

OVERVIEW OF THE BEAM POSITION MONITORS DEVELOPMENT FOR THE NEXT GENERATION LIGHT SOURCES

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Abstract

The development of Beam Position Monitors (BPMs), and particularly the design of the button pickup, is critically important with the new generation of Synchrotron Light Sources. Specifically, the miniaturization of the vacuum pipe and the broadening of the beam spectrum present special challenges for the button's design to meet the superior stability requirements demanded by new feedback systems. This paper will address trends and challenges in BPM design for new light sources, covering material compatibility, precision manufacturing challenges, and the importance of prototyping and testing.

INTRODUCTION

With the rise of fourth-generation light sources (4GLS), new trends have emerged in the design of Beam Position Monitor (BPM) button pickups. These evolutions have been introduced to address the challenges that upgraded machines carry with them, in particular:

- *Miniaturization:* A denser lattice means less space for diagnostics and instrumentation, including BPMs. As these devices are essential to operate the machine, they must be integrated into increasingly tight spaces;
- *Smaller vacuum chamber:* To increase the integrated field of magnets, the transverse dimensions of the vacuum pipe have been reduced. The pickups are now positioned closer to the beam, which improves signal strength but increases challenges regarding impedance;
- *Shorter bunch length:* Furthermore, the bunch lengths of these new machines are shorter, meaning the frequency spectrum excitation is much wider and can intercept higher resonance frequencies. While this is partially mitigated by the use of third-harmonic cavities, it must be taken into account when designing instrumentation that has to operate across a wide range of conditions.

Starting from these considerations, in this paper we will present the solutions adopted by the community and discuss the manufacturing capabilities required for the latest generation of BPM pickups.

PICKUP DESIGN

The design of BPM buttons requires meticulous optimization due to the intrinsic electromagnetic characteristics of the pickup. The gap separating each button from the vacuum

chamber effectively acts as a resonant cavity [1]. If the frequencies of the modes trapped within this gap coincide with the bunch excitation spectrum, significant overheating can occur. The frequencies of these trapped modes can be shifted by carefully optimizing the geometric shape of the BPM pickup. Furthermore, while the strength of these modes is influenced by the proximity of the pickup to the beam, the resulting effects can be mitigated through strategic material selection. Following these analytical considerations, electromagnetic simulation tools such as CST are often used to define and validate the final BPM design [2].

Button Shape

The easiest way to shift trapped mode frequencies toward the higher end of the spectrum is to reduce the button radius r [1]. This is because the fundamental resonance in a cylindrical BPM is closely related to the cutoff frequency of the coaxial-like structure formed by the button and its housing. The resonant frequency f_{res} can be approximated by:

$$f_{\text{res}} \approx \frac{c}{2\pi\bar{r}\sqrt{\epsilon_r}} \quad (1)$$

where c is the speed of light and \bar{r} is the mean radius of the vacuum gap. Since this frequency is inversely proportional to the pickup dimensions, a smaller button inherently pushes the resonances to higher frequencies, potentially moving them outside the bunch excitation spectrum.

Specifically, the voltage amplitude V induced on the button is proportional to the area of the electrode ($V \propto r^2$). Fortunately, in 4GLS where vacuum pipe apertures are significantly reduced (typically $b \approx 10$ mm), the increased proximity of the pickup to the beam partially compensates for this signal loss, as the sensitivity scales with $1/b$. However, while this proximity is beneficial for signal strength, it is detrimental from an impedance perspective. As the pickup moves closer to the beam, the beam-to-electrode coupling increases the longitudinal and transverse impedances, leading to higher wakefield losses and potential beam instabilities that must be carefully managed in the design phase.

While one could adopt alternative shapes—such as spherical or bell-shaped geometries—to further improve this frequency shift and modify the cutoff characteristics [3], such designs often introduce significant manufacturing challenges. A common trade-off is the use of a conical shape, which pushes the resonant frequencies higher due to the tapering that reduces the volume where modes can be trapped. This design has been selected by several 4GLS [4–6]. Although manufacturing is complex due to the difficulty in maintaining concentricity between the tapered button and its housing,

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modern precision techniques now guarantee satisfactory results.

During the design phase, several light source facilities evaluated various button geometries, selecting the optimal configuration based on their specific operational requirements. An example is provided by SOLEIL II, where two distinct button designs were compared, as shown in Fig. 1, [5]. In this comparison, the button radius and the vacuum gap remain constant while the geometry is varied between cylindrical and conical profiles. Simulation results clearly demonstrate that the conical configuration successfully shifts the trapped mode frequencies to higher values.

