OPTICS CHARACTERIZATION AND RESONANCE DRIVING TERM STUDIES FOR THE SPS CRAB CAVITY TESTS IN 2025

P. Zisopoulos*, E. MacLean, M. Stefanelli, CERN, Geneva, Switzerland

Abstract

To prepare for the High Luminosity LHC, the crab cavities to be used in the upgrade have been tested in the CERN Super Proton Synchrotron (SPS). Machine studies have been carried out to investigate optics perturbations introduced by the crab cavities and their relation to resonance driving terms. Particular emphasis was placed on identifying possible sextupolar components and assessing their impact on the betatron tune. Measurements using controlled orbit bumps were performed to isolate the cavity contribution and to benchmark model predictions. The results provide valuable input for the interpretation of beam dynamics observations during the tests and for the refinement of the SPS optics model in view of future crab cavity studies.

INTRODUCTION

The crab cavity (CC) studies at CERN aim to validate CC technology for the High-Luminosity LHC (HL-LHC), which requires transverse RF deflection to restore head-on bunch crossing at the interaction points [1]. A CC test module has been installed in the SPS in Long Straight Section 6 (LSS6) [2] to characterise CC operation with proton beams.

Due to the lack of azimuthal symmetry, higher-order RF multipole components arise [3–5]. With the CC module oriented for horizontal crabbing, the dominant component is the normal sextupolar term b_3, which excites resonance driving terms (RDTs) and causes feed-down tune shifts at non-zero orbit offset. For the Radio-Frequency Deflector (RFD) design (currently installed), $K_3L \approx 0.012\,\mathrm{m}^{-2}$ [3].

In parallel with the CC beam tests, short dedicated studies used the SPS extraction sextupole LSE.20602 to emulate the expected CC sextupolar component and validate the measurement technique. The SPS features 215 beam position monitors (BPMs) [6] that provide turn-by-turn (TbT) data, enabling optics measurements via the Optics Measurement and Correction (OMC) tool [7]. The AC dipole excitation scheme implemented in the SPS [8], using the Base-Band Tune (BBQ) system [9] and the transverse damper (ADT), was used for the RDT measurements.

This paper reports results from studies in 2025 covering feed-down tune shifts and optics model characterisation, and a follow-up study in 2026 for AC-dipole RDT measurements.

EXPERIMENTAL MEASUREMENTS

Set-up

All measurements used the SPS LHC injection (Q20) optics at working point $Q_x/Q_y = 20.13/20.18$. The SPS extraction sextupoles (LSE) can be powered individually to generate controlled feed-down via orbit bumps. LSE.10602 was initially tried but abandoned as a chromatic LSF sextupole within the bump produced a spurious shift; LSE.20602 was used instead. A three-corrector orbit bump produced a closed horizontal displacement at LSE.20602, where the Q20 optics give $\beta_x \approx 97\,\mathrm{m}$, $\beta_y \approx 35\,\mathrm{m}$. Table 1 lists key optics parameters at both locations; the β-function ratio between the two locations sets the K_3L scaling required to recover the expected tune shift at the CC.

Table 1: Nominal Q20 Optics Parameters at the Two Key Locations

Element	s [m]	β_x [m]	β_y [m]	D_x [m]
LSE.20602	1341	97	35	1.13
CC (ACFCAN 61738)	6313	41.3	84.1	−0.59

The bump produced closed displacements of $x_+ = +30\,\mathrm{mm}$ and $x_- = -20\,\mathrm{mm}$ on successive plateaux within the same injection cycle. The sextupole strength $K_3L = 0.0125\,\mathrm{m}^{-2}$ (as set in LSA [10]) matches the estimated CC integrated strength.

Two measurement modes were employed: the BBQ system for continuous tune monitoring during the bump (no kicker needed), and single-kick TbT BPM data for optics measurements (phase advance, beta beating) with the OMC tool. Single kicks were applied inside both bump plateaux; Fig. 1 shows the recorded BPM excitation. The beam was a single pilot bunch (~ 10^{10} protons) for the 2025 sessions.

