ADVANCING BEAM QUALITY CONTROL IN THE CERN PROTON SYNCHROTRON

M. Coly, A. Akroh, Z. Ansari, A. Beeckman, D. Cotte, J. Flowerdew, G. Imesch, A. Huschauer, A. Lasheen, R. Maillet, J. Mccarthy, K. Sabin, S. Sainz Pérez, M. Schenk, Y. Wu
CERN, Geneva, Switzerland

Abstract

Over the past years, the beam quality delivered by the CERN Proton Synchrotron (PS) has significantly improved, driven by major upgrades to both the accelerator and its controls infrastructure. As a result, user requirements have become increasingly demanding, particularly for high-brightness beams for the LHC, but also for fixed-target beams. The PS, known for its versatility in supplying beams with widely varying characteristics to multiple facilities, must now meet tighter performance specifications while maintaining reliability and operational efficiency.

To address these challenges, a new beam quality monitoring framework has been developed, building on recent enhancements in data acquisition and online analysis capabilities. The system defines key beam quality metrics in real time, enabling early detection of drifts, root-cause fault analysis, and provides the foundation for automated corrections and machine learning-based optimisation. Complementing this analytical layer, a dedicated graphical interface provides operators with live observability of key parameters and short-term trends, facilitating rapid decision-making in the control room.

This new approach represents a step change in the way beam quality is monitored and maintained in the PS, from reactive diagnostics to proactive control, supporting both operational stability and the increasingly stringent demands of CERN's experimental program.

INTRODUCTION

The CERN Proton Synchrotron (PS) is part of the CERN injector chain providing beams both for fixed-target experiments and for downstream accelerators such as the Super Proton Synchrotron (SPS) and the Large Hadron Collider (LHC). The PS must deliver beams with a wide range of intensities, bunch structures, and emittances.

With ever-higher performance targets, maintaining beam quality throughout the PS cycle becomes increasingly important. Small deviations in beam parameters can propagate through the injector chain and affect downstream machine performance.

To improve observability of beam conditions during operation, a Beam Quality Monitoring (BQM) framework has been developed. The system combines beam instrumentation data with online analysis algorithms to derive quantitative indicators of beam quality.

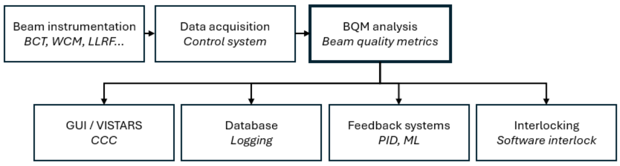

Figure 1: Conceptual architecture of the BQM framework. Signals from beam instrumentation, notably Beam Current Transformers (BCT), Wall Current Monitors (WCM), and Low-Level Radio Frequency (LLRF) systems, are processed online to derive beam quality metrics for several operational purposes.

BEAM QUALITY MONITORING FRAMEWORK

The BQM framework combines beam diagnostics acquisition, online analysis, and data visualisation for operations. Instrumentation data is acquired through the accelerator control system and processed in real time to extract beam quality observables serving as inputs to operational data displays.

These observables are transformed into beam quality metrics describing beam stability and reproducibility throughout the PS beam production processes. Figure 1 shows that the resulting metrics are displayed in operational interfaces used in the CERN Control Centre (CCC) supporting both routine operation and machine development studies.

BQM USE CASES IN PS OPERATION

To help the operations team, BQM metrics are exposed in different ways, depending on operational needs and use cases. The following subsections present representative examples.

Machine-Learning Tools: MTE Efficiency

The BQM framework provides observables to evaluate the efficiency of the Multi-Turn Extraction (MTE) process for the SPS fixed-target experiments, in which the beam is split into five beamlets in the horizontal phase space before extraction [1].

MTE is a resonance-based technique whose performance is determined by the uniformity of the intensity distribution across the beamlets, namely four islands and one core, as illustrated in Fig. 2. The BQM observable, named MTE splitting efficiency, is defined as the average intensity in the islands divided by the total intensity:

$$\eta_{\mathrm{MTE}} = \langle I_{\mathrm{islands}} \rangle / I_{\mathrm{total}}. \quad (1)$$

In case of quality drifts, the operations team can use a machine-learning-based optimisation algorithm to adjust PS

