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BEAM-BASED MEASUREMENT OF SKEW-SEXTUPOLE ERRORS IN THE CERN PROTON SYNCHROTRON

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Abstract

During Proton Synchrotron (PS) commissioning in 2021, beam losses were observed when approaching the $3Q_y$ resonance if the Beam Gas Ionization (BGI) profile monitor was enabled. This indicated the presence of a strong skew-sextupole source in this instrument. Beam-based measurements of the skew-sextupole component in the BGI were performed, to benchmark the BGI magnetic model and provide quantitative checks of sextupole corrections determined empirically to minimize the beam-losses. In this contribution, results of the successfully performed measurements are presented, including tune feed-down, chromatic coupling and resonance driving terms (RDT).

SKEW-SEXTUPOLE IN THE PS BGI

Since 2021 a Beam Gas Ionization monitor is installed in the CERN PS to provide non-destructive emittance measurement [1, 2]. In the BGI, interaction between protons and residual gas generates charged ions. An external electric field accelerates the ionization electrons to a detector system, while a 0.2 T magnetic field (parallel to the electric field) confines the electrons along the plane of interest. A triple-dipole design is employed, where a central dipole provides the instrumental field, and dipoles either side compensate the orbit distortion. Fields inside the BGI are shielded from stray fields of the PS Main Unit magnets (MU) by shielding plates on either side. A schematic of the BGI instrument is shown in Fig. 1.

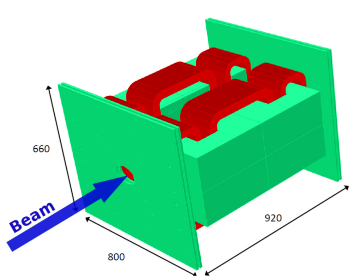

Figure 1: Schematic of the PS BGI and shielding plates [3].

During 2021 PS commissioning tune-scans were performed across the $3Q_y$ resonance. With the BGI magnet disabled minimal beam-losses were observed, but with the BGI enabled it was observed that ≈ 50 % of the beam was lost upon crossing the $3Q_y$ resonance [4].

Observation of losses at the $3Q_y$ upon enabling the BGI indicated the presence of a significant skew-sextupole (a_3) source generated by the BGI instrument [4]. Studies of the magnetic model [3, 5] indicated that an a_3 can be generated by the interplay of the BGI magnet with the shielding plates, but was highly dependent on the aperture design. A series of beam-based measurements were then performed in the PS at injection (magnetic rigidity $B\rho = 9.3$ [Tm]) to attempt to measure the skew-sextupole generated by the BGI in order to compare to the magnetic model prediction. Studies of chromatic-coupling, tune feed-down and the $3Q_y$ RDT were performed. Results of the beam-based studies are presented in this paper.

CHROMATIC-COUPLING MEASUREMENT

Chromatic coupling is the momentum dependence of linear coupling, generated by skew-sextupoles in regions of non-zero horizontal dispersion. It is characterized [6] via the change with $\delta p/p$ of the f_{1001} RDT (driving the $Q_x - Q_y$ linear coupling resonance), where the closest tune approach ($|C^-|$) is related to the RDT as

$$|C^-| \approx 4|Q_{x,frac} - Q_{y,frac}||f_{1001}| \tag{1}$$

and $Qx, y, frac$ are the fractional tunes. The BGI model predicts an integrated skew-sextupole ($n = 3$) field at the reference radius ($R_{ref} = 20$ mm)

$$A_n L = \int \mathrm{d}s \frac{R_{ref}^{n-1}}{(n-1)!} \frac{\partial^{n-1} B_x}{\partial x^{n-1}} = -5.5 \times 10^{-4} \text{ [Tm]} \tag{2}$$

By contrast magnetic measurement of the skew-sextupole field of a PS MU at injection powering (404 A) gives $A_3 L = 1.2 \times 10^{-6}$ [Tm] at the same R_{ref} (2 orders of magnitude smaller) [7]. As such the BGI when powered should represent the dominant source of chromatic coupling.

The PS is not equipped with dedicated kicker magnets for optics studies. Beams can be excited however using the transverse damper (ADT) to drive forced oscillations at a frequency (Q_{AC}) close to the natural tunes (Q_{nat}). This is known as ADT-AC-dipole type excitation, and coupling measurement can be performed as for a conventional AC-dipole [8, 9]. An example of turn-by-turn (TbT) BPM data during an ADT-AC-dipole kick is shown in Fig. 2.