Optics Measurements

In 2025, a significant mismatch in the cumulative betatron phase advance was found between the best-knowledge model (quadrupole strengths from LSA) and a model matched to the measured tunes. As shown in Fig. 2, the best-knowledge model reaches a phase error of up to $0.4 \times 2\pi$. Matching to the measured tunes requires the defocusing quadrupole strengths to be ~1% larger than the LSA settings; this matched model reproduces the BPM phases closely. This mismatch is currently under investigation, as an accurate optics model is important for both CC beam dynamics interpretation and SPS operation. The horizontal phase advance could not be determined with confidence due to the fast horizontal decoherence.

Figure 3 shows fractional tunes from a 60-turn sliding-window analysis [11] of the single-kick TbT data, with the bare SPS machine. The horizontal coherent motion decays significantly faster than the vertical, limiting the useful signal length. Slow tune modulations from 50 Hz mains ripple of the main magnet converters (~900 turn period) and faster modulations at 600 Hz from 12-pulse rectification are also visible.

* panagiotis.zisopoulos@cern.ch

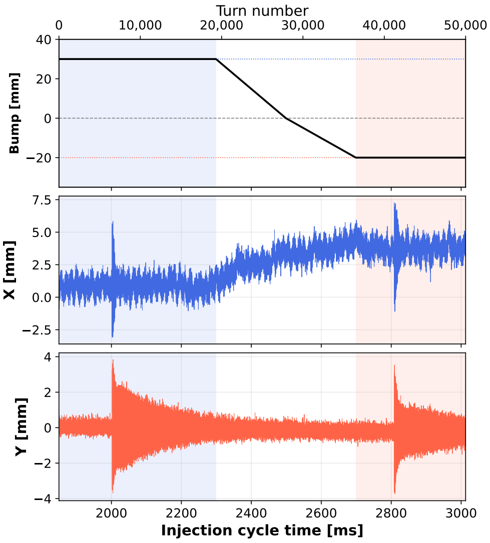

Figure 1: TbT BPM data with single-kick excitation during the orbit bump cycle at LSE.20602. Top: bump amplitude. Middle/bottom: horizontal (BPH.40208) and vertical (BPV.23108) positions. The bottom axis shows time elapsed since injection; the top axis gives the corresponding turn number. Shaded regions mark the +30 mm (blue) and −20 mm (red) plateaux.

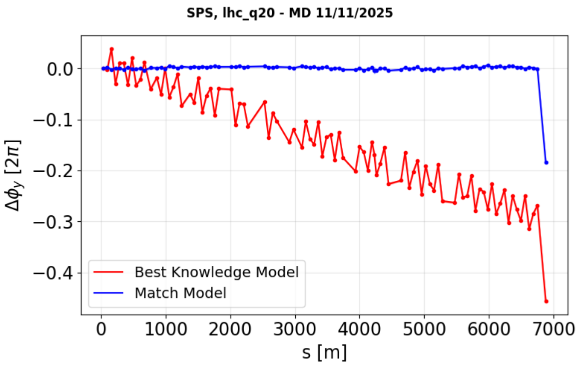

Figure 2: Cumulative vertical phase advance error along the SPS. Red: best-knowledge model (LSA quadrupole settings). Blue: model matched to measured betatron tunes. The best-knowledge model deviates by up to $0.4 \times 2\pi$.

Sextupolar Tune Shifts

A sextupole with integrated strength K_3L [m^{-2}] traversed at horizontal closed orbit offset x_0 shifts the betatron tunes through feed-down:

$$\Delta Q_{x,y} = \pm \frac{1}{4\pi} K_3 L \, x_0 \, \beta_{x,y} \,, \qquad (1)$$

with +/− for the horizontal/vertical plane.

To suppress the modulations visible in Fig. 3 and cancel static orbit drifts, the BBQ system tracks tunes continuously and a tune difference is computed from the two bump plateaux:

$$\Delta Q^{+/-}_{x,y} = Q_{x,y}(x_+) - Q_{x,y}(x_-) = \pm \frac{1}{4\pi} K_3 L \, (x_+ - x_-) \, \beta_{x,y} \,. \qquad (2)$$

