# FREQUENCY-DEPENDENT RF VOLTAGE CALIBRATION USING LONGITUDINAL TOMOGRAPHY IN THE CERN PSB

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## Abstract

Longitudinal phase-space tomography reconstructs the phase-space distribution from a set of bunch profiles and the accelerator parameters, which includes the RF voltage. The quality of the reconstruction depends on the accuracy to which these parameters are known. Therefore, it can be used for beam-based RF voltage calibration by analysing oscillations of a mismatched bunch. The actual RF voltage may be different from the programmed one due to uncertainties of the electrical gap voltage measurements and intensity effects. Tomography-based RF voltage calibration was systematically performed with low-intensity bunches in all four rings of the PS Booster (PSB) at injection and extraction energy. For each of the three RF cavities present in a given ring, the calibration was performed separately to extract the voltage errors while avoiding any influence of phase misalignments. The number of synchrotron oscillation periods available for the voltage calibration was constrained by the short duration of the PSB flat-bottom and top. Longitudinal beam dynamics simulations using the full PSB impedance model were performed to benchmark the results provided by the calibrations.

# **INTRODUCTION**

Longitudinal tomography is a beam-based technique able to reconstruct the bunch distribution in longitudinal phasespace [1–4]. The main inputs are the measured bunch profiles, the output is the phase-space distribution whose projections best match the measured profiles. The discrepancy D represents the degree of matching between measured and reconstructed profiles. In a tomographic reconstruction, Dtypically decreases and reaches an asymptotic value  $\hat{D}$  after a sufficiently large number of iterations.

Tomography provides accurate results only when certain accelerator and beam parameters are known. While parameters like beam energy are normally known with high precision, the actual voltage  $V_d$  acting on the beam and the phase position  $\hat{\varphi}_s$  of the bucket center with respect to the trigger are difficult to measure. In particular,  $V_d$  can be significantly different from the programmed voltage  $V_p$ , due to uncertainties in electrical voltage measurements and collective effects.

Tomography can be used to find  $V_d$  and  $\hat{\varphi}_s$  [5–7] by determining the  $V_{\rm rf}$  and  $\varphi_s$  values which minimize  $\hat{D}$ . Two methods can be used, as shown in Fig.1. The first one computes  $\hat{D}$  for  $V_{\rm rf} - \varphi_s$  pairs forming a rectangular grid to obtain the minimum  $\hat{D}$ . The second method relies on a minimization algorithm which computes  $\hat{D}$  for selected  $V_{\rm rf} - \varphi_s$  pairs and creates a path converging to the minimum  $\hat{D}$ .

Figure 1: Top: bunch profiles measured with the S7 cavity at injection (left) and extraction (right) energy with  $V_p = 4$  kV. Middle: voltage calibrations using as input the corresponding measured profiles shown above. Bottom: corresponding phase-space reconstructions at turn 1. The reconstructed (red) bunch profiles match well the measured (black) ones.

Bunch oscillations are needed for voltage calibration: if the bunch is perfectly matched, low discrepancy values are obtained with any voltage, since the longitudinal emittance is a free parameter.

The PSB consists of four superposed rings. Each ring is equipped with three independent RF cavities [8] in sectors 5 (S5), 7 (S7) and 13 (S13). In this contribution, tomographybased voltage calibration is applied to all the PSB RF cavities, at injection and extraction energies.

# **MEASUREMENTS SETUP**

Beam measurements were performed at injection and extraction energies in each of the four PSB rings. The voltage at h = 1 in each of the cavities S5, S7 and S13 was measured separately in each ring for constant programmed voltages of 4 kV, 5 kV, 6 kV and 7.5 kV. For each combination of ring, cavity and programmed voltage, ten cycles were recorded. Low Level RF (LLRF) beam phase and radial loops were disabled to avoid damping bunch oscillations. The beam had low intensity to limit the influence of collective effects.