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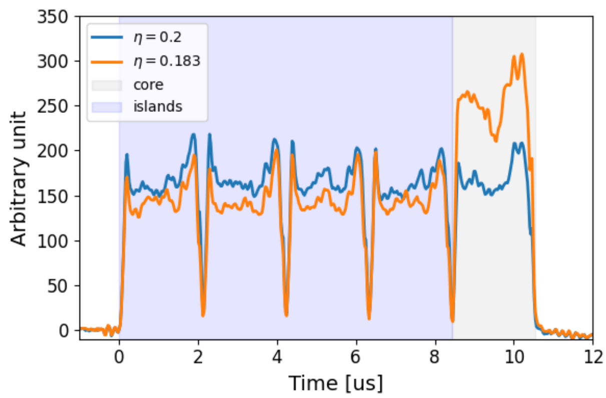

Figure 2: Signal acquired from a BCT in the PS downstream transfer line, from which the intensities of the five MTE beamlets are measured over time. The core is greyed out in the figure. The blue trace corresponds to a balanced intensity distribution across the five beamlets, yielding an optimal splitting efficiency of 0.2, whereas the orange trace corresponds to a higher core intensity and therefore a lower splitting efficiency of 0.183.

machine settings, such as the horizontal tune, to recover efficient beam splitting. The algorithm uses the MTE efficiency observable from the BQM framework as input to a Gaussian Process model [2] to help recover optimal performance.

Operator GUI: CBFB Instability Indicators

Longitudinal coupled-bunch activity is monitored online using instrumentation from the PS LLRF coupled-bunch feedback (CBFB) system. As described in Ref. [3], the CBFB acquisition system provides measurements of the longitudinal beam behaviour at different harmonics in the form of in-phase (I) and quadrature (Q) components, from which the amplitude of the coupled-bunch mode signal M is obtained as:

$$M(t) = \sqrt{I(t)^2 + Q(t)^2}. \tag{2}$$

For each monitored harmonic, dipole and quadrupole sideband amplitudes are recorded during the cycle. The instability indicator is defined as the maximum sideband amplitude across all the modes within an evaluation time window, as follows:

$$A_{\text{mode}} = \max_{t \in [t_1, t_2]} M_{\text{mode}}(t). \tag{3}$$

Dipole sidebands correspond to centroid oscillations of the bunches, while quadrupole sidebands are associated with bunch length oscillations. Figure 3 shows representative diagnostics from stable and unstable beams used for the High Luminosity (HL)-LHC Reliability Run [4], allowing rapid identification of dipolar coupled-bunch activity. The derived observable is then published through the control system and monitored in an operational GUI shown in Fig. 4.

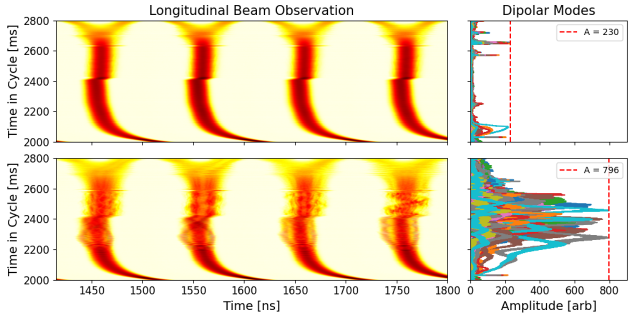

Figure 3: Representative CBFB diagnostics. The first row corresponds to a stable beam, while the second row shows an unstable beam with coupled-bunch instabilities. The left-hand panels show longitudinal waterfall plots of the last 4 bunches of an LHC-type beam at flat top energy (measured with a WCM), and the right-hand panels show the magnitude of the dipolar coupled-bunch instabilities, with each line series corresponding to a mode, and the corresponding observable value A.

VISTAR Views: LHC-type Beam Metrics

In the CCC, large shared screens known as VISTARs, display important information on accelerator performance and are visible throughout the control room. Their content is also distributed via a CERN-wide video stream, allowing teams in the experimental areas to follow machine status in real time. One of these displays is dedicated to the performance of LHC-type beams in the PS, in particular bunch-by-bunch intensity and bunch length (see Fig. 5). The longitudinal beam profile is measured just before PS extraction using the Longitudinal Beam Observation (LBO) system [5] where it is then processed bunch-by-bunch. For the multibunch LHC-type beam used in the HL-LHC Reliability Run, the BQM performs Gaussian fits to a 72 bunch train using:

$$I(t) = a \exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right) + ct + d, \tag{4}$$

where a is the Gaussian amplitude, μ is the bunch centre, σ corresponds to one quarter of the bunch length, and $ct + d$ represents the linear baseline.

The fit is used to extract the intensity and length of each bunch. These observables are required to remain stable over time and as uniform as possible across all bunches within the train in order to maintain a balanced bunch pattern, which is particularly challenging for high-brightness beams. Displaying them on the VISTAR provides fast visibility of drifts in RF manipulations and supports immediate operator checks during production.