To provide an initial qualitative check of the PS skew-sextupole model chromatic coupling was measured using the PS ADT. Figure 3 shows the real and imaginary parts of f_{1001} linear coupling RDT (expressed in C^- units) measured on-momentum, and then upon application of $\Delta p/p = 0.001$ offset. With the BGI unpowered the coupling measurement is unchanged by the momentum trim. With the BGI enabled however, a clear shift in the linear coupling is observed. This confirms the expectation from magnetic models that the BGI skew-sextupole should represent the dominant skew-sextupole source in the PS ring.

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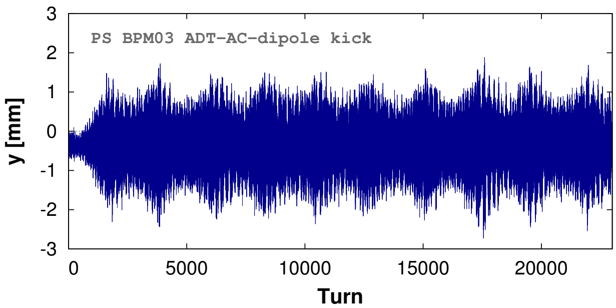

Figure 2: Example of turn-by-turn BPM data during excitation with ADT-AC-dipole.

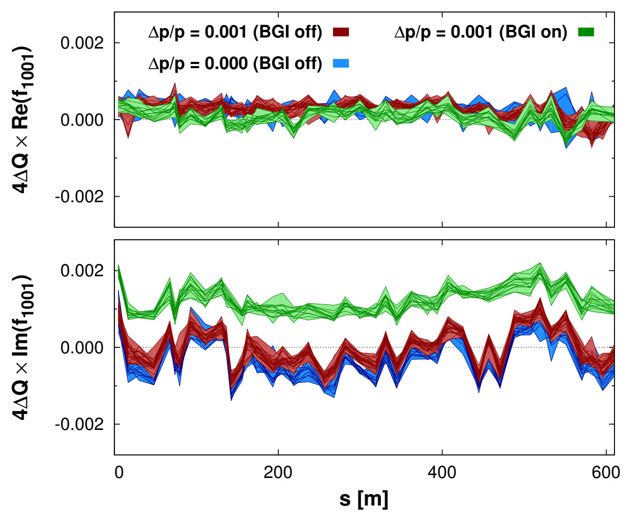

Figure 3: Real and imaginary parts of f_{1001} measured on- and off-momentum with BGI enabled / disabled.

MEASUREMENT OF TUNE FEED-DOWN

Skew-sextupoles feed-down to generate a tune shift with vertical offsets. To check the BGI skew-sextupole strength, vertical orbit bumps were generated across the BGI in a ±8 mm range. A MAD-X simulation of the bump is shown in Fig. 4. Tune was measured for different settings of the orbit bump by obtaining Q_{nat} from the spectrum of kicks with the ADT-AC-dipole. Change of Q_y vs orbit offset at the BGI is shown in Fig. 5 (with similar results obtained for Q_x). With the BGI depowered no tune-change vs orbit can be discerned. With the BGI enabled a clear linear feed-down from the skew-sextupole component is observed. Fits of tune change vs orbit were used to measure integrated skew-sextupole strength ($K_{3s}L$), where integrated strength (in units $[\mathrm{m}^{1-n}]$) is defined:

$$K_{ns}L = \frac{1}{B\rho}(n-1)!A_nLR_{ref}^{1-n} \tag{3}$$

From the magnetic model the expected strength at injection energy was:

$$K_{3s}L = -0.29\ [\mathrm{m}^{-2}] \tag{4}$$

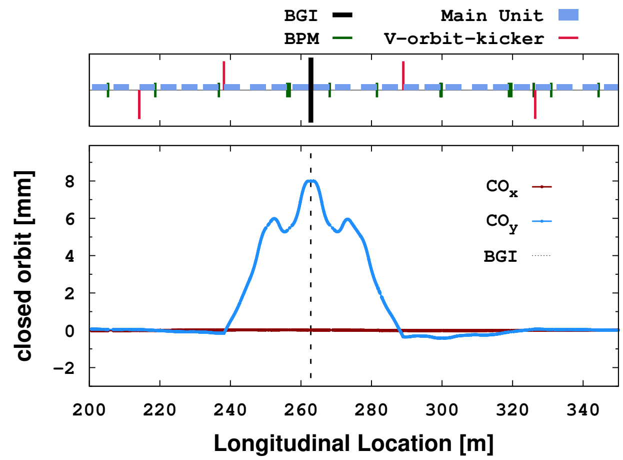

Figure 4: Simulation of orbit bump used to measure feed-down from the BGI skew-sextupole.