At flat-bottom, measurements started at injection and extended for the entire flat-bottom duration of 0.6 ms. At injection, the beam from Linac4 had a rectangular shape in the (dt, dE) phase space and was not matched to the RF

<sup>0.6</sup> . E 7.5 04 .0 g time Cycle ti 2.5 Cycle 0.0 0.0 500 Time [ns] 100 Time [ns]  $185 \frac{\xi_{\rm e}}{\xi_{\rm e}} = -9\%$  $_{90} \left[ \xi_{e} = -10\% \right]$ [de] 85 မ္ခ်ိဳ 180 ອິ 175 80 V<sub>rf</sub> [kV] V<sub>rf</sub> [kV] 0.01 0.025 D 0.000 0.00 1 10 Turn 1 Turn 1 dE [MeV] dE [MeV] 0 0 -10 -14 -500 250 250 0 25000 500 0 20000 dt [ns] dt [ns]



Figure 2: Voltage errors as a function of the programmed voltages for different numbers of synchrotron periods considered for voltage calibration:  $N_{T_s} = 1$  (magenta), 1.5 (yellow) and 2.5 (black). Beam measurements were taken with the S13 cavity in ring 1 at extraction energy. For a given programmed voltage and  $N_{T_c}$ , the dots represent voltage errors for the ten measured accelerator cycles.

bucket, leading to strong quadrupole oscillations (Fig.1, top left). The bunch intensity,  $N_p$ , was below  $8 \cdot 10^{10}$  p/b.

At extraction energy, measurements started at the beginning of the flat-top and extended for 10 ms. A larger time span could not be used due to the start of the extraction synchronization. Before the beginning of the flat-top, fast jumps of the programmed RF voltage enhanced quadrupole oscillations, while the transient when opening the phase loop created dipole oscillations (Fig.1, top right). The bunch intensity was below  $3 \cdot 10^{10}$  p/b.

#### **VOLTAGE CALIBRATION RESULTS**

Voltage calibrations were performed with beam measurements recorded in early 2022. We studied how the relative voltage-error  $\xi_e = (V_d - V_p)/V_p$  varied when the number  $N_{T_s}$  of synchrotron periods used for calibration was increased (Fig. 2). The measured time spans were sufficient to obtain convergence in all the cases, except for some cycles at flat-bottom with  $V_p = 4$  kV. Convergence in  $\xi_e$  was reached for  $N_{T_s} = 2.5$  and  $N_{T_s} = 0.9$  at flat-top and bottom, respectively.

The voltage errors reported in Fig. 3 are those obtained at convergence. They vary between -7% and -20%, the S7 cavity provides the smallest voltage errors, whereas the S13 cavity gives the largest  $\xi_e$ , except in ring 2.

A cavity which provides lower  $\xi_e$  at flat-bottom also gives lower  $\xi_e$  at flat-top, indicating that the voltage errors are consistent amongst each other. For a given ring and cavity,  $\xi_e$ varies by maximum 3% going from flat-bottom to flat-top. Each group of ten measured cycles has usually a voltageerror spread within 1%, indicating an excellent reproducibility of results from cycle to cycle. The voltage-error spreads due to different  $V_p$  are below 3%.

The voltage errors at flat-bottom presented in Fig. 3 correspond well (within 4%) with voltage errors evaluated from beam measurements taken in 2021 (Fig. 4).



Figure 3: Voltage errors as a function of the programmed voltage for the S5 (blue), S7 (red) and S13 (green) cavities in each PSB ring at flat-bottom (left) and top (right). The beam measurements were taken in 2022. For a given beam energy, ring, cavity, and programmed voltage, the voltage errors for the ten measured acceleration cycles are represented by dots. In each plot, the voltage-error averages and spreads varying  $V_{\rm p}$  are reported for the three cavities.

# ESTIMATION OF SYNCHROTRON **FREQUENCY RATIOS**

As a cross-check that the obtained results were consistent amongst each other, we computed small-amplitude synchrotron frequency  $f_{s,0}$  ratios either as square roots of voltage ratios or as ratios of synchrotron periods. The synchrotron periods were derived by examining the evolutions of bunchprofile positions and lengths, which were computed by using the Full Width at Half Maximum (FWHM).

As an example at flat-bottom, we considered two cycles with  $V_{\rm p} = 5 \, \rm kV$  (Fig. 5, top). The first cycle was measured in ring 4 with the S13 cavity, providing  $\xi_e = -17.9\%$  and  $V_{\rm d}$  = 4.10 kV, whereas the second cycle was measured in ring 1 with the S7 cavity, giving  $\xi_e = -7.9\%$  and  $V_d =$ 4.60 kV. The  $f_{s,0}$  ratio was 1.06 using  $V_d$  or synchrotronperiod values, indicating an excellent agreement between the two methods.

