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DESIGN, CHARACTERIZATION, AND VALIDATION OF A PULSED RF BURST SOURCE FOR IN-SITU CAVITY BEAM POSITION MONITOR CALIBRATION

K.O. Kruchinin*
High Energy Accelerator Research Organization (KEK), Ibaraki, Tsukuba, Japan
G. Boorman, A. Lyapin, M.S. McCallum
John Adams Institute at Royal Holloway, University of London, Egham, United Kingdom

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Abstract

Beam Position Monitors (BPMs) are critical instruments in accelerator facilities, providing precise beam orbit measurements with tens of nanometers resolutions, essential for the operation of current linac-based Free Electron Lasers (FELs) and future linear colliders. In this report, we introduce the development and successful testing of a pulsed RF burst source specifically designed for BPM calibration. The source was initially characterized and installed at the ATF2 facility in KEK, Japan. The system injects tailored Radio Frequency (RF) pulses into the BPM cavity via one of the two output ports. With the capability to adjust frequency and pulse width, to emulate beam pulses, the system demonstrated nearly complete cancellation of beam-generated signals when the injected RF pulse overlapped with the beam pulse. This source has the potential for in-situ BPM calibration, mitigation of static signal contributions caused by cavity misalignments and capacity for wakefield compensation. Dedicated hardware development for further refinement of the source is underway at Royal Holloway, University of London, UK, using two *Texas Instruments LMX2820* high-frequency synthesizers triggered by a shared external source to achieve precise phase synchronization between distinct frequencies at defined delays. Preliminary measurements indicate a phase jitter of about 1.2 degrees, currently limited by the trigger signal's slow rising edge (tens of ns), while system requirements demand sub-nanosecond (hundreds of ps) precision for robust, high-frequency phase locking.

INTRODUCTION

Cavity BPMs of various designs are widely deployed across accelerator facilities worldwide [1–5], serving as the cornerstone for high-resolution beam orbit measurements. These devices are essential, offering the only means of achieving tens of nanometer scale resolution — a capability demonstrated most notably at the Accelerator Test Facility (ATF) [6] at KEK, Japan. As part of the final focus system prototype for the proposed International Linear Collider (ILC), the ATF has set benchmark performance standards for cavity BPM technology [7–9].

Despite their critical role, several challenges persist in the design and operation of cavity BPM systems. Cavities are typically mounted in close proximity to optical elements such as quadrupole magnets, often with axial offsets on the order of hundreds of micrometers. These misalignments significantly constrain the useful dynamic range of the BPM system. In addition, regular calibration is often required to mitigate drift effects caused by environmental temperature fluctuations and instabilities in front-end electronics, such as phase shifts [10]. Current calibration procedures [11] — whether through physical displacement of the cavity or beam-based methods like dogleg bumps — are time-consuming and resource-intensive, especially at large facilities managing dozens or even hundreds of BPM units. Furthermore, cavity BPMs are known to introduce wakefields [12] that contribute to emittance degradation, posing a substantial obstacle in maintaining beam quality at the nanometer scale — an essential requirement for next-generation linear colliders.

To address these limitations, we propose a novel technique involving the injection of short, pulsed radio frequency (RF) bursts directly into the cavity via one of its output ports [13]. These pulses are shaped to emulate the electromagnetic signature of an actual beam passage. When synchronized with the beam signal, the injected RF pulse can partially cancel the cavity response, enabling effective calibration without beam presence. This approach not only facilitates fast and fully automated calibration but also provides a method for compensating static signal offsets arising from mechanical misalignments. Additionally, in a dynamic compensation mode, preliminary results suggest that this technique can mitigate wakefields by up to 50%, through pre-filling the cavity with inverse-polarity fields at the moment of beam excitation.