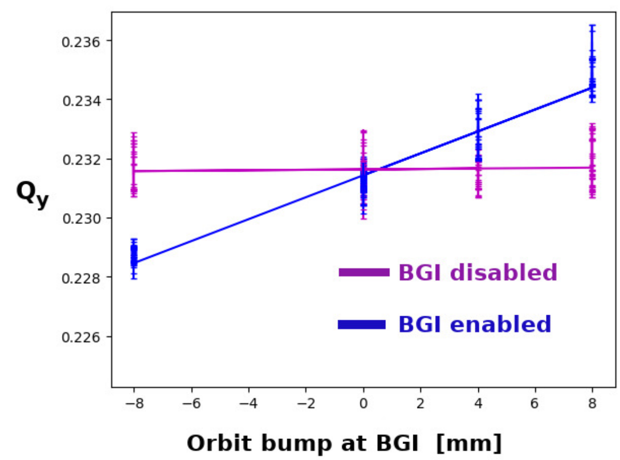

Figure 5: Feed-down to Q_y from the BGI.

Independent estimates from the $Q_{x,y}$ measurements give:

$$K_{3s}L = -\frac{4\pi}{\beta_x}\frac{\partial Q_x}{\partial y} = +0.27 \pm 0.02\ [\mathrm{m}^{-2}] \tag{5}$$

$$K_{3s}L = \frac{4\pi}{\beta_y}\frac{\partial Q_y}{\partial y} = +0.21 \pm 0.04\ [\mathrm{m}^{-2}]$$

Beam-based measurements show comparable magnitude to the magnetic model, but indicate an opposite sign to expectation. The source of the sign discrepancy is not understood, but may reflect an error in handling the orientation of the magnetic model compared to real installation or differing conventions for the errors between magnetic and optics simulations.

MEASUREMENT OF 3Q_y RDT

Skew-sextupoles drive the $3Q_y$ resonance, characterized by the f_{0030} RDT. RDTs can be measured using TbT BPM data excited via AC-dipole [10–12], by measuring resonance lines in the tune-spectra. For the f_{0030} RDT driving $3Q_y$, a spectral line is expected at $-2Q_y$. For a driven oscillation a line is expected at $-2Q_{y,AC}$. A measured frequency-spectra

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for PS excitation with ADT-AC-dipole is shown in Fig. 6. The $-2Q_{y,AC}$ line is clearly visible. The Re component of the driven f_{0030} measured from all BPMs is shown in Fig. 7 (red). Results (green) of a tracking simulation including a BGI error of $K_{3s}L = +0.25\ [\mathrm{m}^{-2}]$ (the weighted mean from Q feed-down results) show a good phase-agreement to the measurement, confirming the sign ambiguity with respect to the magnetic model.

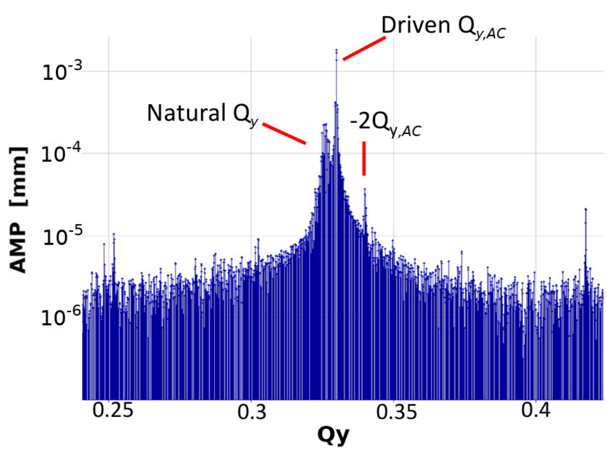

Figure 6: Measured vertical frequency spectra with BGI enabled.

