Development of a DAQ system for a High Resolution Cavity BPM for the Future Linear Collider

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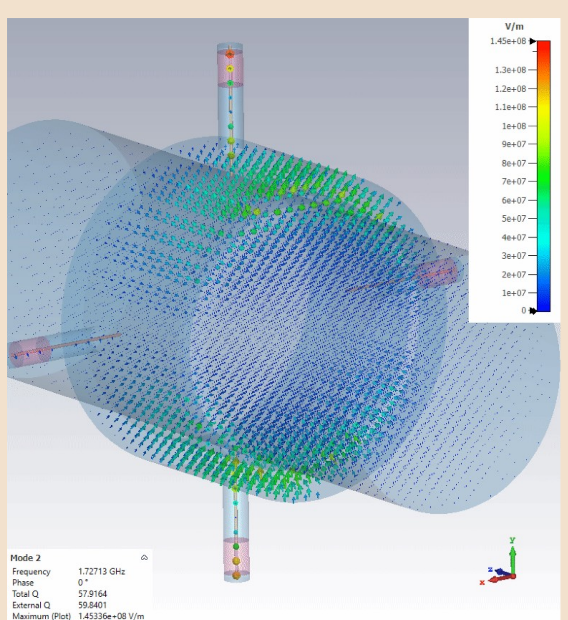
Abstract

A cavity beam position monitor (cBPM) developed by CEA Saclay was **installed at the end of the Accelerator Test Facility (ATF) linac to evaluate the combined performance of the monitor and its associated signal processing system.** The setup incorporates a down-conversion architecture inspired by Royal Holloway, University of London (RHUL), and employs a digital down-conversion (DDC) algorithm to extract beam position. This configuration enables high-sensitivity measurements of the transverse beam position. **Preliminary results confirm successful signal acquisition and a clear position dependent response**, validating the integrated performance of the cBPM, analogue electronics, and digital processing chain. The results underscore the necessity of reliable local oscillator (LO) phase-locking to ensure precise position determination.

CEA SACLAY CAVITY BPM

cBPMs operate under the principle of detection of resonant modes induced by an off-centered beam within a cavity, particularly the TM_{010} and TM_{110} modes [1].

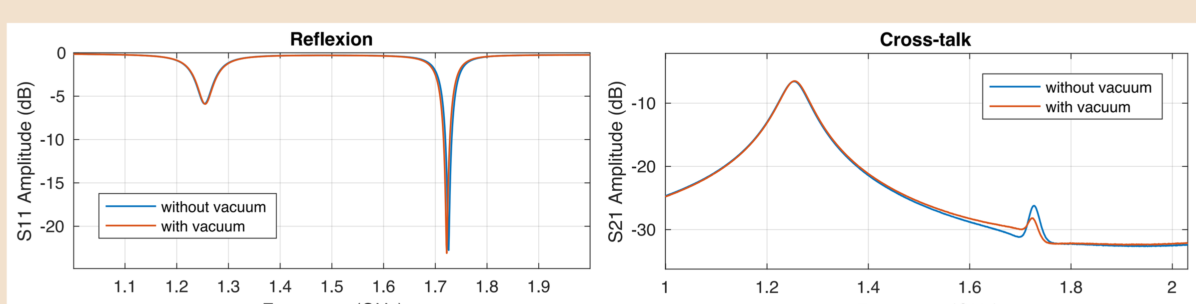


Resonating freq. (GHz): $f_{010} = 1.255$ and $f_{110} = 1.725$

Output signal with beam with an offset δx:

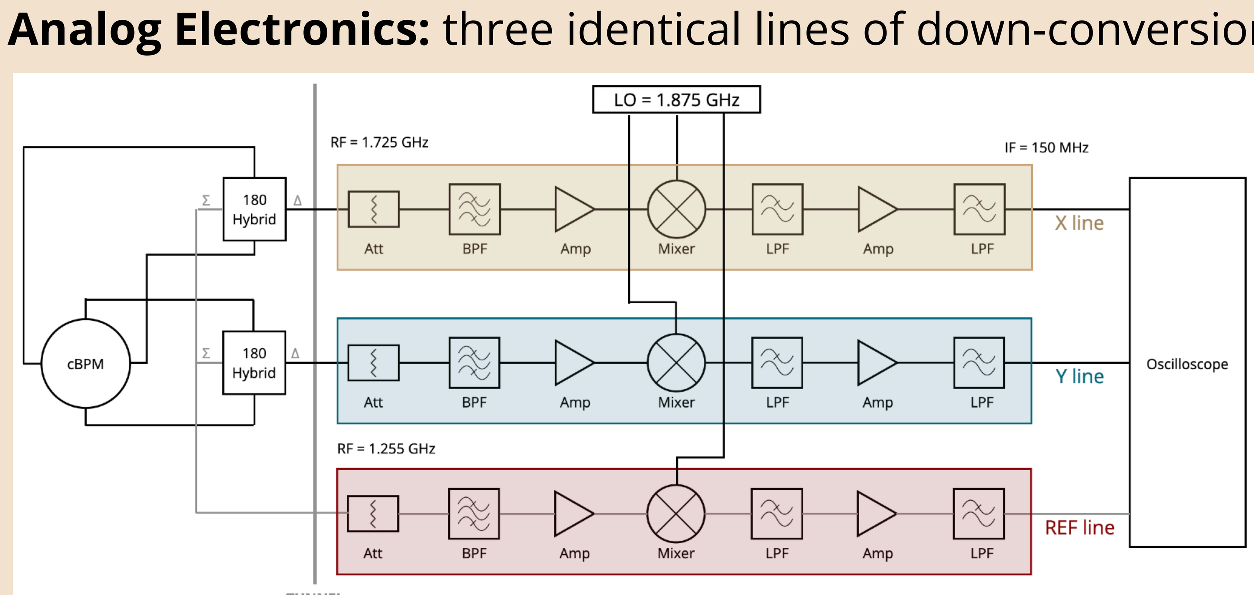
$$V(t) = V_{mnp}\sin(\omega_{mnp}t + \varphi)\exp\left(-t/\tau_{mnp}\right) \quad V_{110} \propto q \cdot \delta x, \quad V_{010} \propto q$$

Model developed by CEA Saclay [2] and currently in operation at the X-FEL facility (DESY). S-parameters where measured before and after installation:



READ-OUT SYSTEM: SIGNAL PROCESSING

Analog Electronics: three identical lines of down-conversion to 150 MHz [3]:



Reference signal is taken from the same BPM and the same LO is used for the 3 signals.
The tail of the reference signal (1.25 GHz) is taken at the position signal frequency (1.725 GHz).

Digital Signal Processing: allows the detection of amplitude and phase of signals position and reference signal after digitalisation [4-5].

$$y_{DDC}(t_i) = \sum_{j=0}^{n} g(t_j - t_i)e^{i\omega_{DDC}t_j} \cdot y_{dig}(t_j)$$

Amplitude: $A(t) = |y_{DDC}(t)|$

Phase:: $\phi(t) = \arg(y_{DDC}(t))$

In-phase and quadrature-of-phase are obtained with normalisation:

$$I = \frac{A_p(t_{s,p})}{A_r(t_{s,r})}\cos\left(\phi_p(t_{s,p}) - \phi_r(t_{s,r})\right)$$

$$Q = \frac{A_p(t_{s,p})}{A_r(t_{s,r})}\sin\left(\phi_p(t_{s,p}) - \phi_r(t_{s,r})\right)$$

After calibration, we can obtain position and tilt signals:

$$P = I\cos\theta_{IQ} + Q\sin\theta_{IQ} \quad (\propto \delta x)$$

$$T = -I\sin\theta_{IQ} + Q\cos\theta_{IQ} \quad (\propto \theta \text{ or } \alpha)$$

References

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[5] WALSTON, Sean et al. Performance of a high resolution cavity beam position monitor system. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2007, vol. 578, no 1, p. 1-22

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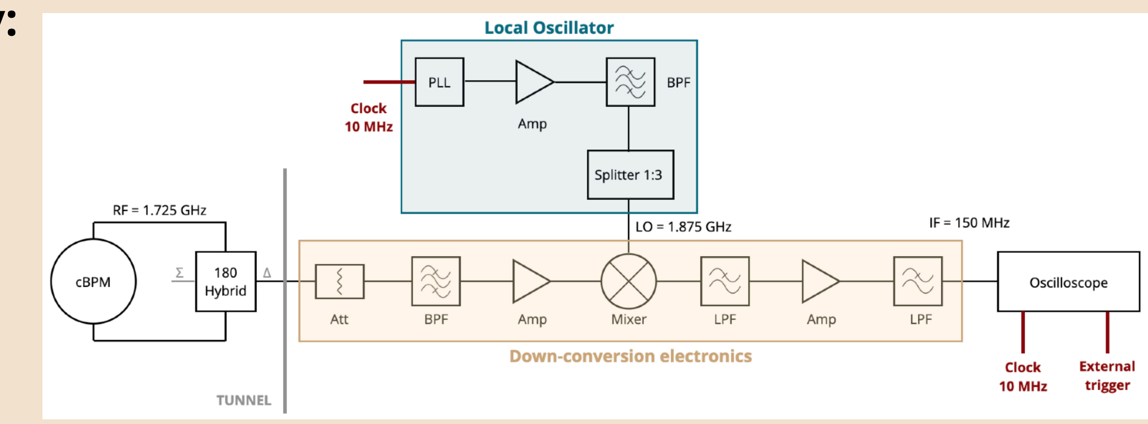
PRELIMINARY TESTS AT ATF LINAC