Results of the injected beam overlapping with the BPM signal generated by the ATF beam and calibration procedure have been presented previously in [14, 15]. In this paper, we present the design, characterization, and validation of an RF burst source tailored for such applications. We detail its key performance metrics, tunability, and limitations, and outline a development roadmap toward fully integrated, in-situ calibration solutions for cavity BPM systems.

RF SOURCE DESIGN

The first prototype of the pulse injection source was developed at ATF using discrete components and sources. The schematic diagram of the final version is shown in Fig. 1. A custom-made local oscillator (LO) operating at 6452 MHz was used as the input signal. This same LO was also fed into the BPM front-end for down-conversion.

* konkruz@slac.stanford.edu (present address: SLAC National Accelerator Laboratory, Menlo Park, CA, USA)

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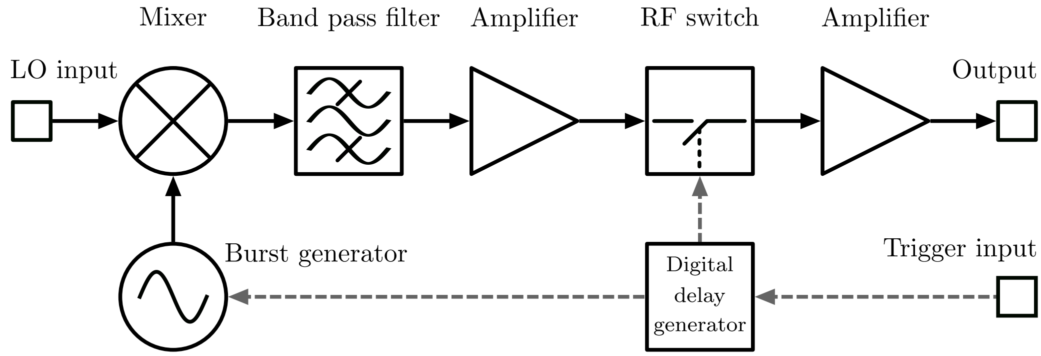

Figure 1: Schematic diagram of the pulse injection source. Solid arrows represent RF paths while dashed grey arrows depict trigger distribution.

To shift the frequency closer to the BPM cavity's resonance, the LO signal was mixed with a burst of low-frequency oscillations generated by an *Agilent 33521* arbitrary waveform generator. Unwanted frequency components were then removed using a narrow-band (~ 10 MHz) band-pass filter, implemented with a spare BPM cavity. Figure 2 displays the signal spectrum both before and after filtering.

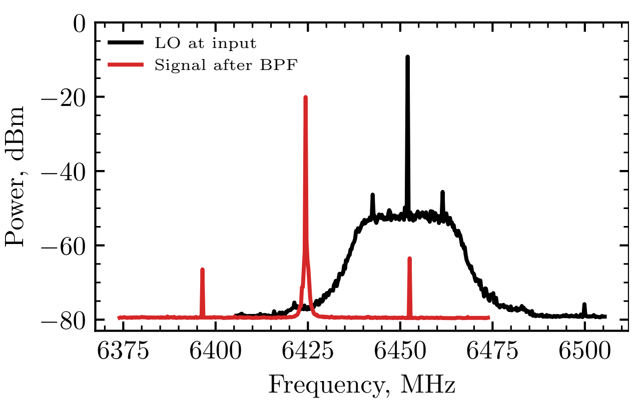

Figure 2: Power spectrum of the LO signal at the input and after the band-pass filter.

A short output burst was generated by a *Narda S213D* fast RF switch, which gated the signal using a fast control pulse lasting only a few tens of nanoseconds. Both the burst generator and RF switch were triggered using a common signal derived from the facility's main RF source. To manage the relative timing of all components, the input trigger was distributed via a *Stanford Research Systems DG535* digital delay generator. An example output waveform, down-converted using BPM front-end electronics, is shown in Fig. 3. To ensure the injected pulse remains in-phase with the signal generated by the beam, which is essential for effective overlap and accurate calibration, the input trigger, low-frequency burst, and LO must be precisely synchronized.

