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FIRST MEASUREMENTS OF A PROTOTYPE STRIPLINE BPM FOR PETRA IV COMPARISON WITH SIMULATION

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Abstract

We present signal and thermal measurements from the first prototype of a stripline Beam Position Monitor (BPM) intended for the PETRA IV synchrotron ring. The monitor was installed at the PETRA III testbed for evaluation and compared against CST Studio Suite simulation results. Initial measurements revealed unexpected signal oscillations and significant heating (up to 135 °C) which were not reproduced in ideal models. For a smooth beam pipe, the expected power loss based on the wake-loss factor would only be 5 W. Including mechanical details such as flanges and copper gaskets in the simulation revealed cavity-induced resonances which increased the power loss up to 96 W. The updated model showed good agreement with the measured signals in both time (TD) and frequency domains (FD) as well as with thermal data. Replacing the gasket with a RF-sealing variant lowered the measured temperature to 65 °C. This study highlights that multiple mechanical and electromagnetic factors must be understood and included in simulations to predict beam-induced effects in high-frequency diagnostics accurately.

INTRODUCTION

The PETRA IV synchrotron [1] requires all vacuum components to have a very low electromagnetic impedance to ensure a stable, high-quality electron beam. Designing diagnostic devices like stripline BPMs is therefore challenging, as they must be sensitive without disturbing the beam.

This paper describes the testing of a stripline BPM prototype for PETRA IV. While simulations of an ideal model predicted successful operation, initial beam tests at the PETRA III facility revealed unexpected problems: the device severely overheated and its signal was distorted.

We demonstrate that these issues were caused by resonant electromagnetic modes trapped in small cavities created by vacuum flanges and gaskets. By identifying this root cause, we developed and successfully tested a modified gasket that solved the problem. Similar challenges with parasitic resonances arising from small geometric discontinuities have recently been reported at the ESRF [2].

This work highlights that for modern accelerators, accurate performance prediction requires simulation of the complete mechanical structure of a component, not just its core elements.

ELECTROMAGNETIC SIMULATION

The BPM geometry was optimized using High Frequency and Wakefield solvers of CST Studio Suite [3]. The resulting signal from the simulation shows good coupling between the strips and feedthroughs without oscillations behind the main signal peaks (Fig. 1). From the wakefield simulation, a loss factor of approximately 2.7e-03 V/pC was obtained. For the nominal PETRA III beam parameters (100 mA, 40 bunches) this corresponds to a power loss of 5 W.

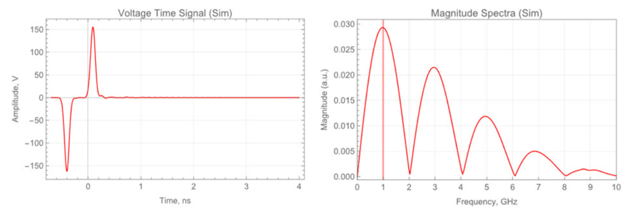

Figure 1: Signal in TD (left) and FD (right). Simulation was performed for bunch length σ_z = 13.2 mm (44 ps), bunch charge = 19.2 nC (100 mA, 40 bunches mode). Working frequency of 1 GHz indicated by the red line.

FABRICATION OF PROTOTYPE

For experimental validation with beam, a prototype was fabricated for installation in the PETRA III test section. While the BPM housing was designed for the 60 mm beam pipe, the core electrode geometry was kept identical to the final 34 mm design intended for PETRA IV (Fig. 2).

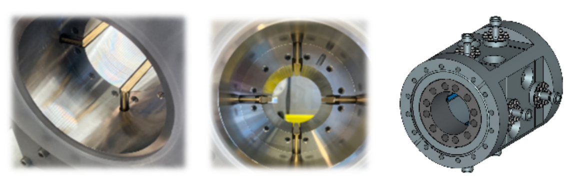

Figure 2: Prototype for PETRA III test section.

RF MEASUREMENTS

Prior to installation, the prototype's RF characteristics were measured using a Vector Network Analyzer. The S11 values for all eight ports were below the -20 dB requirement across the DC 2 GHz frequency range (Fig. 3).

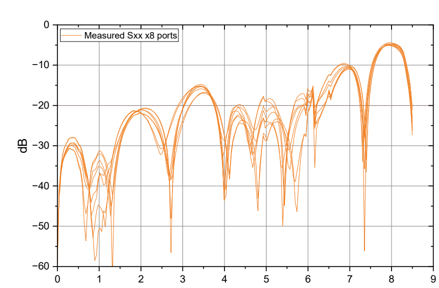

Figure 3: Measured reflection coefficients (S11) of 8 ports.

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BEAM MEASUREMENTS AT PETRA III: A COMPARISON WITH SIMULATIONS

To validate the design under operational conditions, the prototype was installed in a dedicated test section of the PETRA III storage ring. The objectives were to evaluate the BPM signal response and thermal behaviour and to compare these measurements directly with simulations. The test section also consisted of three button-type BPMs and a DCCT (DC Current Transformer) located upstream (Fig. 4).

