ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-MOP020

TOWARDS REAL-TIME CALIBRATION OF CBPMS USING SYNCHRONOUS RF INJECTION

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Abstract

Cavity beam position monitors (CBPMs) are very high-precision devices that, in recent years, have progressed from experimental equipment to standard linac diagnostics in many prominent facilities, most notably free-electron lasers. However, the high sensitivity of these devices comes at the cost of a limited measurement range, even with high dynamic-range electronics. Furthermore, CBPMs need to be calibrated in situ, ideally by introducing a known beam offset, which is often impractical in large installations. This paper reports on a method to match CBPM beam signals by injecting tightly controlled synchronised bursts of radio frequency (RF) oscillations into the sensor cavity and reading back their superposition. The method allows compensation for static beam offsets (with beam) and calibrates CBPMs electronically (no beam required), thus removing some of the operational hurdles. We discuss the first demonstration of this method at the Accelerator Test Facility 2 (ATF2).

INTRODUCTION AND CALIBRATION CONTEXT

Cavity Beam Position Monitors (CBPMs) are high-precision diagnostic devices capable of measuring beam positions with resolutions on the order of tens of nanometres [1–3]. They have become standard in modern facilities such as free-electron lasers and test accelerators like ATF2 [4]. However, their high sensitivity requires frequent recalibration—typically via beam steering or injection of a reference signal—which can be impractical in installations with limited flexibility [5].

CBPMs operate by coupling to the dipole mode excited as an electron bunch passes through a cylindrical cavity. The resulting signal amplitude is proportional to the beam offset and decays exponentially in time:

$$V(t,x) = k\,x\,e^{-\frac{t}{\tau}}\cos(\omega_0 t + \phi) \tag{1}$$

where x is the transverse offset, k is a proportionality constant, ω_0 is the mode frequency, τ is the decay constant, and ϕ is the phase offset.

Recalibration is sometimes triggered by temperature drift or local oscillator instability. At ATF2, for example, a calibration tone is injected after the CBPM to serve as a stable reference, with amplitude and phase drift measured below 0.1% and 0.05° h^{-1}, respectively [4, 6]. Nevertheless, calibration remains an operational burden.

This paper presents a complementary method for CBPM calibration based on injecting radio frequency (RF) pulses directly into the cavity. By synchronising and phasing these signals relative to the beam-induced signal, we show that it is possible to cancel the beam signal or reproduce it without beam [7]. The first demonstration of this approach was carried out at ATF2 in Japan [8]. This has the potential to enable partial calibration without beam and may support real-time in situ signal processing.

EXPERIMENTAL METHOD

The experiment was carried out at the Accelerator Test Facility 2 (ATF2) at KEK, Japan, using one of the operational cavity BPMs from the ATF2 system [4]. A schematic and detailed description of the earlier configuration are provided in our IBIC 2024 paper [8].

For the June 2024 measurements, we upgraded the injection system with a custom-built RF generator delivering a continuous-wave signal approximately 20 MHz above the cavity's resonant frequency. This frequency offset ensures that, after mixing, only the down-converted component overlaps the cavity's dipole mode, while the up-converted sideband lies outside its 10 MHz bandwidth. Consequently, the cavity itself acts as a narrowband filter, suppressing non-resonant components and yielding a cleaner time-domain signal.

In the previous configuration, we had used a Highland Technology T240 fast pulse generator to produce the RF burst. In the new setup, the CW carrier is gated by a fast RF switch driven by a precision delay generator, eliminating unwanted spectral artefacts around the resonant frequency. A 26 MHz burst from an arbitrary waveform generator is mixed with the carrier and triggered by the facility-wide 3.125 Hz distributed trigger, ensuring synchronisation in both time and phase.

The combined RF pulse is injected into the BPM's input port, and the output is fed through the standard down-conversion chain for digitisation.

A beam shift campaign was carried out in June 2024 over offsets ranging from 270 μm to 450 μm. At each position, the injected RF burst was adjusted to cancel the beam-induced signal, and waveforms were acquired via EPICS for offline analysis. From these data, we extracted the amplitudes of both the beam and injected pulses to quantify the matching fidelity at each offset. In principle, integrating these meas-

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ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-MOP020

urements with data from a reference cavity would enable a fully electronic reconstruction of the CBPM calibration, although this full calibration procedure has not yet been applied to the current dataset.

The experimental method consisted of three distinct stages, conducted both with and without beam at the ATF2 facility.

First, to precisely identify the cavity's true resonant frequency, RF bursts were injected into the CBPM with the beam switched off. The injected signal frequency was scanned across a range of ±5 MHz around the nominal dipole mode frequency, and the cavity output amplitude was recorded at each frequency step. The resonant frequency was determined by identifying the frequency that produced the peak cavity response.