RF SOURCE CHARACTERIZATION

The primary purpose of the proposed RF source is to generate a signal that closely replicates the one produced

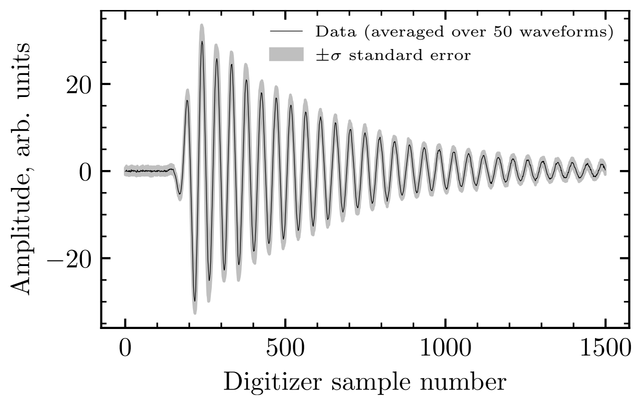

Figure 3: Typical waveform output (down-converted) from the injection source.

by an electron beam passing through a BPM cavity. This facilitates signal overlapping and calibration. To achieve this, the timing, amplitude, and phase of the RF source must be tunable. To match the cavity's resonant frequency, the burst generator's frequency can be adjusted. The optimal frequency corresponds to the point where the output pulse power is maximized. A frequency scan example is shown in Fig. 4. The phase is controlled using the same generator, allowing the injected pulse phase to align with the electron beam signal phase. Another key parameter is the gate pulse for the RF switch. The results of a pulse width scan are presented in Fig. 5. As shown, increasing the gate pulse width causes the signal energy to rise rapidly to the point (~ 25 ns) after which the growth is linear. We also observed a distinct timing shift in the peak position at a specific pulse width (~ 18 ns). The optimal gate pulse width - at which the output signal closely matched the beam signal in terms of temporal structure and decay profile - was found to lie between these two points (the region between the two vertical lines in Fig. 5). Internal timing between source components is controlled by a digital delay generator. Synchronization between the injected pulse and the beam pulse is managed using the facility-wide timing system and trigger distribution based on *SINAP EVO* timing modules.

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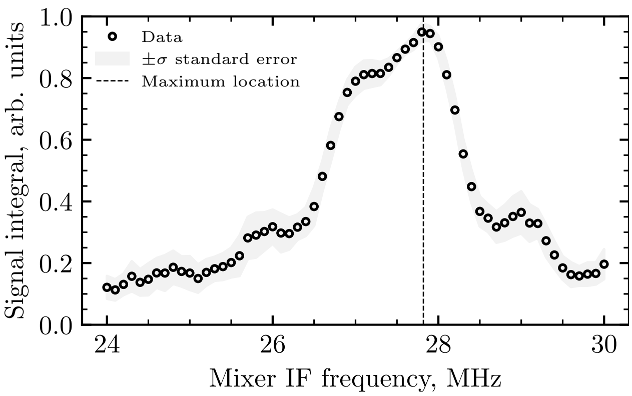

Figure 4: Dependence of the output signal integral on the burst generator frequency.

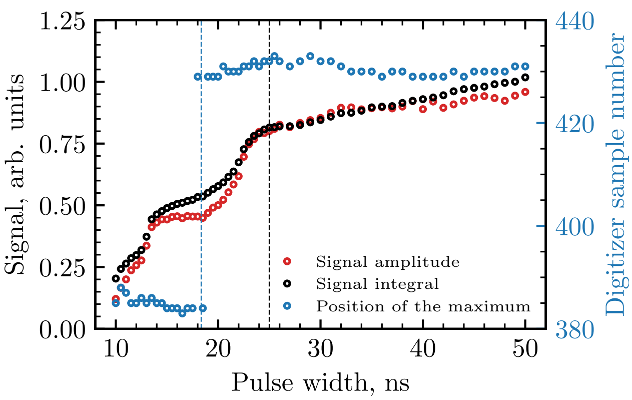

Figure 5: Dependence of the output signal amplitude, integral and peak position on the pulse width of the RF switch gate.