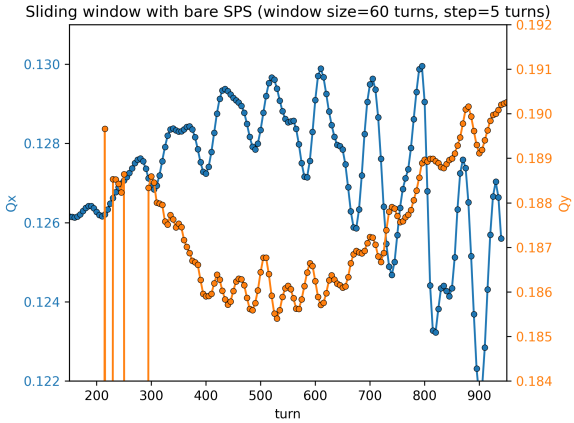

Figure 3: Fractional tunes from using a sliding-window of 60 turns on the TbT data (bare machine, single kick): Q_H (blue) and Q_V (orange). Slow (~900 turn) modulations from 50 Hz mains ripple of the main magnet converters and faster modulations from 600 Hz (12-pulse rectification) are visible alongside the asymmetric decoherence.

Figure 4 shows the BBQ tune readings Q_H and Q_V versus injection cycle time for four K_3L settings of LSE.20602 extraction sextupole. With $K_3L = 0$ (black curve), no tune shift is seen at either plateau, confirming the bump alone does not perturb the tunes. With $K_3L > 0$, Q_H rises and Q_V falls at the positive plateau, both reversing at the negative plateau, in agreement with Eq. (1). The setting $K_3L = 0.0125\,\mathrm{m}^{-2}$ (orange curve) matches the estimated CC sextupolar strength and already produces a clearly visible tune excursion at each plateau.

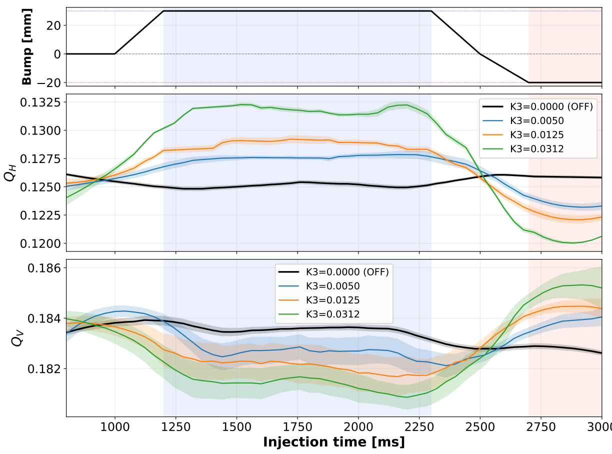

Figure 4: BBQ tune readings Q_H (middle) and Q_V (bottom) versus injection cycle time for four K_3L settings of LSE.20602 (each colour one setting). Top: orbit bump amplitude. Blue/red shading marks the +30 mm/ −20 mm bump plateaux.

Figure 5 shows $\Delta Q^{+/-}_{x,y}$ versus K_3L. Both planes exhibit a clear linear dependence with the correct sign, in agreement with the prediction from Eq. (2) using β-functions from Table 1 and $(x_+ - x_-) = 50\,\mathrm{mm}$. The setting $K_3L = 0.0125\,\mathrm{m}^{-2}$ (matching the CC sextupolar strength) produces a clearly measurable tune shift, confirming sensitivity to the CC b_3 component. Furthermore, owing to the ~2.5× larger β_y at the CC location (Table 1), the highest setting $K_3L = 0.03\,\mathrm{m}^{-2}$ reproduces the tune shift expected from the CC during crabbing operation.

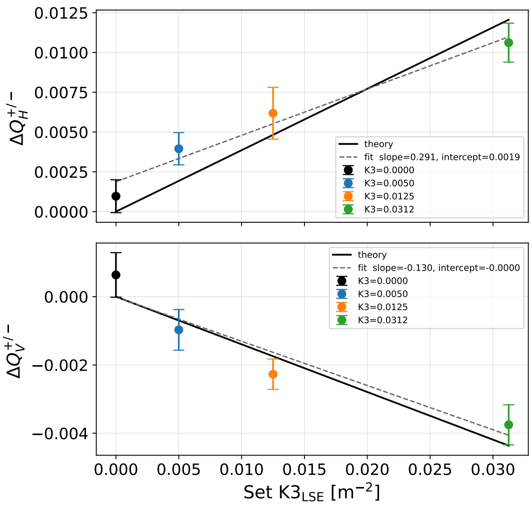

Figure 5: Tune difference $\Delta Q^{+/-}$ vs. K_3L for H (top) and V (bottom). Points: mean ± SEM. Solid line: prediction from Eq. (2); dashed: linear fit. At $K_3L = 0.03\,\mathrm{m}^{-2}$ provides the expected tune-shift at the CC location ($|\Delta Q_H^{+/-}| \approx 0.012$, $|\Delta Q_V^{+/-}| \approx -0.004$).