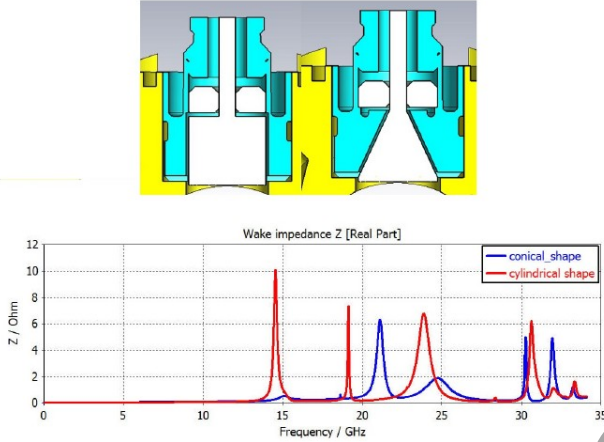


Figure 1: Cylindrical and conical designs for SOLEIL II buttons (top) and impedance simulation results (bottom): cylindrical shape shown in red, conical in blue. Adapted from [5].

Another interesting approach to managing trapped modes is exemplified by the BPM buttons developed for SLS 2.0 [7]. In this design, the intensity of the resonance is reduced by introducing a deliberate eccentricity in the coaxial part of the feedthrough surrounded by the glass insulator. By breaking the axial symmetry, the trapping of resonant modes is disrupted, leading to a significant reduction in the longitudinal impedance. As illustrated in Fig. 2, the effectiveness of this damping depends on both the magnitude of the off-centering and its angular alignment relative to the beam axis.

Materials

A significant development in BPM design is the introduction of borosilicate glass (SiO_2) as an insulator for pickups

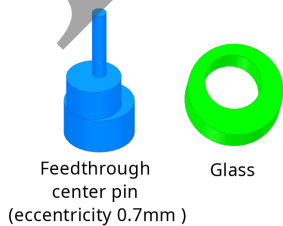


Figure 2: SLS 2.0 button design: the coaxial part in the glass is off-center to reduce the intensity of trapped modes

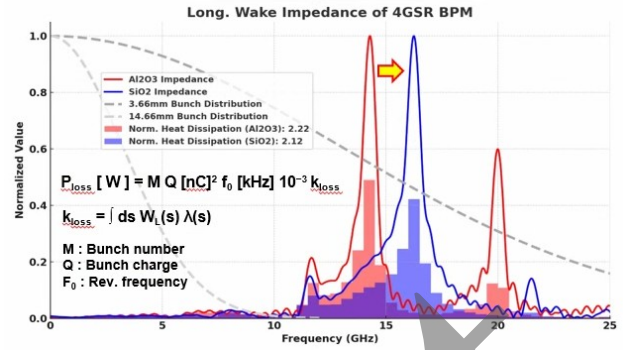


Figure 3: Impedance spectrum for a cylindrical pickup design using alumina (red) and borosilicate glass (blue). Taken from [9].

in synchrotron light sources. While this material has already been successfully implemented in different machines, such as the LHC [8], its adoption in light sources represents a strategic shift in managing electromagnetic performance. Borosilicate glass is characterized by a relative permittivity ($\epsilon_r \approx 4-5$), which is substantially lower than that of standard alumina (Al_2O_3 , $\epsilon_r \approx 9.2-10$).

This lower permittivity is advantageous for two primary reasons. First, the resonant frequency of trapped modes is inversely proportional to the square root of the dielectric constant:

$$f_{\text{res}} \propto \frac{v}{\lambda} = \frac{c}{\lambda \sqrt{\epsilon_r}} \quad (2)$$

where λ represents the characteristic wavelength of the resonant mode, which is strictly determined by the physical dimensions of the button and its housing. By switching from alumina to glass, the propagation velocity v of the fields within the insulator increases, naturally shifting resonances toward the higher, less critical end of the frequency spectrum. Second, a reduced ϵ_r minimizes the parasitic capacitance C of the feedthrough ($C \propto \epsilon_r$), which improves signal bandwidth and reduces the overall coupling impedance.

This is shown for instance in the design work of BPM pickups of the Korean 4th Generation Storage Rings (4GSR). They compared the resonance frequency obtained by cylindrical design using either Alumina or Borosilicate Glass as insulator, and it is clear that the latter provides better results, as shown in Fig. 3 [9].