Measurements methodology:

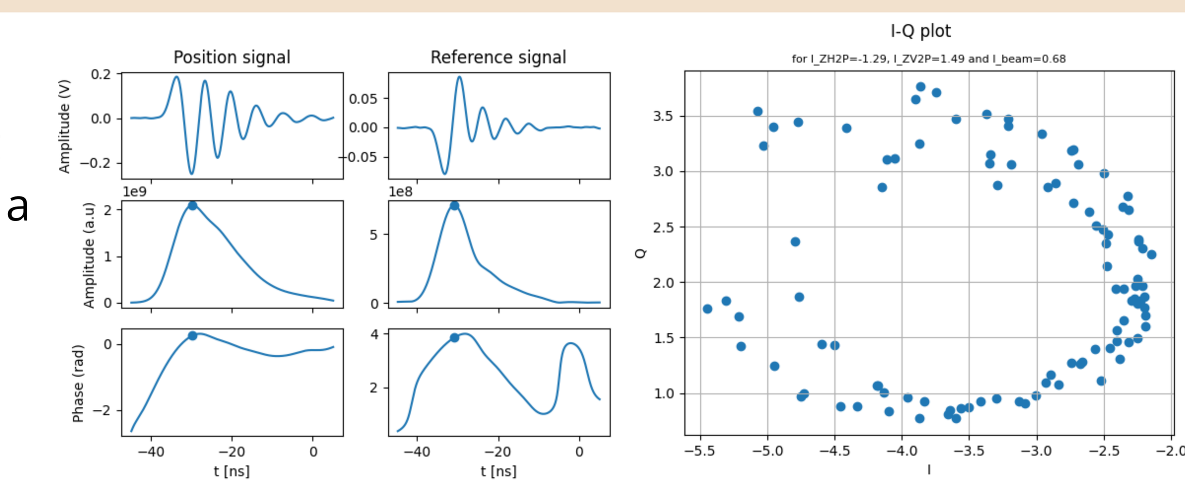
Beam displacements are induced by means of kickers. For each beam position, 100 waveforms are taken. Construction of calibration curve with stripline BPMs.

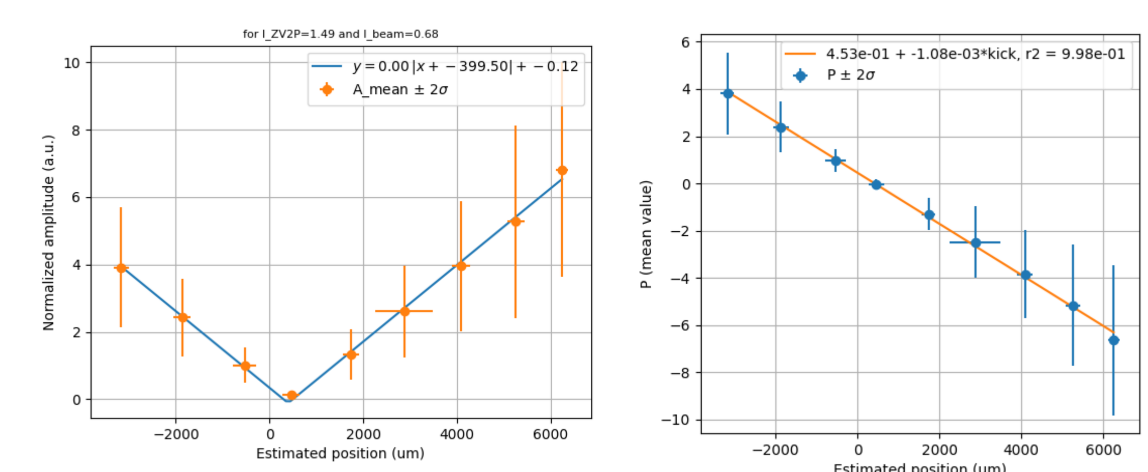


Results:

Using LO = 1.875 GHz to down-convert to 150 MHz:

Determination of A and ϕ by DDC algorithm. IQ-plot ellipsoidal shape suggests a variation in phase difference for each measurement: **the LO is phase-unlocked**.