Initial attempts to measure RDTs used a single pilot bunch at working point $Q_x/Q_y = 20.13/20.41$, near the $Q_x + 2Q_y$ resonance. While the main tune line was visible, resonance sidebands remained below the noise floor and fast horizontal decoherence further limited the coherent signal, making quantitative RDT extraction impossible.

AC-DIPOLE MEASUREMENTS

To improve the signal-to-noise ratio (SNR) for RDT extraction, a 2026 study used AC-dipole excitation [8] with 72 bunches of $\sim 5 \times 10^{10}$ protons. After energy, tune and chromaticity corrections, drive frequencies $Q_{x,d} = 0.145$, $Q_{y,d} = 0.215$ were chosen to approach the $Q_x + 2Q_y$ resonance.

Figure 6 (top) shows TbT data over 60 000 turns with well-sustained oscillations in both planes. The frequency spectrum (bottom) shows well-resolved resonance lines above the noise floor, achievable only with the sustained forced oscillations provided by the AC dipole. Three lines beyond the driven frequencies are resolved: $2Q_x \approx 0.29$ (f_{3000}, the expected normal sextupole signature), and $3Q_y \approx 0.355$, $2Q_y \approx 0.43$ (consistent with octupole and skew sextupole components of the SPS lattice).

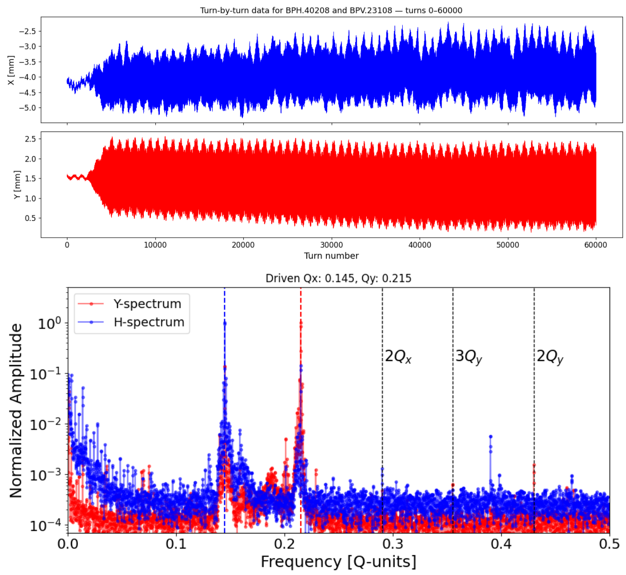

Figure 6: Top: TbT BPM data from the AC-dipole excitation with 72 bunches ($Q_{x,d} = 0.145$, $Q_{y,d} = 0.215$) over 60 000 turns. Bottom: normalised frequency spectrum; resonance lines at $2Q_x$, $3Q_y$ and $2Q_y$ are resolved above the noise floor.

CONCLUSIONS

Using LSE.20602 as a controlled proxy for the CC normal sextupolar component (b_3), tune shifts linear in K_3L were measured in both planes. The BBQ tune measurement at sextupole strength $K_3L = 0.0125\,\mathrm{m}^{-2}$, matching the expected CC strength, confirms that the feed-down technique has sufficient sensitivity to resolve the CC b_3 component during crabbing operation. A cumulative vertical phase error of up to $0.4 \times 2\pi$ between the best-knowledge and tuned models highlights the need for an accurate optics model for CC studies. Single pilot-bunch data gave insufficient SNR for RDT extraction; the higher-intensity multi-bunch AC-dipole measurement resolved $2Q_x$, $3Q_y$ and $2Q_y$ resonance lines, establishing the baseline technique for future CC RDT studies. The H/V decoherence asymmetry and the LSA model discrepancy are subjects of ongoing follow-up studies.

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