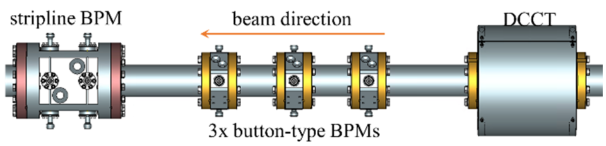

Figure 4: Complete test section at PETRA III.

Initial Signal Measurements

Initial tests using a 100 mA, 40-bunch beam immediately revealed a significant signal deviation from the CST simulations. While the BPM produced a strong primary signal, it was distorted by high-frequency oscillations (ringing), as shown in the TD in Fig. 5. A Fourier transformation of this signal revealed strong spectral peaks at frequencies above the 2.93 GHz cut-off frequency of the 60 mm beam pipe (Fig. 5), indicating the excitation of trapped higher-order modes.

Importantly, the same oscillations and resonances were observed not only in the stripline BPM but also in three button-type BPMs suggesting that the anomalies originated from the surrounding environment of the test section rather than from the BPMs itself.

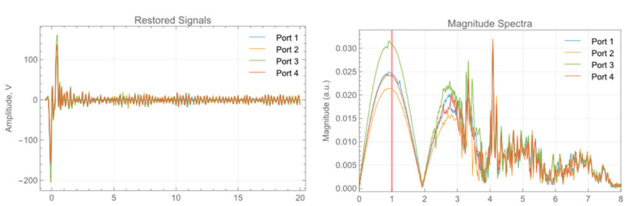

Figure 5. Measured signal in the TD (left) with unexpected oscillations following the main signal peaks. In the FD (right), resonances above cut-off frequency indicate that the source can originate from the surrounding structures.

Thermal Anomaly

In addition to the signal distortions, the initial beam tests revealed a severe unexpected thermal anomaly. The stripline BPM body temperature reached approximately 135 °C, far above the ~35 °C (at ambient temperature of 30 °C) predicted by steady-state thermal simulation based on a 5 W power loss. The large discrepancy strongly suggested that the same resonant phenomena distorting the signal were also the cause of the excessive heating.

Extended Simulations

To understand the origin of the unexpected oscillations, resonances, and the thermal anomaly, the idealized CST model was expanded to include the upstream and downstream cavities formed by flanges and copper gaskets (Fig. 6).

The updated simulation now accurately reproduced the trailing oscillations seen in the measured signal (Fig. 7), confirming that cavities formed by the flanges and oversized gaskets acted as resonators, trapping HOMs. Clear resonances related to cavities in both measured and simulated signals are visible in FD. However, the high-frequency noise was not reproduced and needs additional investigation which will be described in the following sections.

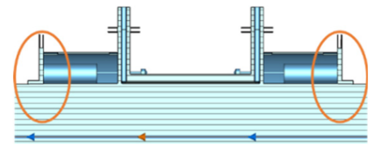

Figure 6: Cross-section of the extended CST model of the stripline BPM. The cavities (indicated in orange) are formed by the vacuum flanges and gaskets with a 95 mm inner diameter and a 2.45 mm width.

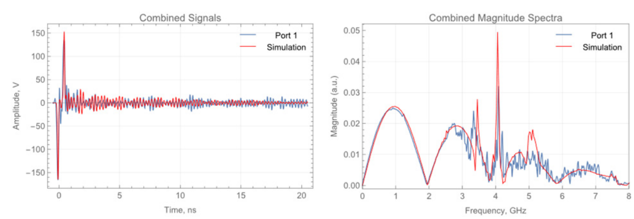

Figure 7: Comparison of the measured signal with the output from the CST simulation. The model with included cavities now reproduces the trailing oscillations observed in the measurements.

Importantly, the simulations also solved the observed thermal anomaly by quantifying the additional power losses introduced by the flange cavities of the stripline BPM. The calculated power loss was 96 W. Thermal steady-state simulation predicted the temperature of the stripline BPM body of ~158 °C which is close to the experimentally measured ~135 °C, confirming that the flange cavities were the primary source of both the signal distortion and the severe overheating.

MITIGATION OF RESONANT HEATING

Gaskets with Smaller Inner Diameter

Based on the simulation results, the first mitigation attempt involved replacing the original gaskets with a version designed to match the 60 mm inner beam pipe diameter. This modification significantly shielded the resonant cavities, though small, unshielded gaps of ~0.225 mm from each side of the gasket remained. A new CST simulation of this modified geometry predicted a reduced power loss of 56 W which corresponds to the temperature of ~60 °C from the steady-state thermal simulation.

This change resulted in a significant improvement: the measured BPM body temperature dropped significantly from ~135 °C to ~92 °C. The result confirmed that the

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source of heating was correctly identified, though the residual heating indicated that the remaining gaps were still significant source of impedance. The difference of ~32 °C between simulation and measurement was not understood.

