ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TUP11

A CRYOGENIC RF CAVITY BPM FOR THE SUPERCONDUCTING UNDULATOR AT LCLS*

C. Nantista†, P. Krejcik, A. Haase, SLAC National Accelerator Laboratory, Menlo Park, CA, USA.

Abstract

The new superconducting undulator beamline at LCLS requires the BPMs to be operated at cryogenic temperatures alongside the undulator magnets. They are used for beam-based alignment of the undulator magnets and quadrupole and require submicron resolution to achieve good FEL performance. This is to be achieved with X-band RF cavity BPMs, as is done now on the permanent undulator beamline. However, operating the cavities at cryogenic temperatures introduces significant challenges. We review the changes in RF properties of the cavities that result from cooling and how the design is changed to compensate for this. This includes a novel approach for employing a rectangular cavity with split modes to separately measure the X and Y position without coupling.

INTRODUCTION

A new superconducting undulator (SCU) is being installed on the hard x-ray undulator beamline (HXR) at the LCLS-II free electron laser at SLAC. The first two cryogenic modules will be installed at the end of the existing HXR permanent magnet undulator (PMU) beamline so that the FEL performance of the SCU can be measured and compared.

SCUs have been used extensively in storage rings as insertion devices but this will be the first time such a device is used in the x-ray FEL beamline at SLAC. An SCU has advantages in an FEL because of its tunability, and stronger magnetic fields in shorter period length undulators. These characteristics will generate brighter, shorter wavelength x-rays than a PMU, with a shorter FEL gain-length, resulting in a more compact beamline.

In order to realize these advantages it is necessary to install the SCU together with the other beamline components that integrate it into an FEL, including correction coils, phase shifter, quadrupole and BPM. All these components are considered necessary for the prototype module as well so that its performance can be quantitatively assessed. The BPM, which is the subject of this paper, is particularly important because it allows beam-based alignment (BBA) of the undulator beamline to be performed with sufficient precision to allow optimum FEL performance to be achieved. Submicron BPM resolution is required with bunch charges of 100 pC so that the BBA will result in full overlap of the electron and photon beams within micron tolerances.

The shorter gain length advantage of the SCU can only be exploited if all the beamline components are compactly arranged on the beamline without wasting any space with cold to warm transitions. That means that all components, including the BPM, must be mounted inside the cryomodule and operated at liquid He temperatures, as shown in Fig. 1.

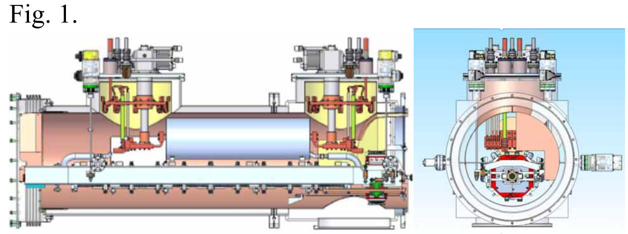

Figure 1: Cutaway and end views of the cryomodule containing the SCU and quadrupole (red) and BPM (copper) at the RH downstream end.

BPM DESIGN CONSIDERATIONS

The LCLS-II free electron laser at SLAC requires monitoring of the beam position with sub-micron level resolution in both x and y. At LCLS we have successfully used X-band RF cavity beam position monitors, or RFBPMs, of a unique configuration, illustrated in Fig. 2, whose design was developed over the last couple of decades [1-3]. It consists of two independent resonant cavities, dipole and reference, with signals coupled out through coaxial vacuum feed-throughs. A distinguishing feature benefiting sensitivity is the magnetic coupling of the dipole cavity fields into side waveguide stubs in a way that shields the pickups from the monopole mode [4].

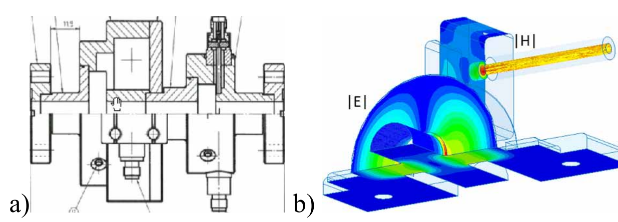

Figure 2: a) cutaway and external view of the LCLS room temperature RFBPM geometry and b) field simulation of dipole cavity coupling [5].