FUTURE DEVELOPMENT

The next stage involves designing a compact, embedded, and cost-effective pulse injection source suitable for mass production. To this end, we have selected the *Texas Instruments LMX2820* - a 22.6 GHz wideband RF synthesizer with integrated phase synchronization [16] - as the core component. A key feature of this chip is its PSYNC function - a dedicated synchronization input that restarts the internal phase engine based on a valid rising edge. This enables a consistent phase relationship between the output waveform and the external trigger, even if that trigger isn't locked to the reference clock. Utilizing two *LMX2820* chips will be sufficient to replicate the functionality of the prototype source shown in Fig. 1. To study and evaluate the synthesizer, a dedicated test bench has been established at Royal Holloway, University of London. Initial tests have confirmed stable frequency synthesis up to 22 GHz, with successful phase synchronization of both RF outputs to the frequencies as high as 350 MHz. In the example shown in Fig. 6, the phase engine aligns two outputs at slightly offset frequencies - 350 MHz and 340 MHz - demonstrating the device's ability to maintain coherent synchronization across independent channels. In our test configuration, both the reference and PSYNC trigger signals are derived from a single *Rohde & Schwarz*

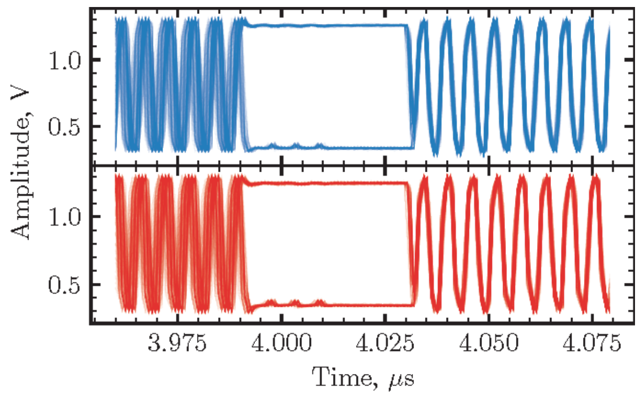

Figure 6: Demonstration of the phase engine aligning two output frequencies: 350 MHz (top) and 340 MHz (bottom) to a common trigger over 500 consecutive acquisitions.

SMA 100A signal generator, ensuring inherent timing alignment and full compliance with PSYNC requirements. Future work aims to assess phase alignment performance at output frequencies up to 12.5 GHz,which is presently limited by the bandwidth and resolution of available data acquisition tools. Addressing these hardware constraints is essential to fully characterize high-frequency phase stability and alignment accuracy. In parallel, improvements to the PSYNC trigger signal are underway, with attention on refining edge transition times toward the sub-nanosecond scale. Ultimately, the system will be integrated into beam diagnostic platforms, where high-fidelity, synchronized RF outputs are essential for advanced accelerator timing and measurement applications.

SUMMARY

We have developed and thoroughly characterized a pulsed RF burst source designed for in-situ BPM cavity calibration. Through tunable timing, amplitude, and phase control, the source effectively replicates the signal produced by an electron beam, enabling direct signal comparison and system calibration. Successful overlap of the synthetic and beam-generated pulses has demonstrated near-complete field cancellation within the BPM cavity.This proof-of-principle effort has laid the groundwork for an embedded, robust version of the system aimed at future beam diagnostic applications. Beyond beam diagnostics, GHz-range pulsed RF sources such as this one have compelling applications in quantum technologies [17]. Additionally, such a source can be particularly valuable at facilities where beam stability is inherently low, for instance, in laser wakefield accelerators [18], making it a versatile tool for environments that demand high-fidelity calibration under fluctuating conditions.

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