Next, with the beam present and held at a static offset, the natural beam-induced CBPM signal was recorded. RF bursts were then injected into the cavity, with their amplitude and phase carefully adjusted until they cancelled the beam-induced signal observed at the readout port. Successful destructive interference confirmed that the injected RF signal closely replicated the beam-induced response. The parameters of the injected signal achieving cancellation were logged and served as proxies for beam position.

Finally, additional calibration scans were performed without beam, where RF pulses of known amplitude were injected and the resulting cavity responses recorded. From these measurements, a calibration curve was generated, correlating the injected pulse amplitude to an equivalent beam displacement. This established an electronic calibration relationship independent of actual beam movement.

These calibration scans consisted of three complementary procedures—timing, amplitude, and phase scans—each crucial for accurately matching the injected pulse to the beam-induced signal:

1. **Timing Scans:** The injected pulse timing was swept across the nominal beam arrival window. At each delay step, the peak amplitude of the combined waveform (injected plus beam-induced signals) was recorded. This amplitude-delay plot exhibited a sinusoidal interference pattern, characterised by alternating peaks (constructive interference) and troughs (destructive interference). A quadratic curve was fitted to the deepest trough, with its minimum point indicating the optimal timing delay for that dataset.

2. **Phase Scans:** With the optimal timing delay established from the timing scans, the relative phase of the injected pulse was systematically varied from 0° to 360°. The combined signal amplitude again displayed sinusoidal behavior. Fitting a quadratic curve to the interference trough identified the precise phase value corresponding to perfect anti-phase alignment (maximum destructive interference), essential for accurate signal matching.

By combining these two scans, we obtain a fully characterised, beam-independent calibration: once timing, phase and amplitude matching are established, the calibration curve can be used online to infer beam displacement directly from the injected-pulse amplitude, without any beam steering.

RESULTS

A dedicated beam shift was conducted at ATF2 in June 2024 to validate the injection matching method. Figure 1 presents three overlaid waveforms: the filtered average of the beam-induced signal (top), the filtered average of the injected RF pulse (middle), and the resulting signal overlap (bottom), each averaged over 50 shots at a fixed beam offset of 280 μm. This comparison illustrates the degree of matching between the injected pulse and the beam-induced cavity response.

The amplitude and phase of the injected signal were adjusted to match the beam-induced signal, setting the injected waveform approximately 180° out of phase (anti-phase) with the beam. This anti-phase condition is most evident during the initial rising portion of the waveforms.

Each waveform was fitted using an exponentially decaying sinusoidal model (illustrated by the orange trace in Fig. 1) to extract key parameters such as amplitude, frequency, decay constant, and phase.

The model used for fitting the measured CBPM signals is described by Eq. (2):

$$y(x) = A\frac{\sin\left[2\pi f(x-x_0)+p\right]e^{-k(x-x_0)}}{1+e^{-b(x-x_0)}}. \tag{2}$$

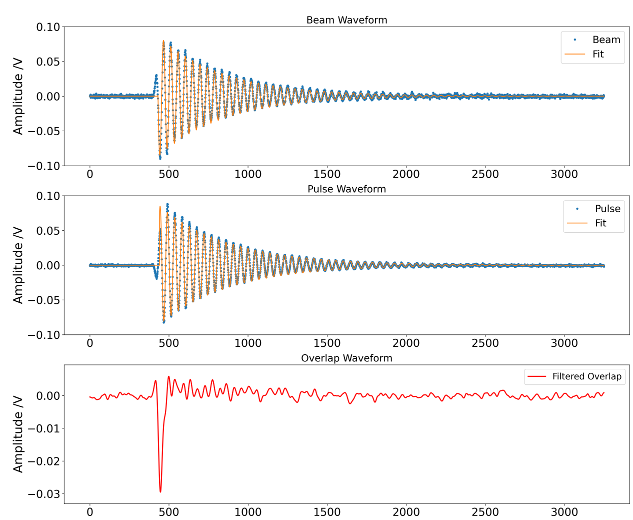

Figure 1: Top: Filtered average of the beam-induced signal. Middle: Filtered average of the injected RF pulse. Bottom: Combined waveform showing destructive interference. All waveforms are averaged over 50 shots at a fixed beam offset of 280 μm. The cancellation fidelity demonstrates how well the injected signal replicates the beam-induced cavity response.

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This model consists of a damped sinusoidal waveform modulated by a sigmoid envelope. Here, A denotes the amplitude of oscillation, f is the frequency, and p is the initial phase offset. The decay constant k characterises how rapidly the signal amplitude diminishes due to cavity damping. The sigmoid function, parameterised by b, shapes the waveform's initial transient rise, while the horizontal offset x_0 marks the start of oscillations in the time domain. Together, these parameters allow accurate representation of both the initial transient and the steady-state decay characteristics of the CBPM signals.