Several factors prevent us taking this RFBPM design and simply mounting it inside the cryomodule. First, the dimensional changes as it is cooled to 40°K produce a large shift in the resonance frequency that must be compensated by machining the cavity to different dimensions at room temperature. Note, that although the SCU coil must operate at 4.2°K, the adjacent components such as the quadrupole and BPM are only cooled to the temperature of the cryomodule thermal shield at 40°K.

The expansion coefficient also decreases exponentially with temperature, as shown in Fig. 3. The coefficient is so small below about 40°K that contraction effectively stops below that temperature, allowing us to accurately predict the machining dimensions at room temperature in order to

* Work supported by U.S. Department of Energy under Contract Numbers DE-AC02-06CH11357.
† nantista@slac.stanford.edu

11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TUP11

achieve the correct tuning frequency at cryogenic temperatures.

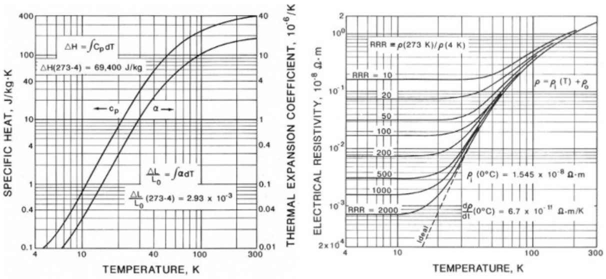

Figure 3: Thermal expansion coefficient (left) and resistivity (right) are shown as a function of temperature for copper.

Secondly, although there is no intention to create a superconducting BPM, the conductivity of the copper decreases significantly at cryogenic temperatures so that the cavity Q factor, and the cavity coupling must be recalculated for the new design so that the loaded Q_L factor is within design requirements. The resistivity of copper is plotted as a function of temperature in Fig. 3, where it is seen to plateau below about 20°K. The residual resistance ratio (RRR) equal to the ratio of its resistivity at 293°K to the resistivity at 4.2°K depends on the composition and purity of the copper used.

The third design consideration is that the RFBPM once mounted in the cryomodule cannot be accessed to adjust the mechanical tuners to adjust either the frequency or cross-coupling of the cavity. For this reason we have developed a design that requires fewer iterations of tuning adjustments to achieve the desired resonant frequency with minimal X-Y coupling. The present LCLS RFBPM evolved from an elegant design concept [4] in which a single, cylindrical dipole cavity is used to measure both the X and Y dipole modes. Separate X and Y coupling slots in this design ensure that only one mode in each plane is coupled to the output port. This concept works perfectly only if the dipole cavity remains perfectly symmetric.

In practice, the LCLS RFBPM has four radial tuning screws that dimple the inner cavity wall so that the X and Y resonant frequencies can be tuned to compensate for machining and brazing imperfections. These adjustments break the symmetry of the cavity and it becomes difficult to simultaneously tune a single cavity to obtain the correct X and Y frequencies as well as minimizing the coupling that gets introduced between X and Y when the frequencies are adjusted. An iterative procedure was developed between SLAC and PAL for using the four tuning screws per dipole cavity, at the 45° positions, that converged in most cases to achieve frequencies and coupling ratios within the specified tolerances [5]. In our new cryogenic design, X-Y signal independence is determined by cavity orthogonality achieved in fabrication and unaffected by cavity tuning. Thus the need for iterative tuning is avoided.

The fourth and final design consideration was motivated by mechanical practicality. The present LCLS RFBPMs are fitted with 6 vacuum, SMA coaxial feedthroughs which are quite fragile and easily developed vacuum leaks during handling. Our preliminary testing of a spare RFBPM on a test stand showed that the feedthroughs are also subject to failure when cryogenically cooled. For this reason, in our new design we will reduce the number of ports from 6 to 3 and we will replace the feedthroughs with more robust waveguide vacuum windows, with commercial waveguide-to-coax adapters on the non-vacuum side.

