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MATCHING STUDIES BETWEEN THE CERN PSB AND PS USING TURN-BY-TURN BEAM PROFILE ACQUISITIONS WITH A RESIDUAL BEAM GAS IONISATION MONITOR

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Abstract

In the framework of the LHC Injectors Upgrade (LIU) project, the Beam Gas Ionisation (BGI) profile monitors installed in the Proton Synchrotron (PS) were fitted with a gas injection system capable of boosting the signal rate high enough to capture single turn acquisitions immediately after injection. This contribution reports on the studies carried out during the beam commissioning of the BGI system in a turn-by-turn matching monitor mode for its eventual implementation in an optimisation framework to preserve emittance during transfer between the PS Booster and PS. The BGI commissioning included a benchmarking with data from a wire-grid secondary emission monitor (BSG) inserted into the circulating beam.

INTRODUCTION

The PS injection kinetic energy was increased from 1.4 to 2.0 GeV to reduce the degradative effects of space-charge as the beam brightness delivered by the Proton Synchronous Booster (PSB) is increased in preparation for the future high luminosity operation of the LHC [1]. The injection system, including the fast-pulsed kickers, septum and transfer line, was upgraded to cope with the increased beam rigidity and to remove the horizontal dispersion mismatch between the PSB and PS. The mismatch would have driven significant emittance growth as the longitudinal emittance (and momentum spread) of the beam is voluntarily increased to help alleviate space-charge effects [2].

The BGI profile monitor system deployed in the PS is capable of providing continuous, bunch-by-bunch and turn-by-turn measurements of the transverse beam profile [3]. Two instruments were installed in Straight Sections (SS) 82 and 84 of the PS for horizontal and vertical profile measurements, respectively. The system was exploited to study the turn-by-turn evolution of the beam envelope immediately after injection and to provide an operational tool to quantify and correct optical mismatch to prevent emittance dilution. Past studies of injection mismatch exploited wire-grids actuated into the circulating beam aperture [4, 5]. Although the wire-grid matching monitor system is well-established, the interaction of the circulating beam with the grid limits the number of turns that can circulate in the machine before it must be dumped to avoid damaging the wires. As a result, the time available for injection mismatch studies has been severely limited because inserting the wire-grids prevents operation of the CERN accelerator complex downstream of the PS. The BGI circumvents this limitation in almost all operational modes, except for parallel ion operation where the injection of gas was observed to degrade the ion lifetime.

TURN-BY-TURN ACQUISITION MODE

Measurement Conditions

The matching monitor studies were carried out with a relatively low intensity, single bunch LHC beam injected from the PSB containing $70-130\times10^{10}$ protons, compatible with the damage limit of the wire-grids, and with a longitudinal emittance of 2 eVs. The LHC cycle operates at a low chromaticity to combat the increased chromatic tune spread from the larger longitudinal emittance. The transverse feedback system is used to stabilise the beam against head-tail instabilities on the injection plateau, rather than relying on linear coupling as done in the past [6]. This paper only considers the horizontal plane because when the measurements were carried out only the horizontal BGI instrument in SS82 was available.

Beam Loss and Background Noise

The BGI profile monitor uses electric and magnetic fields to transport electrons from rest-gas ionisation to a Timepix3 [7] based detection system installed directly inside the beam vacuum. The beam profile is inferred from the transverse distribution of the detected electrons, which is disrupted when charged particles from other sources impinge the detector. The main source of background events stems from beam particles lost on the machine's aperture and the resulting secondary particle showers. The level of background noise is typically negligible throughout the PS cycle and can be filtered reasonably well online by discriminating on the energy of the pixel events alone. However, the beam loss intrinsic to and taking place during the injection process made the background rejection and data analysis more challenging when exploiting the BGI as an injection matching monitor.

Readout Rate Limitations

The readout rate (ionisation electrons per turn) of the front-end electronics was observed to saturate above the theoretical detector readout limit of 160 MHz or ~ 350 events per turn. Figure 1 shows the count rate of ionisation electrons as a function of the circulating beam intensity and gas pressure. The readout rate was also affected by the level of background events crowding the data acquisition system, which depends on the amount of beam lost during the injection process. A

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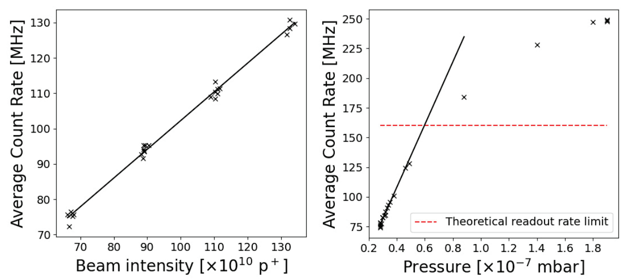
satisfactory signal-to-noise level of a few hundred ionisation events per turn could be attained after some optimisation of the beam loss at injection and a local vertical bump at BGIH82, whilst remaining compatible with the rate limit of the data acquisition system. The analysis, discussed in more detail below, had to be carried out offline in order to carefully remove the relatively large number of beam loss events based on their characteristically shaped clusters, compared to the single pixel events from the ionisation electrons, and to ensure that the timestamp of each event is assigned to the correct turn in the cycle.