Beam Interlocking: Target Brightness Criteria

The PS delivers beam to the neutron time-of-flight (n_TOF) experimental area, where a spallation target [6] is used to produce a neutron beam. To operate below potential damage limits and ensure longevity of the target, beam interlocking relies on brightness-related criteria. A secondary emission monitor (SEM) located upstream of the target is

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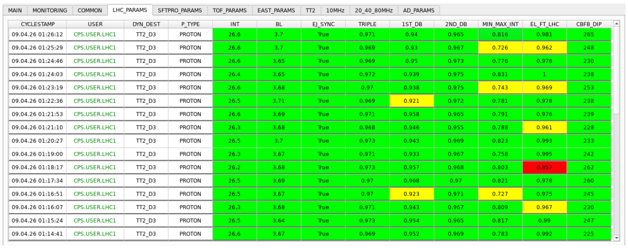

Figure 4: Operational BQM interface used in the CCC. Beam quality indicators are colour-coded according to predefined thresholds (green: nominal, yellow: warning, red: fault).

used to measure the transverse beam profile, from which the BQM derives the horizontal and vertical beam sizes σ_{hor} and σ_{ver}. The beam intensity (I) is measured by a BCT located just upstream. These observables are combined into a brightness metric defined as:

$$B = \frac{I}{\sigma_{\text{hor}}\sigma_{\text{ver}}}, \quad (5)$$

which is used to identify conditions that may exceed target constraints. When thresholds are approached, warnings are generated; when limits are exceeded, an interlock signal is sent through the PS interlocking system described in Ref. [7] to the PS Booster, the PS proton injector, to inhibit beam production and protect the target from being hit by an excessively bright beam.

OPERATIONAL MONITORING INTERFACE

The application-oriented metrics, forming a subset of the broader BQM metrics, are integrated into an operational interface used in the CCC, shown in Fig. 4. The interface provides a compact overview of critical metrics for each beam type, including MTE efficiency, CBFB instability indicators, longitudinal splitting quality, brightness-related interlocking status, and many other metrics.

Each metric is evaluated against predefined warning and fault thresholds. Their definition and adjustment are an essential part of the system commissioning process, ensuring consistency across the machine cycles. Values within the nominal operating range are displayed in green, while warning and fault conditions are highlighted in yellow and red, respectively.

The layout configuration and the set of monitored metrics are easily adjustable via configuration files, making the GUI adaptive to varying operational requirements.

This unified overview allows operators to react quickly in case of drifts, correlate degradations across subsystems, and supports reliability runs with consistent beam-quality supervision.

CONCLUSION

A BQM framework has been developed for the CERN Proton Synchrotron to provide real-time observability of beam quality during operation.

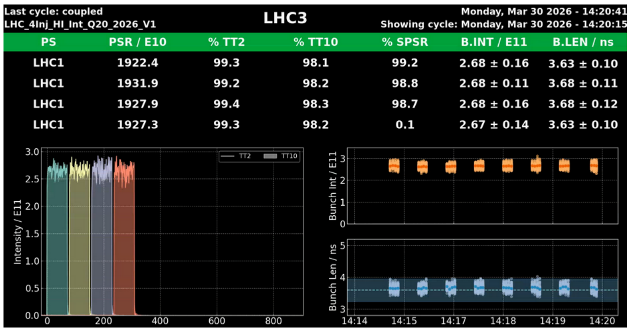

Figure 5: Example of a "PS-to-SPS" VISTAR view used to monitor longitudinal beam quality during operation. The left plot shows four batches of a 72 bunch LHC-type beam measured with a BCT in a PS downstream transfer line. On the right, the red series shows the bunch-by-bunch intensity as a function of time, while the blue series shows the evolution of the bunch length over time.

The system combines beam instrumentation data with online analysis algorithms to derive compact indicators describing beam behaviour. The resulting application-oriented metric set supports, for example, machine-learning optimisation of MTE, GUI-based CBFB diagnostics, VISTAR monitoring of longitudinal splitting, and beam-interlocking supervision based on brightness criteria at target.

The framework is now used intensively in daily operation and has also become an important tool for the HL-LHC Reliability Run. It is used not only by operations teams, but also by equipment and beam specialists, thereby strengthening collaboration across teams. It requires clear metric specifications and centralizes data from various systems in order to provide data for offline performance analysis through the logging database. This collection of data forms the core of future automation efforts, as it is building a comprehensive database for machine learning, enabling advanced predictive analytics and optimization of operational processes.

In the future, the approach could be extended to other CERN accelerators and enriched with additional observables, such as transverse emittance measurements, which could allow for the monitoring of instabilities or emittance growth.

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