In addition to halving the vacuum interfaces and minimizing cost and complexity, this reduction from two ports per mode to one also addresses an RF concern. In use, only one port of each pair in the old design is cabled, while the other is terminated with a load to maintain field symmetry. Change in the match of such loads at cryogenic temperature could affect the cavity frequencies and electrical centers.

Double ports were useful (though not required) for Q_L measurement and, with a single dipole cavity, necessary for symmetry and for tuning out cross-coupling.

One final benefit might be added. Though not often a problem, a few units of the two-cavity RFBPM design were found to be unusable due to excessive frequency separation of the X and Y dipole modes, which cannot be tuned out via the 45° tuning pins. Going to three cavities, with dipole modes independently tunable avoids this problem.

DESIGN WITH DISCRETE POSITION CAVITIES

The distinguishing feature of our new design is that we now replace the single, cylindrical dipole-mode cavity with two rectangular dipole-mode cavities to measure the X and Y positions separately. The rectangular shape ensures that the two dipole modes in each cavity are widely separated in frequency, so that only one dipole mode in each plane is at the 11.424 GHz band of the receiver electronics.

The cost to pay is that the RFBPM must now have three cavities instead of two, and the resultant beamline length is somewhat longer, given the requirement of several beampipe diameter cavity separation. The layout of the internal volume of the two dipole-mode cavities and cylindrical monopole-mode reference cavity is shown in Fig. 4.

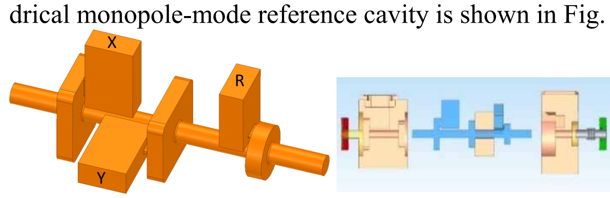

Figure 4: The RF cavity BPM comprises two rectangular X and Y dipole mode cavities and a cylindrical reference cavity.

Cavity RF Designs

Assuming a modest RRR of 50, consistent with the experience of other programs, and an operating temperature of 20 K, the right plot of Fig. 3 predicts a copper resistivity of $\rho = \sim 0.031\times10^{-8}$ Ωm, compared to a value of 1.71×10^{-8} Ωm at room temperature, giving a boost in Q_0 ($\propto \rho^{-½}$) of ~7.43.

To assure sufficient signal decay between bunches, the cavities of the new cryo RFPBM need to retain roughly the

11th Int. Beam Instrum. Conf. IBIC2022, Kraków, Poland JACoW Publishing
ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TUP11

same loaded quality factor $Q_L = (1/Q_0 + 1/Q_e)^{-1}$ in operation as specified for the old design, specifically 1,900 – 3,000. With the significant increase in Q_0, this means Q_e must be reduced by larger external coupling.

Thus, more of the energy deposited by an electron bunch will flow out of the cavity, and with the elimination of a second port discussed above, all emitted energy will go into the diagnostic signal, rather than half being wasted in a load. This will help compensate the increased losses anticipated in bringing the signal out of the cryostat.

Both new cavity designs retain the 0.25″ length of the old design. The beampipe diameter, however, was dropped from 9 mm to 8 mm to limit required cavity separation.

The reference cavity, used for determining the sign of the position measurements and scaling for bunch charge, retains the basic pillbox geometry, with magnetic coupling to a WR75 waveguide machined to overlap behind it as shown in Fig. 5. A transverse slot near the perimeter of the cavity face couples its azimuthal H field to the transverse H field near the waveguide short.

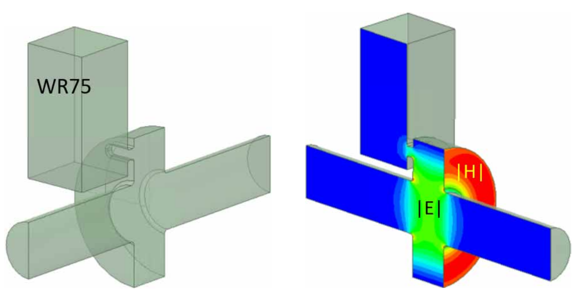

Figure 5: Half views of the reference cavity.

