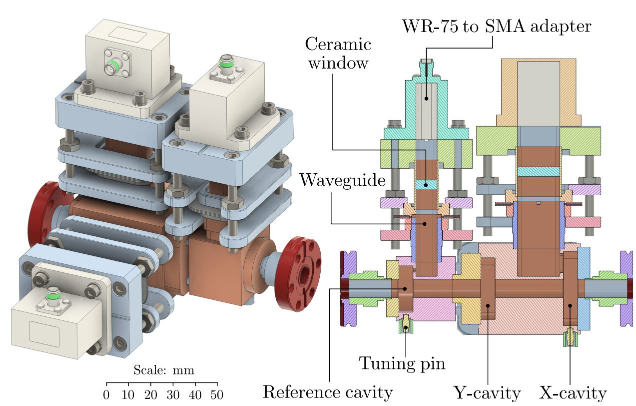

Figure 3: Full mechanical design (left) and cutaway (right) showing main geometrical features of the BPM.

Figure 3 presents CAD renderings of the assembled mechanical design, which incorporates multiple brazed cavity blocks. In this prototype, the windows are mounted using clamped assemblies equipped with welded vacuum bellows.

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This approach was adopted to isolate potential risks associated with component failure. For future versions employing the proven fully brazed design, these assemblies can be omitted. Each cavity includes a single tuning pin positioned on the perimeter opposite the waveguide port. These pins enable minor frequency adjustments via slide-hammer-induced wall deformation. The total flange-to-flange length of the cryogenic cavity BPM is 132.8 mm.

TESTING AND TUNING

Measurements were conducted throughout fabrication to enable rejection or re-machining of components. Two cavity block sets were produced, and extra window ceramics were ordered slightly thick to allow regrinding. These ceramics yielded optimal matching in the 11.27-11.29 GHz range, with insertion loss around 0.06 dB at the 11.39 GHz room temperature target, which was considered satisfactory. Commercial adapters, two right-angle and one straight, were broadly matched at the -40 dB level with ~ 0.15 dB insertion loss. Custom cryogenic cables showed matching in the -30 to -25 dB range and an insertion loss of 0.53 dB. Pressed measurements of unbrazed cavity blocks helped identify the best candidates. Final RF tests on the assembled unit revealed a 13.6 MHz cavity-to-cavity frequency spread, exceeding the tuning capability of LCLS-style BPMs.

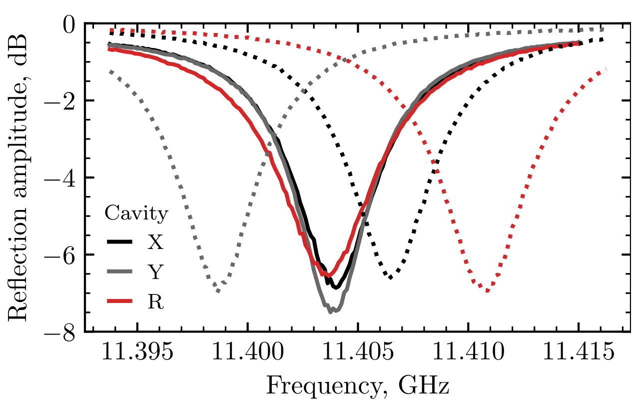

Figure 4: Measured reflection amplitudes (S_{11}) at room temperature for each cavity before (dashed) and after (solid) tuning.

Figure 4 displays the reflection coefficient (S_{11}) measurements for each cavity of the assembled BPM at room temperature, both before and after tuning. All cavities were tuned to approximately 11.4038 GHz, achieving a bandwidth within 1 MHz, thereby demonstrating broad tuning capability.

To further evaluate BPM performance, a cryogenic test was conducted. The BPM was placed inside a cryostat and gradually cooled to approximately 4 K before being warmed back to room temperature over several days. Throughout the warm-up phase, the reflection coefficient was monitored, and the corresponding changes in resonant frequency with temperature were recorded. Figure 5 presents the results, showing the ratio of each cavity's resonant frequency at

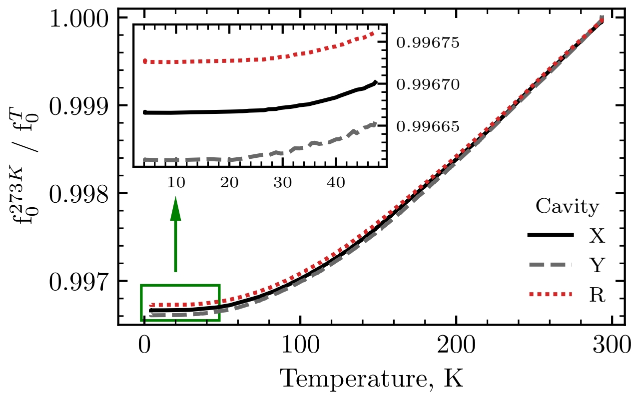

Figure 5: Inverse normalized frequency (ration of resonant frequency at room temperature to the resonant frequency at current temperature) as a function of temperature.

room temperature to that at the current temperature. The data indicate that the resonant frequency rises sharply until reaching approximately 50-60 K, after which the increase flattens, resulting in negligible frequency change with further cooling. At the nominal operating temperature of 40 K, corresponding to conditions inside the proposed SCU cryomodule, the frequency shift for each cavity was approximately 38 MHz (a 0.33% change from room temperature). The measured curve aligns closely with theoretical predictions and with previous results obtained from the LCLS RF BPM tests [5]. The complex reflection data was used to calculate cavity RF characteristics. The predicted values at 40 K scaled from these measurements, for the resonant frequencies are several megahertz higher than our target, but the loaded Q's are within the desired 1700-3000 range.

CONCLUSION

A dedicated BPM tailored for the SCU project at SLAC has been successfully designed, manufactured, and tested. Measurement results exhibit strong agreement with the theoretical design parameters, validating the system's performance. The BPM demonstrates reliable tunability and stable operation under cryogenic conditions, confirming its suitability for low-temperature environments. Ongoing tests at the LCLS beamline aim to determine the BPM's resolution in realistic accelerator conditions at room temperature. The potential integration of the SCU BPM design into the proposed C^3 linear collider project [6, 7] is currently under investigation, with promising prospects for embedding SCU-BPMs into the C^3 cryomodule to enable precise, stable beam diagnostics within the same thermal environment. Co-locating BPMs alongside quadrupoles and alignment movers on the same rafts would minimize thermal gradients and reduce mechanical discontinuities - both critical for beam-based alignment and low-emittance preservation. Such integration is essential for achieving the stringent tolerances on alignment and vibration (few microns to nanometers) required for optimal C^3 performance and leverages the shared infrastructure supporting distributed RF and cryogenic flow.

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