Furthermore, these dielectric characteristics allow for a more effective impedance match of the coaxial feedthrough to the standard 50Ω required by backend electronics. Achieving this match is increasingly difficult with alumina due to the general miniaturization of modern BPM components. The characteristic impedance of a coaxial line is defined by:

$$Z_0 = \frac{60}{\sqrt{\epsilon_r}} \ln \left(\frac{D}{d} \right) \quad (3)$$

where D and d are the diameters of the outer and inner conductors, respectively. In compact designs where the outer diameter D is strictly limited, the high permittivity of alumina would necessitate an extremely thin and fragile center

pin d to maintain 50Ω . In contrast, the lower ϵ_r of borosilicate glass permits the use of a more robust center pin within the same footprint, significantly improving mechanical reliability while minimizing signal reflections.

Despite its electromagnetic benefits, the adoption of borosilicate glass introduces significant engineering challenges, primarily related to its thermal and mechanical properties. The most critical drawback of borosilicate glass is its low thermal conductivity ($\approx 1.1 \text{ W/m}\cdot\text{K}$), which is nearly 30 times lower than that of alumina ($\approx 30 \text{ W/m}\cdot\text{K}$). In storage rings operating with high average currents or high-intensity short bunches, the wakefield power deposited in the pickup cannot be efficiently dissipated from the center pin. This can lead to excessive localized temperatures and significant thermal stress on the vacuum seal, potentially compromising the vacuum integrity of the machine.

Furthermore, the Coefficient of Thermal Expansion (CTE) of borosilicate glass ($3.3 \times 10^{-6}/\text{K}$) is significantly lower than that of standard stainless steel housings ($16 \times 10^{-6}/\text{K}$). Historically, this mismatch required the use of transition materials like Kovar to prevent seal failure during bake-out cycles. Kovar, a nickel-cobalt ferrous alloy, is highly ferromagnetic and can perturb the magnetic field environment near the beam. To address this, recent manufacturing advancements have successfully enabled direct sealing between borosilicate glass and stainless steel, eliminating the need for ferromagnetic transitions.

These manufacturing difficulties generally dictate that borosilicate glass is typically reserved for simpler cylindrical setups, while alumina remains the preferred choice for more complex conical geometries. Nevertheless, some facilities have successfully pushed these technical boundaries; for instance, at Elettra 2.0, successful results were achieved in manufacturing conical buttons using borosilicate glass insulators [10].

Bunch Spectrum

Another defining characteristic of 4GSR light sources is the integration of 3rd harmonic cavities (3HC). The natural bunch length of these new machines is typically less than 10 ps. To improve the Touschek lifetime, these devices are used to longitudinally stretch the beam, providing a lengthening factor of approximately three. However, the action of this lengthening is non-linear and results in a significant modification of the bunch shape. Consequently, the power spectrum is altered, which must be carefully accounted for during pickup design. An example of the effect of the 3HC on the bunch profile of ALBA II is presented in Fig. 4 [11].

Studies performed at SOLEIL suggest that in their case the power trapped by a bunch lengthened by a 3HC can be approximated by that of a Gaussian bunch that is 15% shorter than the actual stretched length. While this serves as a useful first approximation, it may not be sufficiently accurate for trapped mode frequencies below 20 GHz [12]. Since standard electromagnetic solvers like CST do not natively support these complex bunch distributions for wakefield cal-

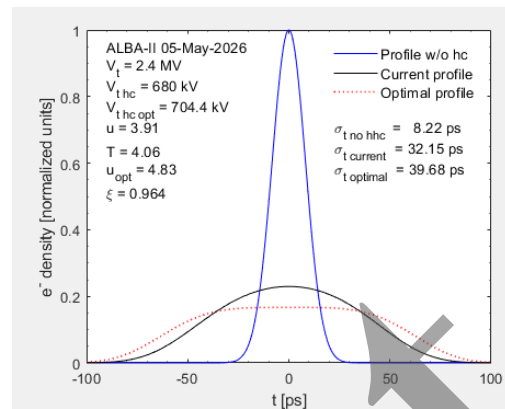


Figure 4: Bunch profile for ALBA II without 3HC (blue), ideal profile with 3HC (red), and real profile with 3HC (black).

culations, the use of specialized codes such as MBTRACK2 is recommended for a more rigorous analysis [13].

MANUFACTURING AND BLOCK ASSEMBLY

Following the design phase, prototyping is an essential practice to validate manufacturing feasibility and identify potential technical problems. Furthermore, the integration of all four buttons into the final BPM block requires careful consideration, as the assembly must withstand high processing temperatures while maintaining the precise geometric positioning required for accurate beam position measurements.