With the resistivity above, simulation of this cavity with Ansoft HFSS yields $Q_0 = 48{,}170$. The coupling slot was adjusted to give simulated $Q_e = 2{,}363$ and $Q_L = 2{,}240$. The cavity diameter was fine tuned to set the TM_{010} resonance at 11.424 GHz.

The new dipole cavities are rectangular with a 1.2 aspect ratio to break the orthogonal polarization degeneracy and rounded corners. A central vertical slot couples the vertical H field of the TM_{210} mode through one face into the side of a WR75 port, as shown in Fig. 6.

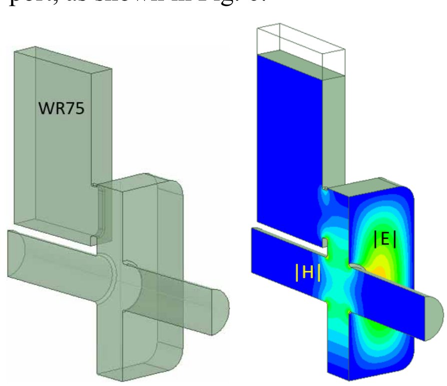

Figure 6: Half views of the dipole cavity.

An unloaded quality value of $Q_0 = 50{,}770$ was calculated with cryogenic resistivity, and the slot then adjusted to give simulated $Q_e = 2{,}332$ and $Q_L = 2{,}227$. The cavity size was adjusted to restore a frequency of 11.424 GHz.

The nearest parasitic modes, TM_{120} and TM_{130}, are respectively 1.10 GHz lower and 3.46 GHz higher, and neither one's fields can geometrically couple to the waveguide.

The effective offset $(R/Q)_\perp$ of the new dipole cavity is calculated to be 3.6 Ω/mm², comfortably above the old >2 Ω/mm² specification. The decay time constant for all cavities is τ = ~62 ns, satisfactory for the ~1 µs minimum bunch spacing of LCLS-II. With Q_e heavily dominating, anything from 50% cryogenic increase to infinite Q_0 would satisfy the Q_L specification range, so our assumption on the RRR is not crucial.

The couplings at operating temperature of the reference and dipole cavity designs are β = ~20.4 and 21.8, respectively, but at room temperature they will be only ~2.74 and 2.93, facilitating cold test characterization.

Vacuum Window

The vacuum window to be incorporated into each of the three signal waveguides (one per cavity), is a standing wave block window, with thickness adjusted for matched transmission. It is centered in a short section of the WR75 port waveguide stub with thinned walls and rounded corners to facilitate brazing. Figure 7 shows the geometry and the simulated return loss.

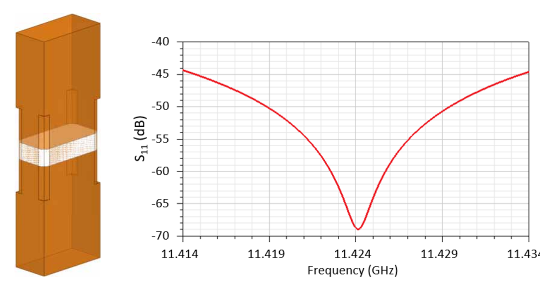

Figure 7: WR75 ceramic waveguide window design with plot of the $|S_{11}|$ match.

Cryogenic RF Test

A spare RFBPM of the old design was installed in an experimental cryostat and brought from room temperature to ~7 K, with coaxial connections to a network analyzer to measure resonant frequency shifts. Results, presented in Fig. 8, agreed well with established thermal expansion data for copper, showing a frequency rise of ~0.33%, flat below 40 K. Our design models will be scaled up in size accordingly for machining. Though its match is fairly broad, the design of the window ceramic will also need to be adjusted to help counter the alumina contraction.

Due to mismatches and lossy cables (stainless rather than copper for thermal conductivity considerations), measurements were not sensitive nor clean enough to experimentally verify the estimated change in Q_0 during this test.