(a) Pressure ≈ 3×10^{-8} mbar (b) Beam intensity ≈ 70×10^{10} p$^+$

Figure 1: Readout rate of ionisation electrons measured during the first 30 turns after injection in the PS.

Emittance Blow-up From Gas Injection

For the 200 - 300 ionisation events needed to profile the beam every turn, a pressure of $\sim 1 - 10 \times 10^{-8}$ mbar of argon was needed for the low intensity LHC bunch studied. Even at the higher end of this pressure range the emittance blow-up from the beam's interaction with the gas via multiple Coulomb scattering is negligible and estimated at 0.1% along the 1.2 s duration of the injection plateau. This is in stark contrast to the large emittance blow-up and beam loss observed when using the wire-grid system [4].

Data Analysis

Due to different limitations of the online front-end software in turn-by-turn mode, the raw data files were saved and analysed offline using a dedicated software package `TeddyBear` [8] provided by the CERN BGI team. Although more time consuming, a short acquisition of the first 30 turns after injection could be analysed in under 20 seconds on a control room console. Longer acquisitions of several hundreds of turns could be acquired without problems but with longer processing times. However, short acquisitions including the first 10 - 30 turns are sufficient to observe and quantify injection mismatch.

The relatively large contribution of dispersion (D) to the beam size on the PS injection plateau, where $\sqrt{\beta\epsilon} \sim D\Delta p/p$, leads to transverse beam profiles that are not strictly Gaussian because of the parabolic nature of the $\Delta p/p$ distribution. Nevertheless, a Gaussian fit to the transverse profiles was shown to be a robust technique for quantifying the beam size and its evolution. Fortunately, for the matching monitor application a good resolution of the turn-by-turn variation of the beam size after injection is of utmost importance, rather than the absolute accuracy of the measurement itself. A satisfactory spatial resolution could be attained whilst at the same time boosting the signal-to-noise ratio by re-binning the Timepix3 detector's resolution by a factor of 20, from 55 μm to 1 mm. Each profile was fitted on the n^{th} turn with a 5-parameter Gaussian fit to return the beam size (σ_n) and position (μ_n). The variance of the beam size (M^2) during the first N-turns was used as the figure-of-merit to quantify the level of injection mismatch,

$$M^2 = \sum_{n=1}^{N} (\sigma_n - \bar{\sigma})^2 / N, \tag{1}$$

where the average beam size is given by $\bar{\sigma} = \sum_{n=1}^{N} \sigma_n / N$.

DISPERSION MISMATCH

The BGI's turn-by-turn acquisition mode could be used to measure the beam trajectory after injection and compare it to the data acquired with the Beam Position Monitor (BPM) and BSG systems. The dispersion was measured every turn by varying the injected beam momentum and correlating it with the beam position; the amplitude of the dispersion mismatch (M_D) could be measured by observing the turn-by-turn dispersion beating at the frequency of the fractional tune (q_x),

$$\Delta D(n) = M_{D_x} \cos\left(\theta + 2\pi(n-1)q_x\right). \tag{2}$$

This formalism for quantifying injection mismatch can be found described in more detail in [4,5]. The improvement of the dispersion matching after the upgrade of the PS injection system during the recent Long Shutdown 2 (LS2: 2018 - 2021) was clearly observed and is shown in Fig. 2.

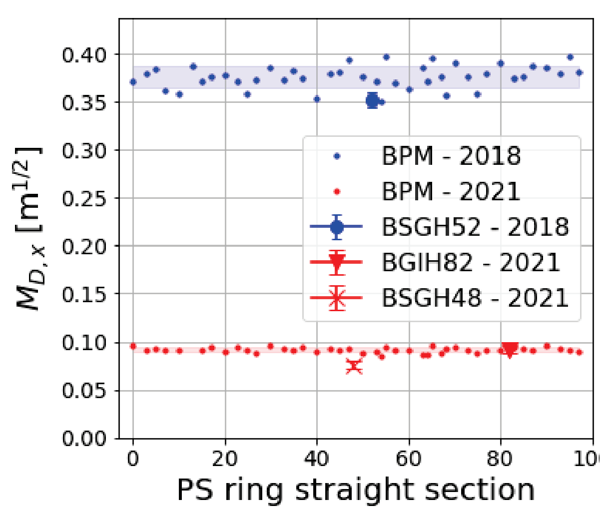


Figure 2: Horizontal dispersion mismatch factor (M_{D_x}) measured during the first 30 turns after injection in the PS.