To achieve effective signal cancellation, the injected RF pulse was iteratively adjusted in amplitude and phase to closely match the beam-induced waveform. Figure 1 illustrates the resulting overlap between the beam and injected signals after filtering. The significantly reduced amplitude of the combined signal demonstrates high matching fidelity.

Finally, the beam position was varied between 270 µm and 450 µm to investigate the robustness of signal matching across different offsets. Figure 2 shows the measured amplitudes of the beam-induced, injected, and combined (overlapped) signals. While matching and cancellation were effective at lower offsets, reduced cancellation fidelity at larger offsets suggests increased sensitivity to phase mismatches and timing jitter, highlighting areas for further improvement.

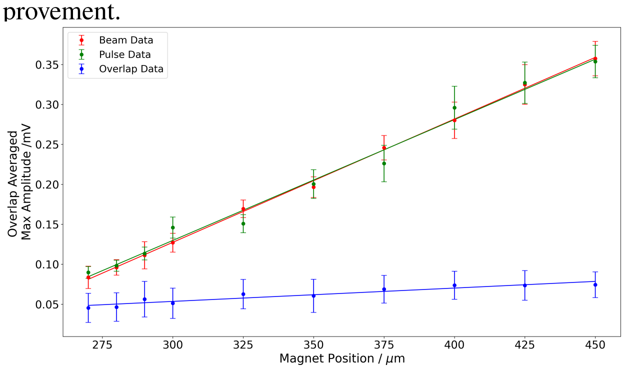

Figure 2: Comparison of beam-induced, injected, and combined RF signals at the CBPM output across various beam offsets. The blue trace represents the residual amplitude after matching.

DISCUSSION AND APPLICATIONS

This work demonstrates a proof-of-principle technique for replicating the beam-induced CBPM signal using externally injected RF. The ability to match and cancel the beam signal provides a diagnostic tool to assess how well the injected waveform reproduces the cavity's dipole mode response. However, without a beam-induced reference cavity signal, this approach does not offer a complete calibration.

Instead, the method should be viewed as a complementary step within the broader calibration process. It establishes a semi-calibrated state, which could reduce the duration and disruption of traditional beam-based calibration once the beam is available. This is particularly valuable in environments with limited beam steering capability or tight time constraints.

One notable limitation of the method is the increasing sensitivity to timing jitter at larger beam offsets. As the beam offset increases, the amplitude of the cavity response also increases. Consequently, any residual phase mismatch or timing jitter between the beam-induced and injected signals has a proportionally larger effect on the cancellation. This underscores the need for precise synchronisation in any implementation of this technique.

This injection-based method provides a practical and scalable complementary calibration strategy for modern linear accelerators and free-electron laser facilities. It is particularly suited to installations that lack beam movers or experience limited access to beam steering. During commissioning, CBPMs can be brought close to a calibrated state electronically before the beam is introduced, reducing setup time.

In routine operation, the technique may serve as a fast-check diagnostic to verify CBPM alignment or to maintain calibration stability between full beam-based procedures. However, its effectiveness is contingent on stable timing systems, especially when working at higher beam offsets where jitter-induced mismatch becomes more pronounced.

Future deployments could integrate the method with EPICS control systems to enable automated RF injection, remote calibration procedures, and potentially live correction routines. Combined with dedicated hardware and FPGA-based processing, the technique could evolve into a semi-autonomous calibration system that supports adaptive diagnostics in high-performance environments.

CONCLUSION

We have demonstrated a practical method for replicating and cancelling the beam-induced CBPM signal using synchronised RF injection. This technique reduces reliance on beam shifts by establishing a semi-calibrated state based on precise signal matching.

While not a complete standalone calibration, the method significantly reduces setup time and operational overhead, particularly in facilities where beam movement is limited. Our results show high matching fidelity at small beam offsets, with successful signal cancellation achieved through careful tuning of amplitude, phase, and timing. However, reduced performance at larger offsets highlights the importance of jitter-free synchronisation hardware.

Looking ahead, this technique offers a scalable path toward real-time, in situ CBPM calibration. With further development, particularly through integration with EPICS control systems and dedicated timing electronics, it could evolve into an automated diagnostic tool for high-performance linacs and free-electron laser facilities.

ACKNOWLEDGEMENTS

We thank the ATF2 team at KEK for their support during the June 2024 beam shift campaign. This work was supported by UK STFC (Grant ST/P00203X/1) and Japan's MEXT Program (JPMXP1423812204).

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