Beyond the challenges of mechanical precision, these high temperatures pose a significant risk to the structural integrity of the insulator. The thermal stress induced during the brazing or sealing process, exacerbated by the different expansion rates of the metallic block and the dielectric, can lead to fracturing or "breaking" of the glass or ceramic.

Tolerances and Integration

Due to significant progress in feedthrough manufacturing, mechanical tolerances have become increasingly stringent. For a standard 5 mm diameter button, a tolerance of $50 \mu\text{m}$ is now considered a standard requirement for 4GSR projects. This precision has paved the way for cylindrical BPM designs that omit the traditional "sleeve" assembly.

By specifying these tight tolerances, the button can be integrated directly into the vacuum chamber body, such that the vacuum gap is formed between the pickup and the chamber metal itself. This configuration facilitates superior heat dissipation and avoids the formation of parasitic cavities associated with additional structural components.

However, prototyping remains a critical step to validate the manufacturer's ability to meet these specifications. In practice, the two most critical parameters to control are the concentricity of the assembly and the axial distance of the button relative to the beam pipe center (flushness). These have been found to be the hardest for manufacturers to meet [9].

An example of a BPM without sleeves is the design for ALBA II presented in Fig. 5. In the figure, the critical mechanical tolerances are explicitly marked [14].

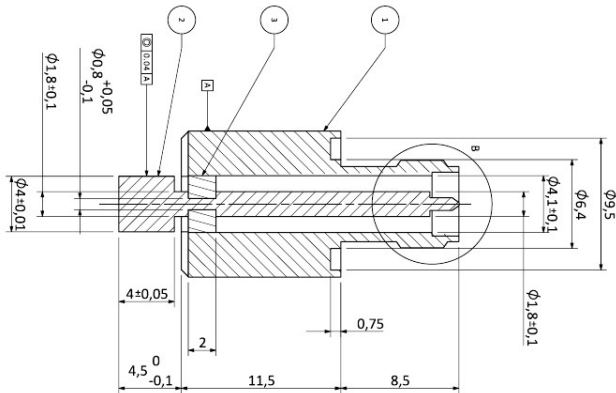


Figure 5: BPM button designed for ALBA II. No sleeves surround the pickup; the gap is generated directly between the button and the vacuum chamber wall.

Connectors

Another characteristic feature for 4GSR button pickups is the implementation of female Reverse Polarity SMA (RP-SMA) connectors [15]. These connectors are a telecommunication standard that offer superior resilience to thermal stress. While the outer housing follows standard SMA dimensions, the inner part utilizes a male pin. This configuration ensures that when the button is subjected to high temperatures and the pin undergoes thermal expansion, the mechanical contact with the cable interface is actually enhanced. The design illustrated in Fig. 5 exemplifies the integration of this connector type.

Material and Thermal Constraints

The adoption of advanced materials for both the button pickups and the vacuum chambers necessitates rigorous compatibility checks during the design phase. For instance, many 4GSR vacuum chambers are fabricated from CuCrZr (Copper Chromium Zirconium) to enhance heat dissipation. However, spatial constraints often require the direct integration of BPM buttons into the chamber wall, precluding the use of a dedicated stainless steel mounting block.

The integration of stainless steel components into a copper-based chamber presents significant challenges due to welding incompatibilities. While brazing is a potential alternative, it is frequently avoided to prevent the annealing of the vacuum chamber, which would compromise its mechanical strength. Furthermore, the high temperatures reached during assembly and operation induce significant thermal stress; the CTE of stainless steel ($16 \times 10^{-6}/\text{K}$) differs substantially from both CuCrZr ($17.6 \times 10^{-6}/\text{K}$) and common insulators like Alumina or Borosilicate glass.

To mitigate this, the pickup housing can be manufactured from a material with a CTE closely matched to the insulator. For Borosilicate glass, Kovar is the industry standard.

However, Kovar's high ferromagnetism poses a risk of interfering with the storage ring magnetic lattice. While the resulting linear steering effects can be corrected by the orbit feedback system, the non-linear field components require careful study. These effects can be minimized by ensuring the Kovar housing is recessed or positioned as far as possible from the beam axis to reduce its influence on the magnetic field quality at the center of the vacuum chamber.