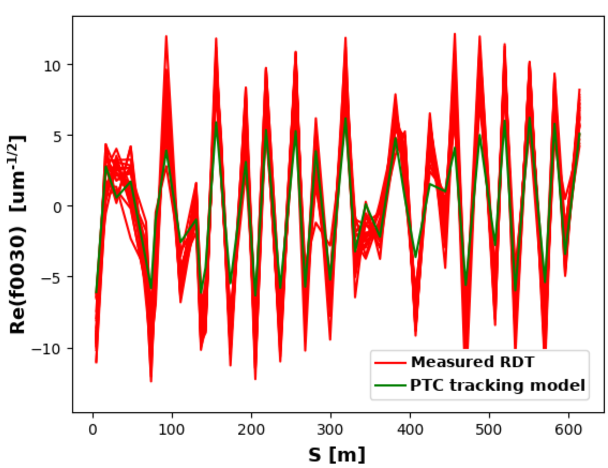

Figure 7: Measured and modelled Re(f_{0030}).

Corrections for the BGI skew-sextupole were determined empirically in 2021, by varying a_3 correctors to minimize beam-loss upon crossing $3Q_y$ [4]. A frequency-spectra measured after correction is shown in Fig. 8. The $-2Q_y$ line is substantially reduced compared to Fig. 6. Figure 9 shows the f_{0030} measured in all BPMs before (red) and after (green) correction. Measurement with correction applied but BGI disabled is also shown (blue). The beam-loss correction is seen to correct the RDT all around the ring. Comparing red and blue measurements the beam-loss correction acted in anti-phase to the BGI error, confirming the high quality of the empirical compensation.

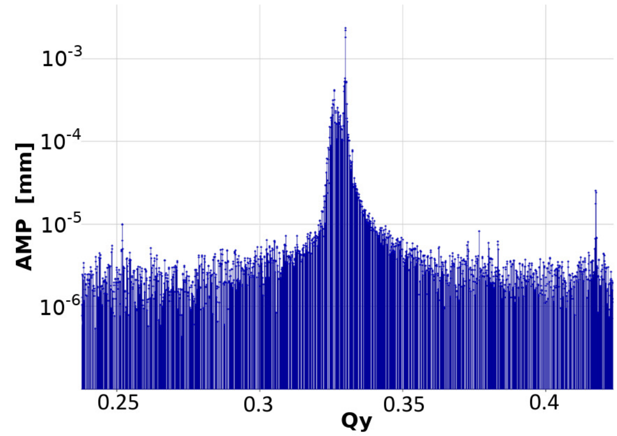

Figure 8: Measured vertical spectra with BGI enabled and empirical correction to minimize beam-loss applied.

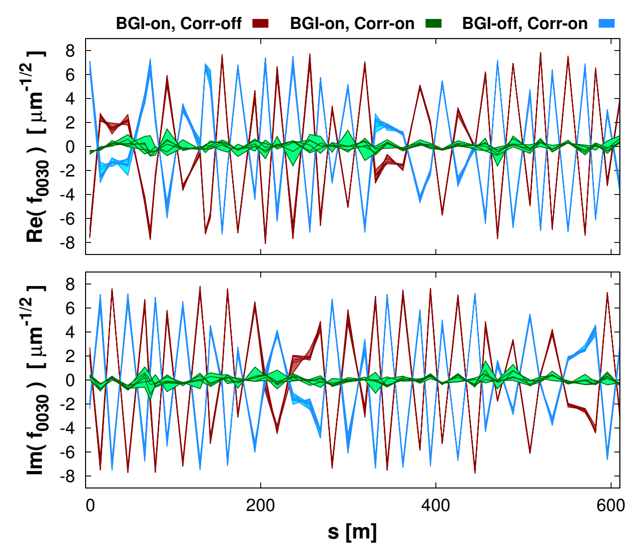

Figure 9: Real and imaginary parts of f_{0030} with BGI enabled before (red) and after (green) correction. f_{0030} with correction on and BGI off is also shown (blue).

CONCLUSIONS

PS beam-loss upon crossing $3Q_y$ indicated a substantial a_3 was generated by the BGI instrument. Measurement of chromatic coupling was consistent with expectation from magnetic simulations that the BGI should be the dominant a_3 source in the PS. Measurements of Q feed-down find a similar magnitude source as expected, but reveal an error in the sign which is under investigation. A clear measurement of the f_{0030} RDT was obtained via ADT-AC-dipole excitation. Corrections determined to minimize beam-losses were found to have minimized f_{0030}.

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