ISBN: 978-3-95450-241-7 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2022-TUP11

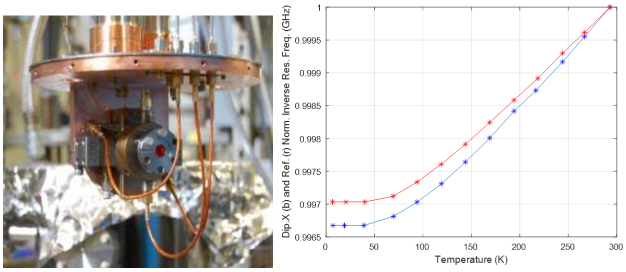

Figure 8: A spare X-band RFBPM mounted for insertion in a cryostat and normalized plots of the inverse measured resonance frequencies of the cavities during cooldown.

Mechanical Design

The cavities will be machined out of blocks of copper, with waveguide coupling slots to the ports where waveguide windows are mounted, as shown in Fig. 9.

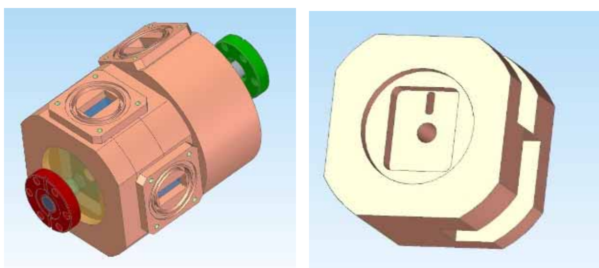

Figure 9: View of the brazed assembly (left), and a detail of the machining of a rectangular cavity with a single waveguide coupling slot.

Each dipole cavity, as well as the reference cavity, now has only one tuning screw (not shown in the preliminary CAD images) to adjust the resonant frequency, since the out-of-plane frequency mode is no longer important and has no effect on X-Y coupling. The tuning procedure is to tune the cavities on a test bench at room temperature to a frequency lower than the nominal 11.424 GHz by an amount Δf which has been calculated beforehand and experimentally confirmed, so that the correct tune is obtained at the cryogenic operating temperature. Our cryogenic testing shows that this frequency shift Δf is very repeatable within our operating tolerance.

The three windows will be fabricated separately and attached, after RF and vacuum testing, via weld flanges (not yet incorporated into Fig. 9). Waveguide-to-coax adaptors will be connected to the instrument-flanged ports, and three coaxial cables will connect the RFBPM to external feedthroughs on the cryomodule.

CONCLUSION

We have developed a new RF cavity BPM design for installation within a superconducting undulator cryomodule. Consideration of thermally induced changes in frequency and conductivity as well as lessons learned and accessibility has led to significant changes from the design successfully employed at room temperature in the LCLS-II undulator beamlines. Most notably, the dipole modes are separated into distinct cavities and fewer, more robust windows are employed. The effort toward producing a prototype is currently underway.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the preliminary design exploration of Changbum Kim, the technical effort of Bobby McKee, the cryogenic test accommodation of Paul Welander and the mechanical design contribution of Stephen Boo.

REFERENCES

[1] R. Johnson *et al.*, "An X-Band Cavity for a High Precision Beam Position Monitor", in *Proc. DIPAC'03*, Mainz, Germany, May 2003, paper PT13, p. 196.

[2] A. Young *et al.*, "Performance Measurements of the New X-Band Cavity BPM Receiver", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper WEPC24, pp. 735-738.

[3] S. J. Lee *et al.*, "PAL-XFEL Cavity BPM Prototype Beam Test at ITF", in *Proc. FEL'15*, Daejeon, Korea, Aug. 2015, pp. 468-470. doi:10.18429/JACoW-FEL2015-TUP043.

[4] Z. Li *et al.*, "Cavity BPM with Dipole-Mode-Selective Coupler", in *Proc. PAC'03*, Portland, OR, USA, May 2003, paper ROAB004.

[5] C. D. Nantista *et al.*, "Performance of the SLAC-PAL-Vitzrotech X-band Cavity BPMs in the LCLS-II Undulator Beam Lines", in *Proc. IBIC'21*, Pohang, Korea, Sep. 2021, pp. 136-139. doi:10.18429/JACoW-IBIC2021-MOPP34