RF-Sealing Gaskets

To eliminate the residual gaps, a final set of custom RF-sealing gaskets were designed and installed. These components feature an inner structure that makes full contact with the adjacent surfaces to create a continuous conducting path for the beam's image currents.

This final modification proved highly effective. The measured temperature on the BPM body was further reduced from ~92 °C to ~65 °C.

The thermal simulation showed ~35 °C steady-state temperature at the ambient 30 °C for the ideal geometry. The same remaining discrepancy of ~30 °C is likely attributed to additional geometric features of the prototype – such as asymmetries or additional small gaps – that were not considered and are currently being studied further.

IDENTIFYING SOURCES OF HF NOISE

To understand the influence of other surrounding devices on the signal and therefore to find the HF noise sources, the CST model was expanded even further to include the entire test section of PETRA III with neighbouring devices and discontinuities, particularly the DCCT located ~70 cm upstream and all flanges with inner diameters larger than the nominal 60 mm beam pipe.

To isolate the impedance contribution of each component, a series of simulations was performed. As an example, Fig. 8 shows the result when only the upstream DCCT is included in the model. Wakefields generated within the DCCT travel downstream behind the beam and appear in TD as a delayed packet of oscillations at the stripline BPM.

The final simulation included all upstream components simultaneously (Fig. 9). The combined wakefields from all discontinuities produced a complex ringing that confirmed the cumulative effect of the surrounding environment was the primary source of the signal anomaly.

The final comparison of the simulation with included upstream discontinuities against the measured signal after installing RF-sealed gaskets explains that part of the noises comes from upstream devices and discontinuities of the test section (Fig. 10).

CONCLUSION

We have presented the successful design, characterization, and validation of a stripline BPM prototype for the PETRA IV storage ring. Initial beam tests at PETRA III revealed a significant discrepancy between the predicted and measured performance. The prototype exhibited severe overheating to ~135 °C and strong signal oscillations, in contrast to the 5 W power loss and clean pulse predicted by simulations.

Through a detailed investigation, we have demonstrated that these anomalies were driven by cavity-like resonances created by the BPM flanges and oversized gaskets. By including these mechanical features into the CST simulation model, we were able to accurately reproduce the measured signal characteristics and predict a power loss of 96 W, which is in good agreement with the observed thermal behaviour.

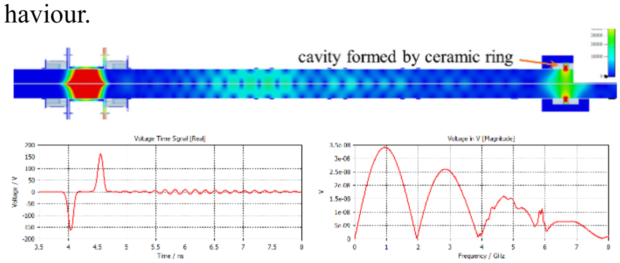

Figure 8: Simulation results show how wakefields generated in the DCCT alone propagate to the BPM causing delayed signal oscillations.

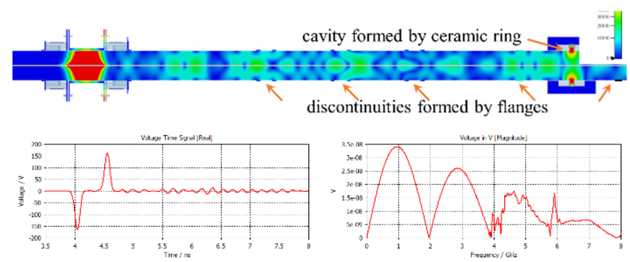

Figure 9: Simulation results for the complete test section model including all upstream discontinuities.

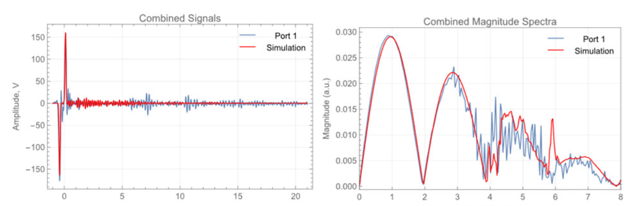

Figure 10: The simulation result against the measured BPM signal with RF-sealing gaskets.

Based on this understanding, an engineering solution was implemented by replacing the standard gaskets with custom RF-sealing gaskets. This modification successfully shielded the resonant cavities, reducing the measured operating temperature from ~135 °C to ~65 °C.

The central conclusion of this work is a critical one for the accelerator community: for modern, low-impedance machines like PETRA IV, the traditional approach of simulating only the active parts of a diagnostic component is no longer sufficient. The full mechanical assembly including flanges, gaskets, and other discontinuities, must be considered as an integral part of the electromagnetic design. Only through such comprehensive and accurate model can the beam-induced effects be accurately predicted and controlled ensuring the robust and reliable operation of the next generation of synchrotron light sources.

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