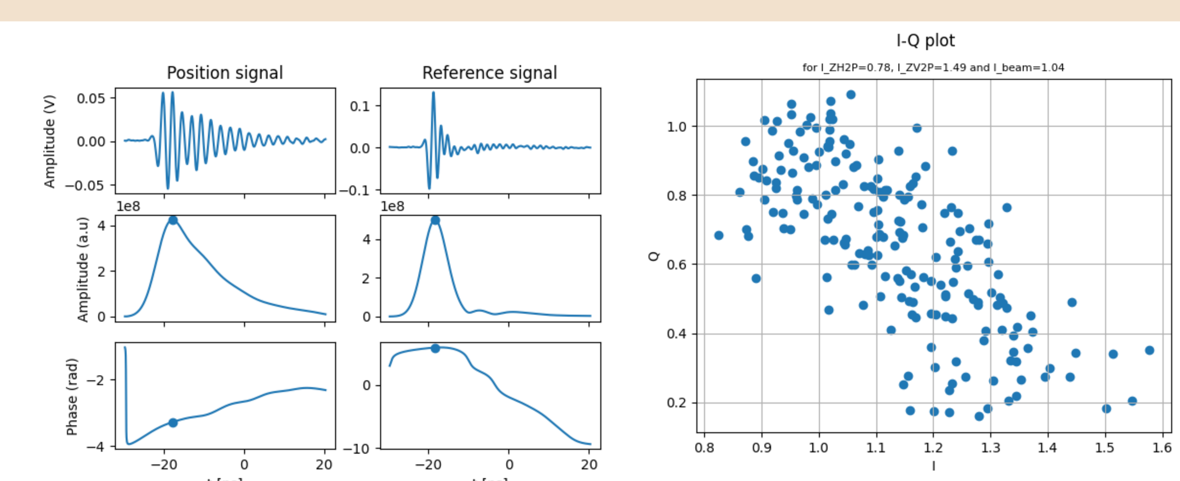


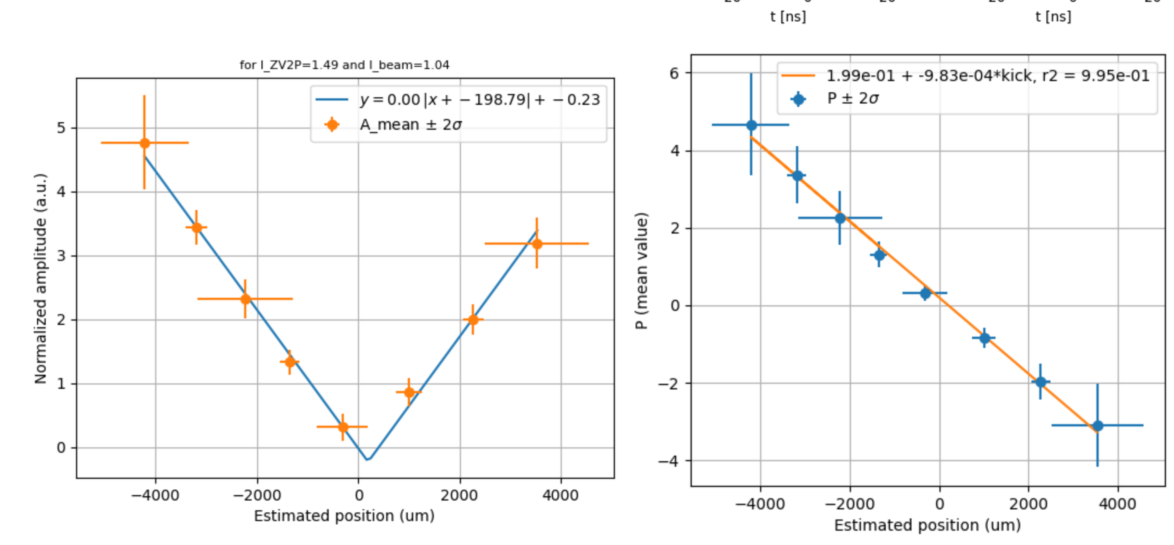


Calibration curve with large error bars due to poor phase-locking. Good linearity is proven. Slight misalignment of around 100 μm.

Using LO = 2.142 GHz (harmonic of 714 MHz) to down-convert to 417 MHz:

IQ-plot suggests that the **LO is phase-locked**. Higher IF frequency required modification of the down-converting electronics.





We observe the effects of beam jitter on IQ-plot. Error bars are reduced. Phase locking allows to perform more precise and consistent measurements.

Measurements of BPM and associated electronics spacial resolution is ongoing.

Conclusion

This work reports the implementation and preliminary testing of the CEA Saclay cavity BPM at the ATF linac, integrated with a dedicated read-out and digital signal processing system. **The measurements confirm successful signal extraction and position sensitivity using digital down-conversion and IQ analysis**. Calibration measurements revealed a mismatch between the electrical and mechanical centers of the BPM, likely due to installation misalignment. **Phase instabilities, attributed to imperfect LO phase-locking, were also identified and addressed by mixing the cBPM RF signal with a harmonic of the 714MHz ATF bunch spacing signal**. These tests underscore the critical importance of robust phase-locking for achieving accurate and stable position measurements. **Future work will focus on resolution studies to fully characterize the performance of the BPM and read-out chain.**

Acknowledgments

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