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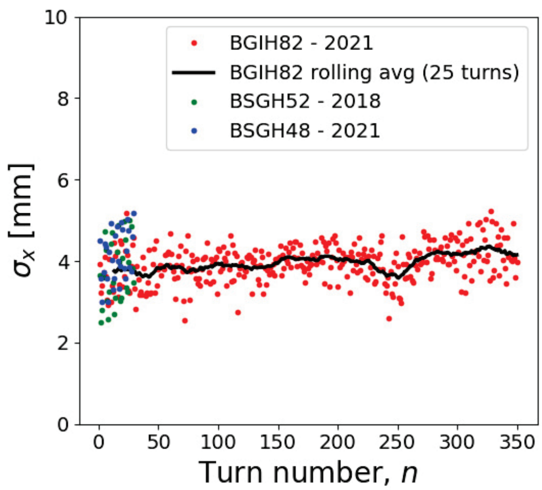
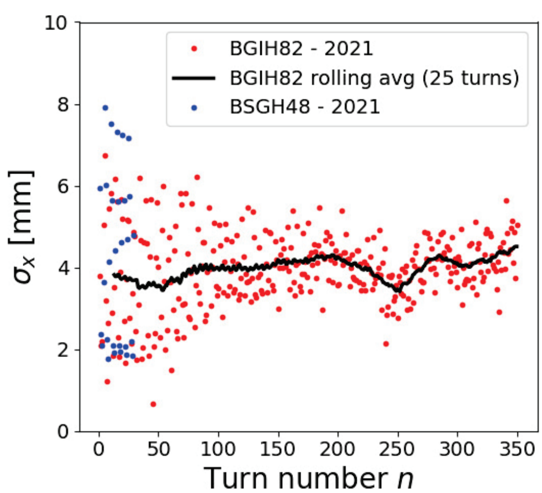
MATCHING MONITOR MEASUREMENTS

The gradient (K_1) of the final quadrupole (BTP.QNO60) in the injection transfer line was varied to voluntarily mismatch the beam. The turn-by-turn beam size measured on both BGIH82 and BSGH48 during the first 350 turns after injection is compared for the nominal quadrupole gradient and a mismatched case in Fig. 3. Data taken on BSGH52 before LS2 shows that the amplitude of the beam envelope beating has been reduced, however, a direct comparison is difficult to make because of the different emittances, and in particular, the increased momentum spread after LS2.



(a) $\Delta K_1/K_1 = 0$ %



(b) $\Delta K_1/K_1 = -16$ %

Figure 3: Example turn-by-turn beam size measurements compared between the BGIH82 and BSGH48.

The filamentation of the beam envelope in the mismatched case is clearly observed, along with a hint of slow growth of the average beam size in both cases. The sudden reduction of the beam size after ~ 250 turns happens to coincide with the end of the injection bump as it collapses to zero and when the closed-orbit is violently perturbed. The perturbation is caused by a poor regulation of the currents in the independently powered in and out-of-vacuum injection bumper magnets as the current tends to zero. Further studies are needed to assess the significance of this effect and the perturbation on the optics seen by the circulating beam.

The mismatch parameterised by M in Eq. 1 and measured over a different number of turns after injection using the BGI is presented in Fig 4. For longer acquisitions, M is observed to decrease as expected when it is averaged over timescales longer than the filamention time. The sensitivity to mismatch is evident and the comparison with the BSG system is impressive, with short acquisitions of only 10 turns needed to quantify the mismatch. A significant level of noise persists on the measured beam envelope, even in the matched case, and well after the apparent filamentation time, which requires further investigation and may limit the ultimate performance of the matching monitor.

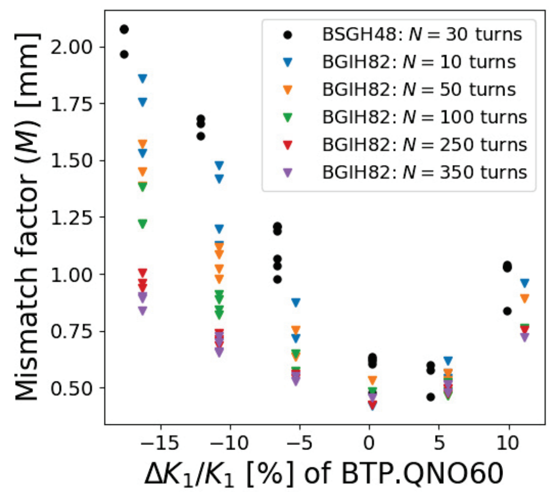


Figure 4: Mismatch factor (M): BGIH82 vs. BSGH48 measured over a different number of turns (N) after injection.

SUMMARY AND OUTLOOK

With the addition of a gas injection system, the PS BGI system has been exploited to observe emittance blow-up along the cycle and to optimise optical matching at injection. Further work is needed to commission the vertical BGI system and to implement the data analysis into an online optimisation framework [9] that can be deployed opertionally. An updated version of the BGI readout electronics is under development, which aims to carry out more of the offline processing presented in this paper on the front-end electronics. This is done through the use of an Xilinx MPSoC device [10] that contains processors capable of running Linux and programmable logic on the same chip with high-speed connections between them. The steps of the event processing can therefore be optimised across different domains and standard software libraries, such as `TeddyBear`, can be used online.

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