At extraction energy, we examined two cycles with  $V_{\rm p}$  = 4 kV (Fig. 5, bottom). The first cycle was measured in ring 1 with the S13 cavity, providing  $V_d = 3.28$  kV, the

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 $-8.3 \pm 0.4$ [%] % 37 error [ error -15 'oltage 9 ± 0.5  $15.8 \pm 0.5$ -20 Ring 1 FB Ring 2 FB -21 rammed voltage [kV] Programmed voltage [kV] +0.6[%] 1.0 -10 /oltage error  $14.3 \pm 0$ -15 Voltage  $14.7 \pm 1.0$ -20 -20  $17.7 \pm 0.6$ Ring 3 FB Ring 4 FB -25 Programmed voltage [kV] Programmed voltage [kV]

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Figure 4: Voltage errors as a function of  $V_p$  for the S5 (blue), S7 (red) and S13 (green) cavities in each PSB ring at flatbottom. The beam measurements were taken in 2021. For a given ring, cavity, and programmed voltage, the voltage errors for the ten measured acceleration cycles are represented by dots. Averages and spreads varying  $V_{\rm p}$  are reported.



Figure 5: Top: examples of bunch-length evolution for two cycles at flat-bottom with  $V_p = 5$  kV. Left: S13 measured in ring 4. Right: S7 measured in ring 1. Bottom: examples of bunch-position evolution for two cycles at flat-top with  $V_{\rm p}$  = 4 kV. Left: S13 measured in ring 1. Right: S7 measured in ring 3. The bunch lengths are derived by computing the FWHM of the measured bunch profiles, the bunch positions correspond to the central points of the FWHM. For each plot, the vertical lines determine half (top) or one (bottom) synchrotron period, whose values are given as numbers.

second cycle was measured in ring 3 with the S7 cavity, giving  $V_{\rm d} = 3.60$  kV. The  $f_{\rm s,0}$  ratios using detected voltages and synchrotron periods were 1.05 and 1.03, respectively, showing a good agreement (within 2%) between the two methods.

## **BENCHMARKS WITH SIMULATED DATA**

Beam-dynamics simulations including collective effects and using realistic initial bunch distributions were performed



Figure 6: Left, from top to bottom: simulated profiles at injection energy, profile (blue) at 0.3 ms with space charge (red), impedance (orange) and total (green) induced voltages, voltage calibration. Right: corresponding plots for simulated profiles at extraction energy.

with the CERN BLonD code [9]. The goal was to verify that voltage calibrations using the simulated profiles provided as result the RF voltage (4 kV) assumed in simulations.

At flat-bottom, the bunch intensity was  $N_p = 8 \cdot 10^{10} \text{ p/b}$ and the space charge was modelled as an inductive impedance with  $|Z/n| = 640 \Omega$  [10]. The voltage calibration provided a voltage error of just -0.5% (Fig. 6, left).

At flat-top, the induced voltage was dominated by the resistive impedance of the RF cavities, the space charge voltage  $(|Z/n| = 17 \Omega)$  became almost negligible. Figure 6 (right) shows that  $\xi_e$  was only -0.2%. The voltage difference was just 7 V, much lower than the peak induced voltage of 500 V during bunch oscillations: the induced voltage was mostly resistive, so the bunch synchrotron frequency, and therefore  $V_d$ , was only slightly affected by collective effects.

## **CONCLUSIONS**

Tomography-based voltage calibrations were systematically applied in the PSB. The measured time-spans were in general sufficient to obtain convergence in voltage errors, which arrived up to 20%. The spreads from cycle to cycle were negligible. The spreads due to different programmed voltages and beam energies were small. Since the transfer function for the gap return has approximately constant gain over the considered frequency range and is independent of signal amplitude, this was expected.

Synchrotron frequency ratios were computed using detected voltages and synchrotron periods. The agreements were good, demonstrating the consistency of the voltagecalibration results. Benchmarks with realistic simulated profiles provided voltage errors below 1%, indicating that

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the voltage calibrations applied to the measured profiles are reliable.

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