Integration of Buttons into the BPM Block

Even when using standard vacuum chamber materials, the integration of pickups into the BPM block presents significant engineering challenges. In designs where space permits, flange-mounted connections are an available option; these allow for the mechanical adjustment of the pickup, which can be utilized to compensate for the electromagnetic offset of the block during installation [16].

In more compact designs, welding is typically required, with Tungsten Inert Gas (TIG) and Laser Welding being the primary methods. When employing TIG welding, the proximity of the weld pool to the insulator is a critical concern; the high heat deposition characteristic of this method can induce thermal stress or damage the vacuum seal due to the small scale of the components. Laser welding represents an alternative approach that has been successfully implemented in some 4GLS projects. Because the heat deposition is significantly more localized and can be applied in pulsed modes, it reduces the overall thermal load on the insulator during the integration process [17].

TESTING AND VALIDATION

The stringent orbit stability requirements of 4GSR demand unprecedented precision from the BPM system. Even when high-quality manufacturing processes are employed, infinitesimal variations in component geometry or material properties can shift the electrical center of the pickup assembly. Consequently, a comprehensive testing and validation campaign is necessary. This process is divided into two main phases: the characterization of individual buttons to ensure balanced sensitivity, and the global validation of the fully assembled BPM block.

Button Characterization and Sorting

A critical stage in the production of BPM pickups is the individual testing and sorting process. Since a standard BPM station comprises four buttons arranged around the vacuum chamber, any discrepancy in their individual response can lead to a significant electrical offset. To minimize this, buttons are characterized and sorted into matched sets of four before they are permanently integrated into the BPM block.

There are three primary methodologies for further characterizing individual BPM pickups:

- **Button Capacitance Measurement:** This is the standard industrial approach, typically achieved through Time Domain Reflectometry (TDR) to identify impedance discontinuities or by measuring S_{11} with a

Vector Network Analyzer (VNA). This method is advantageous as it reveals internal defects such as cracked ceramics [16, 18].

- **Transfer Impedance Measurement:** This involves the construction of a specialized coaxial line to simulate the beam. A VNA is used to measure S_{21} from the central conductor to the button electrode, providing a direct measurement of sensitivity and frequency response [7].
- **Mechanical Characterization:** Buttons are grouped based on identical mechanical dimensions, specifically the flushness [19].

While electromagnetic testing is widely adopted, it presents unique challenges for “sleeveless” button designs. Because these buttons lack an integrated grounded sleeve, their capacitance must be inserted into a specialized test fixture that mimics the geometry of the vacuum chamber housing. Despite these challenges, characterizing all buttons remains a critical best practice.

BPM Block Validation

Beyond individual component testing, it is essential to validate the performance of the fully assembled BPM block to ensure the geometric and electrical centers are correctly aligned.

The standard procedure for system validation is the Lambertson method [20, 21]. This coaxial technique characterizes the electrical offset of the assembled BPM block by comparing the signal transmission between the four pickups. While effective for detecting obvious hardware malfunctions or assembly errors, the results are highly sensitive to measurement repeatability.

Another approach to characterizing the full block is the use of a stretched wire [22]. In this setup, a thin wire is used to simulate the beam; either the wire or the BPM block is moved via high-precision stages to map the electrical center relative to the mechanical reference.

While bench characterization of the BPM block is a prerequisite for a successful commissioning phase, it is important to note that these measurements are ultimately a proxy for the beam’s actual behavior. In operational environments, Beam-Based Alignment (BBA) is considered the superior method for determining the magnetic center of the quadrupoles relative to the BPMs [23]. Consequently, bench validation serves to provide a precise initial calibration and to identify hardware outliers, while BBA is used to achieve the sub-micron orbit stability required for 4GSR operation.

SUMMARY AND CONCLUSION

The evolution of fourth-generation light sources has fundamentally shifted the paradigms of BPM pickup development. Technological advances in electromagnetic modeling have enabled the validation of complex geometries—such as conical profiles—specifically designed to cope with the broad frequency spectra generated by increasingly short

bunches. Simultaneously, the introduction of new materials like borosilicate glass has improved coupling impedance and signal bandwidth, although it necessitates careful management of thermal conductivity and material compatibility issues during the design of both the pickup and the complete BPM block.

While design challenges have grown in complexity, the procedures for individual button characterization and sorting remain a well-established and indispensable practice. By rigorously validating button capacitance, transfer impedance, and mechanical flushness before installation, facilities can effectively minimize electrical offsets and identify hardware defects early. This comprehensive validation workflow ensures that the BPM system meets the stringent orbit stability requirements essential for the commissioning and operation of next-generation machines.

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